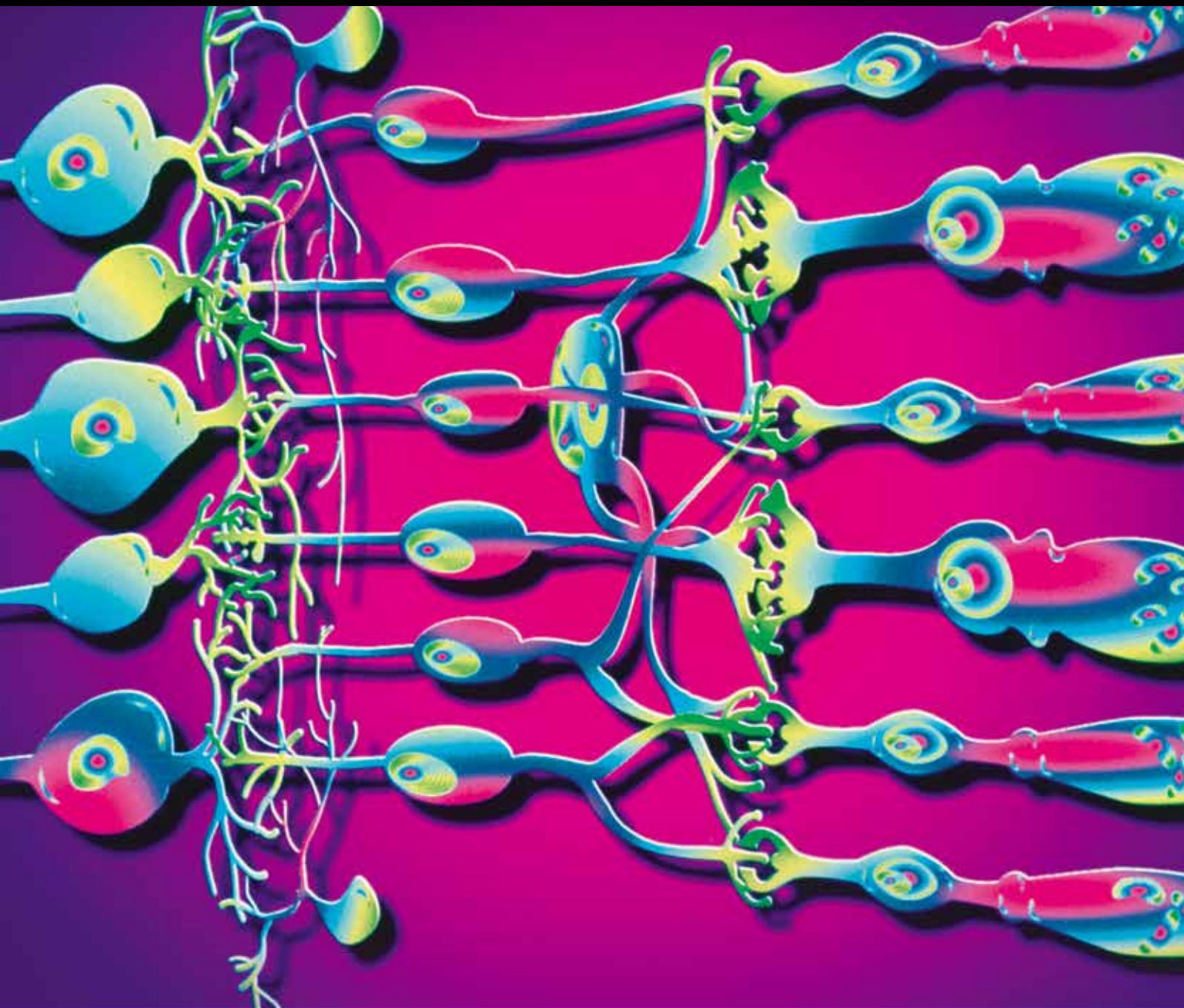


Eye Movement Control

Guest Editors: Stefanie I. Becker, Gernot Horstmann, and Arvid Herwig





Eye Movement Control

Journal of Ophthalmology

Eye Movement Control

Guest Editors: Stefanie I. Becker, Gernot Horstmann,
and Arvid Herwig



Copyright © 2014 Hindawi Publishing Corporation. All rights reserved.

This is a special issue published in "Journal of Ophthalmology." All articles are open access articles distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Editorial Board

M. L. Acosta, New Zealand
Hee B. Ahn, Korea
Luis Amselem, Spain
Usha P. Andley, USA
S. Ansari-Shahrezaei, Austria
Taras Ardan, Czech Republic
F. Arnalich-Montiel, Spain
Takayuki Baba, Japan
Antonio Benito, Spain
Mehmet Borazan, Turkey
Gary C. Brown, USA
David J. Calkins, USA
Francis Carbonaro, Malta
Chi-Chao Chan, USA
Haoyu Chen, China
Lingyun Cheng, USA
Chung-Jung Chiu, USA
Daniel C. Chung, USA
Colin Clement, Australia
Miguel Cordero-Coma, Spain
Vasilios F. Diakonis, USA
Priyanka P. Doctor, India
Michel E. Farah, Brazil
Paolo Fogagnolo, Italy
Farzin Forooghian, Canada
Brian A. Francis, USA
Joel Gambrelle, France
M.-A. Gamulescu, Germany
Ian Grierson, UK
Vlassis Grigoropoulos, Greece
Koray Gumus, Turkey
Vishali Gupta, India

Takaaki Hayashi, Japan
Takeshi Ide, Japan
Vishal Jhanji, Hong Kong
Thomas Klink, Germany
Naoshi Kondo, Japan
Bobby S. Korn, USA
Ozlem G. Koz, Turkey
Rachel W. Kuchtey, USA
Hiroshi Kunikata, Japan
Toshihide Kurihara, Japan
George D. Kymionis, Greece
Timothy Y. Lai, Hong Kong
Van C. Lansingh, USA
Theodore Leng, USA
C. Leung, Hong Kong
Kin S. Lim, UK
Paloma B. Liton, USA
Marco Lombardo, Italy
Tamer A. Macky, Egypt
Edward Manche, USA
Flavio Mantelli, Italy
E. Mencia-Gutiérrez, Spain
Marcel N. Menke, Switzerland
Lawrence S. Morse, USA
Darius M. Moshfeghi, USA
Majid M. Moshirfar, USA
Hermann Mucke, Austria
R. Naranjo-Tackman, Mexico
Magella M. Neveu, UK
Neville Osborne, UK
Suresh K. Pandey, India
Jijing Pang, USA

Anand Parthasarathy, Singapore
Enrico Peiretti, Italy
Pai-Huei Peng, Taiwan
David P. Piñero, Spain
Pawan Prasher, India
Yi Qu, China
Antonio Queiros, Portugal
Eduardo B. Rodrigues, Brazil
Dirk Sandner, Germany
Ana R. Santiago, Portugal
Patrik Schatz, Sweden
Kyoung Y. Seo, Republic of Korea
Wisam A. Shihadeh, USA
Bartosz Sikorski, Poland
Katsuyoshi Suzuki, Japan
S. K. Swamynathan, USA
Suphi Taneri, Germany
Christoph Tappeiner, Switzerland
Stephen C. Teoh, Singapore
P. G. Theodossiadis, Greece
Biju B. Thomas, USA
Lisa Toto, Italy
David A. Wilkie, USA
Wai T. Wong, USA
Victoria W. Y. Wong, Hong Kong
S. Chien Wong, UK
Huseyin Yetik, Turkey
Terri L. Young, USA
Hyeong Gon Yu, Republic of Korea
Hunter Yuen, Hong Kong
Vicente Zanon-Moreno, Spain

Contents

Eye Movement Control, Stefanie I. Becker, Gernot Horstmann, and Arvid Herwig
Volume 2014, Article ID 262541, 2 pages

Inhibition of Return in Fear of Spiders: Discrepant Eye Movement and Reaction Time Data,
Elisa Berdica, Antje B. M. Gerdes, Andre Pittig, and Georg W. Alpers
Volume 2014, Article ID 183924, 8 pages

Centre-of-Gravity Fixations in Visual Search: When Looking at Nothing Helps to Find Something,
Dustin Venini, Roger W. Remington, Gernot Horstmann, and Stefanie I. Becker
Volume 2014, Article ID 237812, 14 pages

The Bifixation Field as a Function of Viewing Distance, Philip M. Grove, Alistair P. Mapp,
and Hiroshi Ono
Volume 2014, Article ID 274803, 13 pages

Alterations of Eye Movement Control in Neurodegenerative Movement Disorders, Martin Gorges,
Elmar H. Pinkhardt, and Jan Kassubek
Volume 2014, Article ID 658243, 11 pages

Selective Age Effects on Visual Attention and Motor Attention during a Cued Saccade Task,
Wendy E. Huddleston, Brad E. Ernest, and Kevin G. Keenan
Volume 2014, Article ID 860493, 11 pages

Using Eye Tracking to Assess Reading Performance in Patients with Glaucoma: A Within-Person Study,
Nicholas D. Smith, Fiona C. Glen, Vera M. Mönter, and David P. Crabb
Volume 2014, Article ID 120528, 10 pages

Salient Distractors Can Induce Saccade Adaptation, Afsheen Khan, Sally A. McFadden, Mark Harwood,
and Josh Wallman
Volume 2014, Article ID 585792, 11 pages

Response Time, Visual Search Strategy, and Anticipatory Skills in Volleyball Players, Alessandro Piras,
Roberto Lobietti, and Salvatore Squatrito
Volume 2014, Article ID 189268, 10 pages

Suppression of Face Perception during Saccadic Eye Movements, Mehrdad Seirafi, Peter De Weerd,
and Beatrice de Gelder
Volume 2014, Article ID 384510, 7 pages

Attentional Capture and Inhibition of Saccades after Irrelevant and Relevant Cues, Heinz-Werner Priess,
Nils Heise, Florian Fischmeister, Sabine Born, Herbert Bauer, and Ulrich Ansorge
Volume 2014, Article ID 585921, 12 pages

Human Gaze Following Response Is Affected by Visual Acuity, Marcella Spoor, Behdokht Hosseini,
Bart van Alphen, Maarten A. Frens, and Jos N. van der Geest
Volume 2014, Article ID 543478, 7 pages

**The Influence of Attention and Target Identification on Saccadic Eye Movements Depends on Prior
Target Location**, David R. Hardwick, Timothy R. H. Cutmore, and Trevor J. Hine
Volume 2014, Article ID 850606, 10 pages

Editorial

Eye Movement Control

Stefanie I. Becker,¹ Gernot Horstmann,² and Arvid Herwig²

¹ School of Psychology, University of Queensland, Brisbane, QLD 4072, Australia

² Department of Psychology, Bielefeld University, 3361 Bielefeld, Germany

Correspondence should be addressed to Stefanie I. Becker; s.becker@psy.uq.edu.au

Received 11 June 2014; Accepted 11 June 2014; Published 21 July 2014

Copyright © 2014 Stefanie I. Becker et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

It is well-known that eye movements are central to visual perception [1]. Visual acuity decreases dramatically in the periphery of vision, and precise eye movements to specific locations are vital to foveate objects of interest and identify them with high accuracy [1–4]. Given the importance of eye movements for visual perception, there has been a surge of interest in the topic, with numerous studies being conducted to clarify the variables that determine our eye movements (for a historical review see [5]).

In fact, Google Scholar shows that eye movements are discussed in over a million publications, and a Web of Science search reveals 17,000 publications with eye movement in the title or abstract. As shown in Figure 1, the number of publications with eye movement in the title or abstract has also steadily increased over years, culminating in about 200 papers published in 2013.

Despite the surge of interest in eye movements, many questions remain unresolved. This is also reflected in this special issue on eye movement control. First, there are a variety of different eye movements [2, 4]. Among the most widely known eye movements are the fast, ballistic saccades (including superfast express saccades) (e.g., B. de Gelder et al., this issue), smooth-pursuit eye movements (J. N. van der Geest et al., this issue), and vergence eye movements (e.g., P. M. Grove et al., this issue) required to fixate objects at different depths. Less well-known and yet intensely researched are

microsaccades, tremor, slow drift, and vestibuloocular and optokinetic eye movements that stabilize gaze during motions of the head and motions of large regions of the image on the retina [2, 4].

Secondly and more importantly for the current special issue, eye movements are also controlled by a variety of different factors [1, 4]. Apart from being subject to diverse muscular and ocular constraints, successful voluntary control over eye movements critically depends on the quality of the visual input, which in turn depends on a variety of internal and external factors [1, 6, 7]. The contributions to the present special issue clarify key elements of both internal and external factors in eye movement control (G. W. Alpers et al., U. Ansorge et al., B. de Gelder et al., P. M. Grove et al., D. R. Hardwick et al., W. E. Huddleston et al., J. Kassubek et al., A. Khan et al., A. Piras et al., N. D. Smith et al., J. N. van der Geest et al., and D. Venini et al., this issue).

In the present contributions, eye movements have also been used to provide new insights into ocular and neurological disorders (J. Kassubek et al., N. D. Smith et al., this issue) and shed new light on the relationship between covert attention and eye movements (e.g., G. W. Alpers et al., U. Ansorge et al., D. R. Hardwick et al., and A. Khan et al., this issue; see also [6–9]). Together, the papers in this special issue provide a timely update on eye movement control that reflects current hot topics in the field, spanning the range

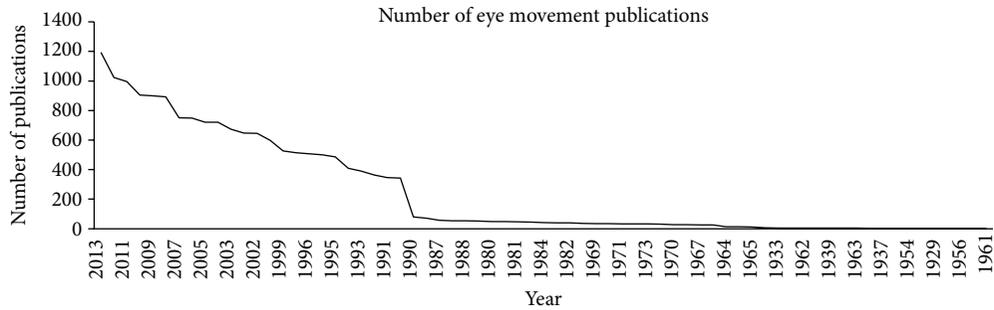


FIGURE 1: The number of publications with the “eye movement” in the title or abstract, according to a Web of Science search 2014.

from cognitive science over applied psychology to clinical psychology and neuroscience.

Stefanie I. Becker
Gernot Horstmann
Arvid Herwig

References

- [1] K. Rayner, “Eye movements in reading and information processing: 20 years of research,” *Psychological Bulletin*, vol. 124, no. 3, pp. 372–422, 1998.
- [2] S. Martinez-Conde, S. L. Macknik, and D. H. Hubel, “The role of fixational eye movements in visual perception,” *Nature Reviews Neuroscience*, vol. 5, no. 3, pp. 229–240, 2004.
- [3] A. C. Schütz, D. I. Braun, and K. R. Gegenfurtner, “Eye movements and perception: a selective review,” *Journal of Vision*, vol. 11, no. 5, pp. 1–30, 2011.
- [4] D. A. Robinson, “Control of eye movements,” *Comprehensive Physiology*, pp. 1275–1320, 2011.
- [5] N. J. Wade and B. W. Tatler, *The Moving Tablet of the Eye: The Origins of Modern Eye Movement Research*, Oxford University Press, Oxford, UK, 2010.
- [6] S. I. Becker, “The role of target-distractor relationships in guiding attention and the eyes in visual search,” *Journal of Experimental Psychology*, vol. 139, no. 2, pp. 247–265, 2010.
- [7] A. Herwig and W. X. Schneider, “Predicting object features across saccades: evidence from object recognition and visual search,” *Journal of Experimental Psychology*. In press.
- [8] G. Rizzolatti, L. Riggio, I. Dascola, and C. Umiltà, “Reorienting attention across the horizontal and vertical meridians: evidence in favor of a premotor theory of attention,” *Neuropsychologia*, vol. 25, no. 1, pp. 31–40, 1987.
- [9] T. Moore and M. Fallah, “Control of eye movements and spatial attention,” *Proceedings of the National Academy of Sciences of the United States of America*, vol. 98, no. 3, pp. 1273–1276, 2001.

Research Article

Inhibition of Return in Fear of Spiders: Discrepant Eye Movement and Reaction Time Data

Elisa Berdica, Antje B. M. Gerdes, Andre Pittig, and Georg W. Alpers

Department of Psychology, Clinical and Biological Psychology and Psychotherapy, School of Social Sciences, University of Mannheim, L13, 15-17, 68131 Mannheim, Germany

Correspondence should be addressed to Georg W. Alpers; alpers@uni-mannheim.de

Received 11 November 2013; Accepted 12 May 2014; Published 3 July 2014

Academic Editor: Gernot Horstmann

Copyright © 2014 Elisa Berdica et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Inhibition of return (IOR) refers to a bias against returning the attention to a previously attended location. As a foraging facilitator it is thought to facilitate systematic visual search. With respect to neutral stimuli, this is generally thought to be adaptive, but when threatening stimuli appear in our environment, such a bias may be maladaptive. This experiment investigated the influence of phobia-related stimuli on the IOR effect using a discrimination task. A sample of 50 students (25 high, 25 low in spider fear) completed an IOR task including schematic representations of spiders or butterflies as targets. Eye movements were recorded and to assess discrimination among targets, participants indicated with button presses if targets were spiders or butterflies. Reaction time data did not reveal a significant IOR effect but a significant interaction of group and target; spider fearful participants were faster to respond to spider targets than to butterflies. Furthermore, eye-tracking data showed a robust IOR effect independent of stimulus category. These results offer a more comprehensive assessment of the motor and oculomotor factors involved in the IOR effect.

1. Introduction

We have a limited capacity to process all of the visual information that enters our visual field at any point in time. For this reason, selective attention to salient stimuli is necessary as it helps us decide where to move our eyes next [1]. In this regard, our attentional system enhances the processing of relevant information and diminishes the processing of less relevant information. This preferential detection can be visible in healthy individuals [2] but it is particularly enhanced in anxiety-prone individuals who are vigilant in detecting threat [3–7] and show disengagement deficits later on [7]. This quick detection of threat is evolutionary adaptive; however, when it interferes with everyday activities and generalizes to neutral stimuli, it can exacerbate the individual's anxious state [8].

When studying attentional biases and inhibitory processes, a relevant phenomenon is inhibition of return (IOR). This refers to an attentional bias against returning the attention to a previously attended location. It was first demonstrated by Posner and Cohen [9] in a spatial cueing paradigm. They presented participants a cue and subsequently a target

which appeared in the cued or uncued location. Participants had to press a button when the target appeared. They found a facilitation effect for short stimulus-onset asynchronies (SOAs—the time between the presentation of the cue and the start of the presentation of the target) and an inhibitory aftereffect for longer SOAs (300–3000 ms). Facilitation refers to shorter reaction times to valid trials in comparison to invalid trials for short SOAs (0–300 ms SOA) while inhibition refers to longer reaction times to valid trials in comparison to invalid trials for longer SOAs (300–3000 ms). This inhibitory aftereffect suggests that more time is needed to redirect the attentional system to previously attended than to unattended locations. Its function is considered to be a foraging facilitator and is thought to help optimize visual search [10]. An increased likelihood to inspect new areas is adaptive when it comes to finding food or possible sources of threat. This mechanism suggests that search would not be efficient if we kept returning to locations that were inspected before.

Research on IOR is scant in clinical psychology but may be particularly relevant to anxiety disorders. This delayed response to previously attended locations may be less adaptive when individuals have to detect a threatening target.

Inhibition of threatening information and facilitation of positive information would be a more plausible behavior. For this reason, recent research has started to examine the question whether threatening stimuli can actually interrupt this phenomenon when it is adaptive to pay attention to a fear-evoking cue and not just inhibit its processing. This would be in line with an evolutionary perspective. Until now, however, IOR has been shown to be very robust, nonflexible, even when emotional stimuli were used as cues [11–13]. In a study which employed a simple detection task, we were also unable to find a reduced IOR effect for spider cues and targets, in comparison to butterflies in a high spider fearful group [14]. On the other side, some studies seem to suggest that IOR is not completely immune and can be interrupted in some anxiety-related emotional states such as obsessive compulsive disorder [15], trait anxiety [16–18], and worry [19].

Previous work has mainly involved detection tasks; participants were instructed to press a button to localize the target. In their everyday life people are, however, faced with the need to discriminate and make judgments among a huge variety of stimuli. Therefore, the use of discrimination tasks may be more suitable when it comes to the processing of these emotional stimuli. Such discrimination tasks are used widely in the study of IOR and there is an ongoing debate concerning the time course of the IOR effect in discrimination. Lupiáñez and colleagues [20] argued that in a discrimination task the IOR effect appears later and disappears sooner in comparison to simple detection tasks. When combining discrimination and pictorial stimuli, we are aware of only one previous study which used biologically relevant stimuli in a discrimination task [11]. Taylor and Therrien based the discrimination on the identity of the target (discrimination among face and nonface targets). In the first two experiments they found a larger IOR effect for face targets in comparison to nonface targets when the target was made task relevant. In a third experiment the IOR effect for face targets emerged later than for nonface targets, suggesting that additional processing time may be needed when a task-relevant face target is presented. In their study eye movements were not prohibited.

While constraining the eye movements is common for IOR tasks, one could argue that this might not be representative for normal viewing conditions. Previous research has indeed demonstrated that the IOR effect has a close relationship to eye movements. The attentional and oculomotor components of the IOR effect were evaluated by Hunt and Kingstone [21]. They demonstrated that these components are often independent of one another offering a dissociation between the attentional and motor components of IOR. According to them, IOR reflects a bias against allocating covert attention to a previously cued location when the eyes remain stationary and a bias against executing a saccade to the cued location when the eyes are free to move to the target. However, until now, studies which combine eye-tracking and manual reaction times in an IOR task with fearful stimuli are missing; most of them only use neutral stimuli such as squares, circles, or dots.

Therefore, the present study investigates saccadic reaction times and manual reaction times in an IOR discrimination task. Eye movements were monitored while participants had

to manually discriminate among emotional targets. This study further investigated whether the magnitude of IOR would be modulated by the emotional relevance of the targets that were used. Neutral stimuli were used as cues. In such tasks, the emotionality of the target might be more relevant since the response needs more time to develop. While the reflexive nature of the IOR might suggest that the mechanism underlying this effect should be insensitive to the emotionality of the stimulus that appears after the cue, we propose that the cue should not inhibit the processing of the target, when this target is threatening. For this reason, neutral cues and emotional targets were used.

It was expected that the spider fearful group would show a reduced IOR effect in comparison to the control group when spider targets appear, that is, no (or less) inhibition to validly cued targets. This reduction of the IOR effect is not expected to be visible for butterfly targets. It was also possible to investigate the way IOR affects later discrimination of the target; the same amount of IOR was expected for both short and long SOAs. It was further predicted that eye movements and manual reaction times go to the same direction.

2. Method

2.1. Participants. Sixty participants were recruited from the general population and from the student population of the University of Mannheim. Students received partial course credit and participants from the general population received information about spider phobia in exchange for their participation. Participants were selected according to their scores on the German version of the Fear of Spiders Questionnaire (FSQ, see [22]). Following Rinck et al. [22], participants with scores between 0 and 6 were assigned to the control group and participants with a score of 15 or higher to the fearful group. All participants had normal or corrected-to-normal vision. Exclusion criteria were serious medical conditions, substance abuse or dependence, and current use of psychotropic medication. All participants volunteered to participate and provided written informed consent prior to the experiment. The procedures were approved by the ethic committee of the University of Mannheim. In total, 60 participants completed the experiment. Data from seven participants were excluded due to technical failure during the eye-tracking recording. In addition, three participants were excluded because they did not follow the experimental instructions. Thus, the total sample for all further analyses consisted of 50 participants: 25 spider fearful and 25 control participants.

Table 1 shows demographic and questionnaire data for both groups. Statistical analysis supported that fear of spiders was significantly higher in fearful compared to control participants. The average level of fear of spiders for the spider fearful participants in the present study was comparable to the level of clinical samples with spider phobia in other studies [23].

No significant group differences were found for sex ratio, trait anxiety, and state anxiety at the beginning of the experiment but significant differences were apparent for spider fear and age. Age was included as a covariate in further analyses, but there was no significant effect of this factor on

TABLE 1: Demographics and questionnaire means and standard deviations for both fearful and control participants.

Measure	Control participants		Fearful participants			<i>P</i>
	M	SD	M	SD	<i>t</i> (48)	
Age	24.60	5.29	31.04	13.19	2.26	<0.001
FAS	2.80	3.12	52.32	25.94	9.47	<0.001
SPF	5.72	2.83	15.32	5.61	7.63	0.001
STAI-T	39.32	9.49	38.40	8.50	-0.36	0.624
STAI-S Before	36.24	7.82	37.56	9.60	0.53	0.817
STAI-S After	24.60	5.29	31.04	13.19	2.66	0.481

Note. Definitions of questionnaire abbreviations used in the table can be found in the procedure section.

the general IOR effect. This analysis was not reported in the results to avoid redundant information.

2.2. Stimuli. Black-and-white drawings of spiders and butterflies were chosen from the Internet and were enclosed into square frames. They were adjusted with Adobe Photoshop for their size and brightness and with ElectroMagnetic EncephaloGraphy Software (EMEGS) for their contrast [24]. At the end the stimuli consisted of 12 butterflies and 12 spiders, and a dot (see Figure 1). The picture size and orientation were identical to procedures used elsewhere [14]. Thus, the pictures were about 110×110 pixels in size (visual angle 3.3°); the frames were 146×146 pixels in size (visual angle 4.3°) and they were situated 197 pixels away from the fixation cross. Stimuli were presented with presentation software (Neurobehavioral Systems) on a 22 inch monitor with a resolution of 1024 by 768 pixels.

2.3. Eye Tracking. Eye monitoring was performed with an SMI RED250 eye-tracking device. It automatically tracked eye movements and compensated for head movements to ensure accurate and reliable results with a sampling rate of 250 Hz and tracking resolution of 0.03° . For the data analysis BeGaze eye-tracking analysis software was used. The areas of interest consisted of a square surrounding the frames where the stimuli appeared. They were about 146×146 pixels in size. The other area of interest consisted of a circle around the fixation cross. The saccades that were taken into consideration for further analyses were the eye movements from the fixation cross area to the target area of interest.

2.4. Procedure. After informed consent was obtained, participants completed a questionnaire battery. One questionnaire assessed sociodemographic data (age, sex, profession, handedness, smoking, and caffeine consumption) and whether participants had normal or corrected-to-normal vision. In order to control for individual levels of trait and state anxiety prior to the experimental paradigm, unspecific state and trait anxiety were assessed with the State-Trait Anxiety Inventory (STAI: [25]; German version: [26]). Fear of spiders was assessed with two self-report questionnaires; the Spider Phobia Questionnaire (SPQ: [27]; German version: [22]) and the Fear of Spiders Questionnaire (FSQ: [28]; German version: [22]). After completion of the questionnaire battery, participants were seated approximately 50 cm away from the monitor. After they read the instructions and completed

the practice trials, they went through the 6-point calibration process, which involved fixating on a dot as it moved to different screen locations. Once the calibration was complete, the experiment (the IOR task) commenced.

An example of a valid and invalid trial is shown in Figure 2. Each trial started with a presentation of the two empty frames on the left and right of the fixation cross for 500 ms (A). Afterwards a cue (always a dot) appeared in one of the frames for 200 ms (B), which was followed by another screen with empty frames and the fixation cross (C). The *stimulus onset asynchrony* (SOA) was either 400 ms or 800 ms long. After the SOA interval, a butterfly or a spider was presented as target stimulus in one of the frames until the participants responded or for a maximum duration of 2 s (D). They were instructed to make a saccade in the direction of the target as fast as possible and then indicate which of the two pictures was presented with a button press. To discriminate between both types of target stimuli (spiders and butterflies), they were instructed to press the “arrow up” or the “arrow down” key. The button-picture assignment was counterbalanced (i.e., 50% of the participants had to press “arrow up” for the spider and “arrow down” for the butterfly, whereas this assignment was reversed for the other 50%). The “arrow up” and “arrow down” were chosen as response keys to prevent interference of keys on responses towards the stimuli presented to the left or right of the fixation cross.

The validity of the cue depended on the position relative to the target stimulus in each trial. Following the typical IOR task, in valid trials, cue and target stimulus were presented at the same location whereas in invalid trials, they were presented at different locations.

Fifty practice trials were used to familiarize participants with the task and to ensure that they understood and followed instructions. The subsequent experimental trials varied in terms of three experimental factors: (1) target stimulus type (spider versus butterfly); (2) validity of the cue (valid versus invalid); and (3) the stimulus onset asynchrony (SOA) interval (400 ms versus 800 ms). For each of the eight conditions (target stimulus * validity * SOA), 42 experimental trials were presented (8 different conditions all counterbalanced), which resulted in a total of 312 experimental trials. The order of these experimental trials was pseudorandomized and the different conditions (validity, target stimulus type, and SOA) were combined equally often.

At the end of the task, participants were again asked to fill in the state version of the STAI in order to assess

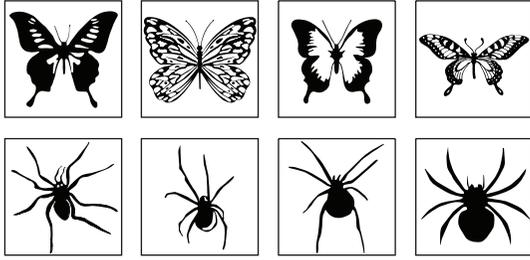


FIGURE 1: Example of the stimuli used in the experiment.

changes in state anxiety after the task. In addition, they rated each spider and butterfly stimulus using the 9-point *Self-Assessment Manikin* (SAM) rating system [29]. The SAM is a picture-based rating system to directly measure the valence (from “1” pleasant to “9” unpleasant) and emotional arousal (from “1” not at all aroused to “9” extremely aroused) associated with the individual reaction to a different stimuli. The entire experiment lasted 45 minutes.

2.5. Statistical Analyses. Two dependent variables were measured. First, *entry times* were calculated using eye-tracking data. Entry time was defined as the first saccade after target onset issued from the fixation cross to the correct target stimulus. Errors in the eye movement task were considered trials where participants’ eyes moved to the direction of the cue first, or when the saccade was missing completely. In the beginning of the experiment participants were instructed to never move their eyes toward the cue. There were, though, a few error trials per participant. This was easy to detect as the eyes are not in the fixation cross area of interest in the moment when the saccade starts. So these error trials were excluded from further analyses. The practice trials served as a way to get used to the procedure so that during the experiment there were only a few errors occurring.

For outlier correction, all entry times below 158 ms and above 398 ms (two standard deviations smaller and bigger than the general mean score) were excluded from further analysis. Second, *reaction times* were calculated as time between the presentation of the target stimulus and the participant’s discrimination response. For outlier correction, reaction times below 439 ms and above 838 ms (again, two standard deviations from the general mean score) were excluded from further analysis. To make sure that the outlier correction is accurate, a further analysis was conducted. The cutoffs were computed based on the SD separately for each anxiety group. The same results were obtained. Only the RT changed with about 10 ms. In addition, in this case it was necessary to add and subtract only one SD from the general mean, while in the general outlier correction two SDs were added and subtracted, as for the errors in the eye movement task.

Both entry and reaction time data were analyzed separately with a $2 \times 2 \times 2 \times 2$ analysis of variance (ANOVA) with cue validity (valid versus invalid), target stimulus (spider versus butterfly), and SOA interval (400 ms versus 800 ms) as within-subject factor and fear of spiders (fearful versus nonfearful) as between-subject group factor. According to

Lupiáñez et al. [20] the IOR effect is different for short and long SOAs in discrimination; therefore separate analysis for the 400 ms SOA and 800 ms SOA was further conducted in our experiment.

In addition, valence and arousal ratings were analyzed as a manipulation check in order to verify that spider fearful participants rated the spider pictures as less pleasant and more arousing. To this end, valence and arousal ratings were analyzed with a 2×2 ANOVA with target stimulus (spider versus butterfly) as within-subject factor and fear of spiders (fearful versus nonfearful) as a between-subject group factor, respectively.

3. Results

3.1. Manipulation Check. The pictures we presented as targets induced the expected emotional responses. For valence ratings, the repeated measures ANOVA yielded a significant main effect of picture category, $F(1, 45) = 140, P < 0.001, \eta_p^2 = 0.75$, and a significant interaction of picture category and fear of spiders, $F(1, 45) = 22.8, P < 0.001, \eta_p^2 = 0.34$. Spider fearful participants rated the pictures of spiders as more unpleasant (spiders: $M = 2.59, SD = 1.27$, and butterflies: $M = 7.13, SD = 0.90$) in comparison to the control participants (spiders: $M = 4.35, SD = 0.81$, and butterflies: $M = 6.28, SD = 0.90$): $t(45) = 5.67, P < 0.001$ for spider valence rating and $t(45) = 2.55, P = 0.014$ for butterfly valence rating.

For arousal ratings, the repeated measures ANOVA again revealed a significant main effect of picture category, $F(1, 45) = 54, P < 0.001, \eta_p^2 = 0.54$, and a significant interaction of picture category and fear of spiders, $F(1, 45) = 24.3, P < 0.001, \eta_p^2 = 0.35$. Spider fearful participants rated spider pictures as significantly more arousing ($M = 6.21, SD = 2.4$) in comparison to the control participants ($M = 3.35, SD = 1.8$), $t(45) = 4.53, P < 0.001$, but no statistically significant difference was detected for ratings of butterflies pictures (fearful participants: $M = 2.53, SD = 1.41$; control participants: $M = 2.63, SD = 1.57, t(45) = -0.227, P = 0.821$). Thus, the stimulus material used in this experiment was rated as expected among fearful and control participants.

3.2. Eye-Tracking Data: Entry Times. The factors that were used for the analyses include cue validity (valid versus invalid), target stimulus (spider versus butterfly), SOA interval (400 ms versus 800 ms), and fear of spiders (fearful versus nonfearful). Eye-tracking data revealed an IOR effect which was not modulated by emotional target content. The ANOVA with mean entry time as a dependent variable revealed a main effect of cue validity, $F(1, 48) = 47.2; P < 0.001, \eta_p^2 = 0.49$ ($M = 292, 18$ for valid and $M = 271, 8$ for invalid trials); SOA: $F(1, 48) = 75.9; P < 0.001, \eta_p^2 = 0.61$ ($M = 295.45$ for the 400 ms SOA and $M = 268.54$ for the 800 ms SOA); target stimulus, $F(1, 48) = 8.38; P = 0.006, \eta_p^2 = 0.15$, and a significant interaction of Cue Validity \times SOA: $F(1, 48) = 6.68; P = 0.013, \eta_p^2 = 0.12$ (suggesting that the IOR effect is different for the two SOAs used in the experiment: stronger

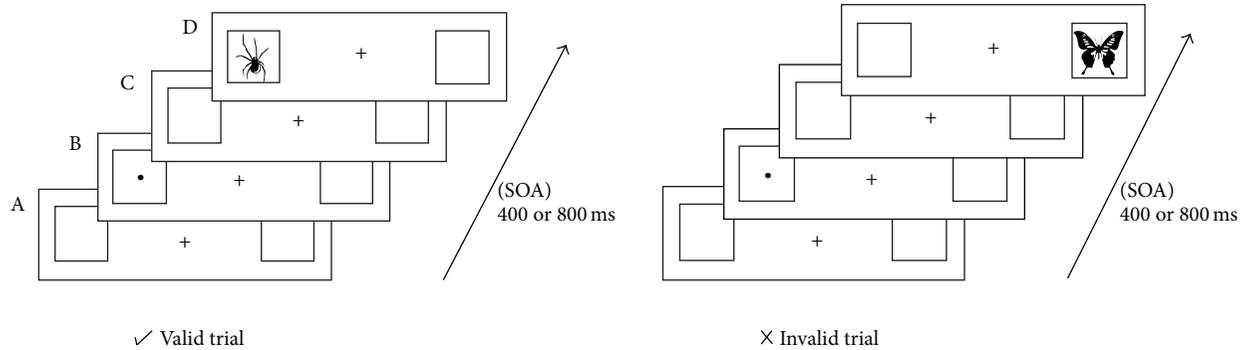


FIGURE 2: Sequence of events in a valid and invalid trial: (A) two empty frames appeared on the left and right of the fixation cross; (B) cue was presented for 200 ms in one of the frames; (C) two empty frames appeared again for 400 ms or 800 ms; (D) target stimulus was presented in the cued or uncued location.

for short SOAs and weaker for long SOAs). The Cue Validity \times Fear of Spiders interaction was not significant: $F(1, 48) = 1.79$; $P = 0.18$, $\eta_p^2 = 0.04$. Likewise the Cue Validity \times Target Stimulus interaction was not significant: $F(1, 48) = 0.10$; $P = 0.75$, $\eta_p^2 = 0.002$ suggesting that the IOR effect is not modulated by the emotionality of the target (Figure 3).

To further explore the effect of the different SOAs used in the experiment, separate analyses were conducted for the 400 ms SOA and for the 800 ms SOA. For the 400 ms SOA, there was a main effect of cue validity, $F(1, 48) = 43.2$; $P < 0.001$, $\eta_p^2 = 0.47$, and a main effect of the target stimulus $F(1, 48) = 9.61$; $P = 0.003$, $\eta_p^2 = 0.16$. While for the 800 ms SOA condition, the analysis revealed only a main effect of cue validity, $F(1, 48) = 23.4$; $P < 0.001$, $\eta_p^2 = 0.32$, meaning that there was an IOR effect for the entire group independently of stimulus type or fear of spiders and there was no interaction of Cue Validity \times Target Stimulus \times Fear of Spiders $F(1, 48) = 0.11$; $P = 0.74$, $\eta_p^2 = 0.00$ (Figure 3).

3.3. Motor Response Data: Reaction Times. Manual responses did not show an IOR effect—there was no main effect of cue validity $F(1, 48) = 0.35$, $P = 0.55$, $\eta_p^2 = 0.007$, but a main effect of the target stimulus, $F(1, 48) = 18.6$, $P < 0.001$, $\eta_p^2 = 0.28$ ($M = 604.51$ for spider targets and $M = 618.51$ for butterfly targets): in general both groups were faster to press the button for spiders than for butterflies. More specifically, there was a significant interaction of Target Stimulus \times Fear of Spiders, $F(1, 48) = 4.96$, $P = 0.03$, $\eta_p^2 = 0.09$; that is, spider fearful participants are faster to press the button for spider targets than butterfly targets, in comparison to the control group. The interaction of Cue Validity \times Target Stimulus was not significant, $F(1, 48) = 0.12$, $P = 0.72$, $\eta_p^2 < 0.001$.

A further exploratory analysis for the two different SOAs revealed that this interaction was valid only for the 800 ms SOA, $F(1, 48) = 6.9$, $P = 0.01$, $\eta_p^2 = 0.12$ (Figure 4(b)) but not for the 400 ms SOA, $F(1, 48) = 2.2$, $P = 0.14$, $\eta_p^2 = 0.04$ (Figure 4(a)).

In sum, the analysis of the motor responses (the button press) did not show any IOR effect.

4. Discussion

Inhibition of return is thought to facilitate foraging behavior. Although the phenomenon is generally found to be very stable, it is plausible that it can be affected by emotional content of the stimuli which are presented. In the present study, eye-tracking was used to investigate the IOR effect with phobia relevant stimuli as targets. There was no evidence for the influence of fear on the IOR effect. However, separate analyses of the eye-tracking data and manual reaction times showed different patterns of the IOR effect. Eye-tracking data revealed a strong IOR effect independent of diagnostic group and independent of the target stimulus. This effect was mainly present in the 400 ms SOA condition while for the 800 ms SOA condition, this effect was relatively weak. Considering the two SOAs separately indicates that timing matters in discrimination; a stronger IOR effect is visible for shorter SOAs and less of an IOR effect for longer SOAs.

There were some other unexpected findings; we found that participants were generally faster to move their eyes toward the butterflies compared to spiders. We cannot conclusively argue that this is a result of the stimulus properties as they were controlled for contrast, color, and size. An explanation for this result, however, may be the shape of the butterflies which could capture the visual attention more easily. We are not aware of a comparable effect in the literature.

In contrast, the IOR effect was not found in the manual responses. Participants were generally faster to press the button for spiders than for butterflies but this effect was more pronounced in spider fearful participants. This may be interpreted as a sign of vigilance toward threatening stimuli but is in conflict to the eye-tracking data, where greater vigilance toward butterflies was found. Previous work recommends an enhanced hypervigilance toward all kinds of stimuli in spider fearful individuals [30], consistent with what we found in the manual reaction times. The hypervigilance of threat hypothesis would predict higher vigilance of spiders as evidenced by faster saccades toward spiders [31–35]. However, we found that participants detect butterflies faster with their eyes but are able to react more quickly toward spiders. The first response (turning the eyes in the direction of the

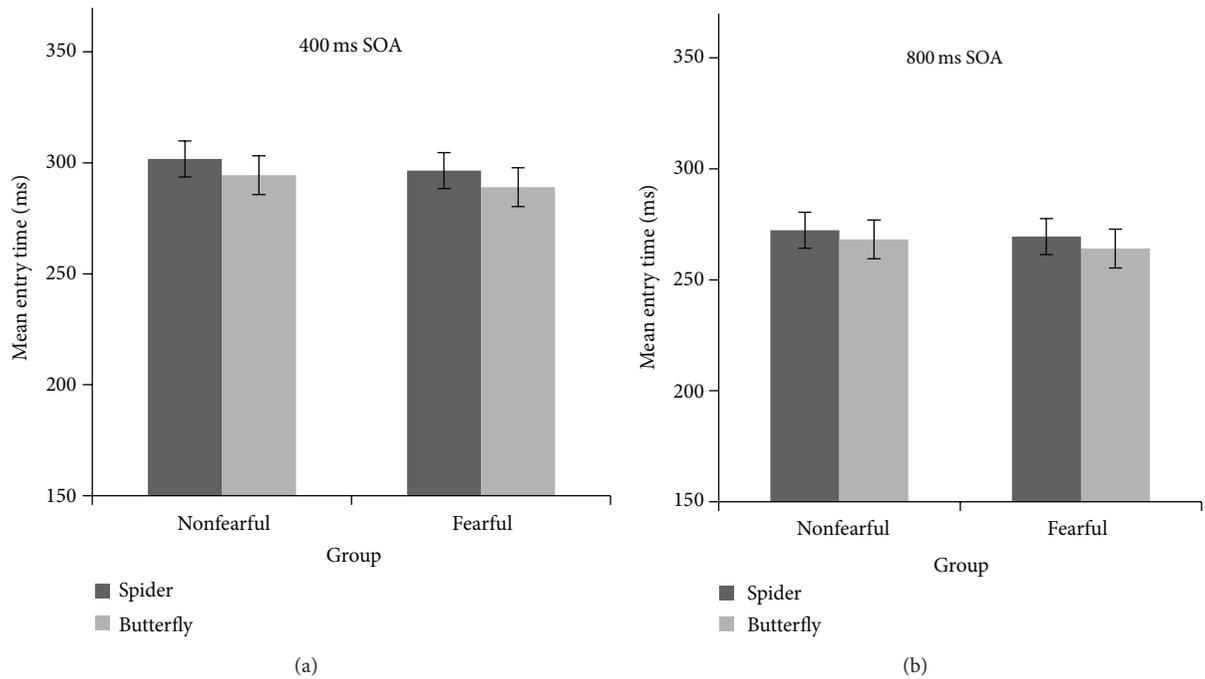


FIGURE 3: Eye-tracking data—mean entry time on target area in milliseconds for the control group and spider fearful group for the 400 ms SOA (a) separately for spider and butterfly targets and for the 800 ms SOA (b). Bars represent the standard error of the mean.

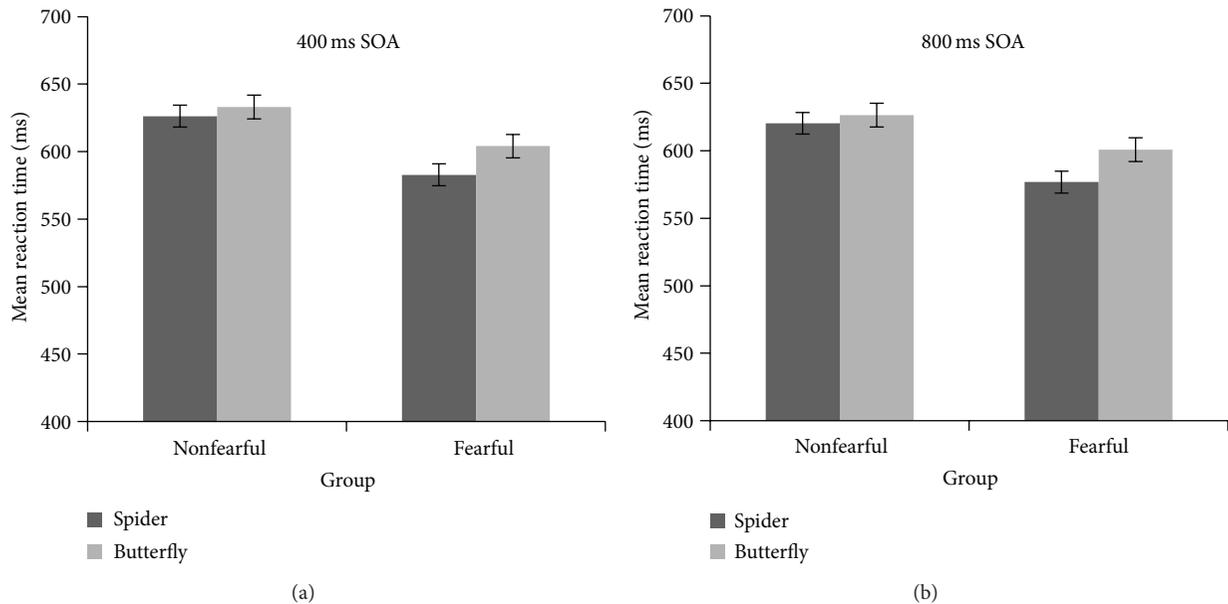


FIGURE 4: Mean reaction time in milliseconds for the control group and spider fearful group for the 400 ms SOA (a) separately for spider and butterfly targets and for the 800 ms SOA (b). Bars represent the standard error of the mean.

target) likely did not depend on a semantic analysis, because the pictures which appeared in the periphery at first, low-level features may have driven the initial response. However, once the target was fixated the manual response was more likely to be influenced by specific features. Taking into account the fact that spider fear is spider specific [36] an explanation for this result might be the fact that spiders are more unambiguous

than butterflies and they are processed preferentially in our brain when they are attended to [37]. Moreover, faster manual responses to spider targets might result from preparation for motor action in response to potential threat [38]. Thus, these discrepant results for saccadic and manual response times could depict the fact that not all aspects of attentional engagement, disengagement, and behavioral response to

a task will be reflected in our multilevel assessments. In particular, readiness to respond to threatening stimuli may be different in the optical system (eye-tracking) and the motor system (manual response). As we conclude also from the present study, with an emotional stimulus response execution is speeded up. Future research should aim at dismantling these different components of the IOR effect.

Although there is a general discussion about the time course of the IOR effect during discrimination, the present results suggest that IOR is detectable for short and long SOAs. This runs contrary to Lupiáñez et al.'s observation that this effect is only observed for longer SOAs [20]. One could argue that this is not a typical discrimination procedure as participants responded to the targets first by moving the eyes toward them, whereas fixation was maintained in Lupiáñez work. Perhaps our results would be similar to other studies that suggest that IOR is not visible in discrimination [39] had we instructed participants not to move their eyes; however this would also have reduced the ecological validity of our design.

Our results are particularly interesting because we make use of both eye movement measures and reaction time measures. In line with previous studies, our finding suggested that eye movement latencies show IOR [40]. However, the eye movement differences did not result in an IOR effect in reaction time data. Still, in routine searches, people are expected to make eye movements toward targets and these eye movements are usually followed by motor responses. That is, action typically follows detection—when spider fearful individuals encounter a spider, the threat is first detected and then some action is taken. For this reason we chose not to constrain eye movements in our study. Previous IOR research has generally limited the procedures to only saccadic eye movements or manual reaction time responses, but this does not seem to accurately reflect behaviors that occur in natural settings. As Klein et al. [41] argue, attention plays a crucial role in the execution of eye movements and one of the goals of the present study was indeed to further examine whether IOR is reflected in the saccade latencies and/or in the motor responses. Such discrepancies have been observed by other groups who use similar assessments [42]. Using a change detection paradigm, they recorded eye movements and manual response times and also found discrepant findings—participant's eye movements and manual responses went into different directions.

The button press discrimination in the present study was used as a control measure to ensure that participants fully paid attention to the target stimulus. Discrimination of emotional and neutral stimuli using saccadic and manual responses was investigated previously also by others who showed that eye movements, in contrast to manual responses, require little information to distinguish emotional faces [43]. This interpretation is also in line with our findings. In the present study, all saccadic reaction times were quick in comparison to manual reaction times as well.

5. Conclusions

Taken together, our findings help to further extend the motor and oculomotor explanation of the IOR effect and provide greater support for the lack of a strong influence of emotional

stimuli on this attentional bias. It seems to be a stable phenomenon and not easily interrupted by the emotional valence of the stimuli, even when potential threat is presented. This is not in line with the evolutionary perspective, which suggests that quick detection of threatening stimuli has survival value and the attentional capture in this case is automatic, but of course this is not to say that such mechanisms may appear under most circumstances.

This study combines findings from research on anxiety, inhibition of return, and attention with findings from eye movement research. We recommend that further research should focus on the oculomotor aspect of IOR and on the specific conditions under which this effect is weakened.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

This work was partially funded by a scholarship from the Albanian Ministry of Education and Science. Special thanks are due to Christian Flöser and Christina Kolbensschlag for their help with the data collection as part of a course requirement.

References

- [1] M. Carrasco, "Visual attention: the past 25 years," *Vision Research*, vol. 51, no. 13, pp. 1484–1525, 2011.
- [2] G. W. Alpers, "Eye-catching: right hemisphere attentional bias for emotional pictures," *Laterality*, vol. 13, no. 2, pp. 158–178, 2008.
- [3] E. Fox, "Allocation of visual attention and anxiety," *Cognition and Emotion*, vol. 7, no. 2, pp. 37–41, 1993.
- [4] I. T. Kolassa, A. Buchmann, R. Lauche et al., "Spider phobics more easily see a spider in morphed schematic pictures," *Behavioral and Brain Functions*, vol. 3, article 59, pp. 1–15, 2007.
- [5] G. W. Alpers, A. B. M. Gerdes, B. Lagarie, K. Tabbert, D. Vaitl, and R. Stark, "Attention and amygdala activity: an fMRI study with spider pictures in spider phobia," *Journal of Neural Transmission*, vol. 116, no. 6, pp. 747–757, 2009.
- [6] K. Mogg and B. P. Bradley, "Time course of attentional bias for fear-relevant pictures in spider-fearful individuals," *Behaviour Research and Therapy*, vol. 44, no. 9, pp. 1241–1250, 2006.
- [7] A. B. M. Gerdes, P. Pauli, and G. W. Alpers, "Toward and away from spiders: eye-movements in spider-fearful participants," *Journal of Neural Transmission*, vol. 116, no. 6, pp. 725–733, 2009.
- [8] S. G. Hofmann, G. W. Alpers, and P. Pauli, "Phenomenology of panic and phobic disorders," in *Oxford Handbook of Anxiety and Related Disorders*, M. M. Antony and M. B. Stein, Eds., pp. 34–46, Oxford University Press, New York, NY, USA, 2009.
- [9] M. I. Posner and Y. Cohen, "Components of visual orienting," in *Attention and Performance X*, pp. 531–556, 1984.
- [10] R. Klein, "Inhibition of return," *Trends in Cognitive Sciences*, vol. 4, no. 4, pp. 138–147, 2000.
- [11] T. L. Taylor and M. E. Therrien, "Inhibition of return for the discrimination of faces," *Perception and Psychophysics*, vol. 70, no. 2, pp. 279–290, 2008.

- [12] W. Lange, K. Heuer, A. Reinecke, E. Becker, and M. Rinck, "Inhibition of return is unimpressed by emotional cues," *Cognition and Emotion*, vol. 22, no. 8, pp. 1433–1456, 2008.
- [13] R. S. Stoyanova, J. Pratt, and A. K. Anderson, "Inhibition of return to social signals of fear," *Emotion*, vol. 7, no. 1, pp. 49–56, 2007.
- [14] E. Berdica, A. B. M. Gerdes, and G. W. Alpers, "Fear and inhibition of return. Does the target matter?" Poster session presented at the 55 conference of Experimental Psychologists, Wien, 2013, https://www.teap.de/archiv/teap13/docs/teap2013_final_programme_updated.pdf.
- [15] B. Harkin and K. Kessler, "Deficient inhibition of return in subclinical OCD only when attention is directed to the threatening aspects of a stimulus," *Depression and Anxiety*, vol. 29, no. 9, pp. 807–815, 2012.
- [16] C. Pérez-Dueñas, A. Acosta, and J. Lupiáñez, "Attentional capture and trait anxiety: evidence from inhibition of return," *Journal of Anxiety Disorders*, vol. 23, no. 6, pp. 782–790, 2009.
- [17] A. M. Waters, A. B. Nitz, M. G. Craske, and C. Johnson, "The effects of anxiety upon attention allocation to affective stimuli," *Behaviour Research and Therapy*, vol. 45, no. 4, pp. 763–774, 2007.
- [18] E. Fox, R. Russo, and K. Dutton, "Attentional bias for threat: evidence for delayed disengagement from emotional faces," *Cognition and Emotion*, vol. 16, no. 3, pp. 355–379, 2002.
- [19] B. Verkuil, J. F. Brosschot, P. Putman, and J. F. Thayer, "Interacting effects of worry and anxiety on attentional disengagement from threat," *Behaviour Research and Therapy*, vol. 47, no. 2, pp. 146–152, 2009.
- [20] J. Lupiáñez, E. G. Milán, F. J. Tornay, E. Madrid, and P. Tudela, "Does IOR occur in discrimination tasks? Yes, it does, but later," *Perception and Psychophysics*, vol. 59, no. 8, pp. 1241–1254, 1997.
- [21] A. R. Hunt and A. Kingstone, "Inhibition of return: dissociating attentional and oculomotor components," *Journal of Experimental Psychology: Human Perception and Performance*, vol. 29, no. 5, pp. 1068–1074, 2003.
- [22] M. Rinck, S. Bundschuh, S. Engler et al., "Reliabilität und Validität dreier Instrumente zur Messung von Angst vor Spinnen," *Diagnostica*, vol. 48, no. 3, pp. 141–149, 2002.
- [23] A. B. M. Gerdes, G. W. Alpers, and P. Pauli, "When spiders appear suddenly: spider-phobic patients are distracted by task-irrelevant spiders," *Behaviour Research and Therapy*, vol. 46, no. 2, pp. 174–187, 2008.
- [24] P. Peyk, A. De Cesarei, and M. Junghöfer, "Electromagnetic encephalography software: overview and integration with other EEG/MEG toolboxes," *Computational Intelligence and Neuroscience*, vol. 2011, Article ID 861705, 10 pages, 2011.
- [25] C. D. Spielberger, R. L. Gorsuch, R. Lushene, P. R. Vagg, and G. A. Jacobs, *Manual for the State-Trait Anxiety Inventory*, Consulting Psychologists Press, Palo Alto, Calif, USA, 1983.
- [26] L. Laux, P. Glanzmann, P. Schaffner, and C. D. Spielberger, *Das State-Trait-Angstinventar. Theoretische Grundlagen und Handanweisung*, Beltz Test GmbH, Weinheim, Germany, 1981.
- [27] F. N. Watts and R. Sharrock, "Questionnaire dimensions of spider phobia," *Behaviour Research and Therapy*, vol. 22, no. 5, pp. 575–580, 1984.
- [28] J. Szymanski, "Fear of spiders questionnaire," *Journal of Behavior Therapy and Experimental Psychiatry*, vol. 26, no. 1, pp. 31–34, 1995.
- [29] P. Lang, A. H. Tuma and, and J. D. Maser, "The cognitive psychophysiology of emotion: fear and anxiety," in *Anxiety and the Anxiety Disorders*, A. H. Tuma and J. D. Maser, Eds., Lawrence Erlbaum, Hillsdale, NJ, USA, 1985.
- [30] M. Weymar, A. B. M. Gerdes, A. Löw, G. W. Alpers, and A. O. Hamm, "Specific fear modulates attentional selectivity during visual search: electrophysiological insights from the N2pc," *Psychophysiology*, vol. 50, no. 2, pp. 139–148, 2013.
- [31] E. H. W. Koster, G. Crombez, B. Verschuere, and J. De Houwer, "Selective attention to threat in the dot probe paradigm: differentiating vigilance and difficulty to disengage," *Behaviour Research and Therapy*, vol. 42, no. 10, pp. 1183–1192, 2004.
- [32] W. G. T. Lange, K. J. Tierney, A. H. Reinhardt-Rutland, and P. Vivekananda-Schmidt, "Viewing behaviour of spider phobics and non-phobics in the presence of threat and safety stimuli," *British Journal of Clinical Psychology*, vol. 43, no. 3, pp. 235–243, 2004.
- [33] O. V. Lipp, "Of snakes and flowers: does preferential detection of pictures of fear-relevant animals in visual search reflect on fear-relevance?" *Emotion*, vol. 6, no. 2, pp. 296–308, 2006.
- [34] A. Öhman, A. Flykt, and F. Esteves, "Emotion drives attention: detecting the snake in the grass," *Journal of Experimental Psychology: General*, vol. 130, no. 3, pp. 466–478, 2001.
- [35] H. M. Peperkorn, G. W. Alpers, and A. Mühlberger, "Triggers of fear: perceptual cues versus conceptual information in spider phobia," *Journal of Clinical Psychology*, 2013.
- [36] A. B. M. Gerdes, G. Uhl, and G. W. Alpers, "Spiders are special: fear and disgust evoked by pictures of arthropods," *Evolution and Human Behavior*, vol. 30, no. 1, pp. 66–73, 2009.
- [37] A. B. M. Gerdes and G. W. Alpers, "You see what you fear: spiders gain preferential access to conscious perception in spider-phobic patients," *Journal of Experimental Psychopathology*, vol. 5, no. 1, pp. 14–28, 2014.
- [38] A. Flykt, "Preparedness for action: responding to the snake in the grass," *American Journal of Psychology*, vol. 119, no. 1, pp. 29–43, 2006.
- [39] K. M. Terry, L. A. Valdes, and W. T. Neill, "Does 'inhibition of return' occur in discrimination tasks?" *Perception & Psychophysics*, vol. 55, no. 3, pp. 279–286, 1994.
- [40] R. A. Abrams and R. S. Dobkin, "Inhibition of return: effects of attentional cuing on eye movement latencies," *Journal of Experimental Psychology: Human Perception and Performance*, vol. 20, no. 3, pp. 467–477, 1994.
- [41] R. Klein, A. Kingstone, and A. Pontefract, "Orienting of visual attention," in *Eye Movements and Visual Cognition*, K. Rayner, Ed., pp. 46–65, Springer, New York, NY, USA, 1992.
- [42] J. Huijding, B. Mayer, E. H. W. Koster, and P. Muris, "To look or not to look: an eye movement study of hypervigilance during change detection in high and low spider fearful students," *Emotion*, vol. 11, no. 3, pp. 666–674, 2011.
- [43] R. L. Bannerman, M. Milders, and A. Sahraie, "Processing emotional stimuli: comparison of saccadic and manual choice-reaction times," *Cognition and Emotion*, vol. 23, no. 5, pp. 930–954, 2009.

Research Article

Centre-of-Gravity Fixations in Visual Search: When Looking at Nothing Helps to Find Something

Dustin Venini,^{1,2} Roger W. Remington,¹ Gernot Horstmann,^{3,4} and Stefanie I. Becker^{1,3}

¹ The University of Queensland, Brisbane, Australia

² School of Psychology, The University of Queensland, McElwain Building, Brisbane, QLD 4072, Australia

³ Centre for Interdisciplinary Research, Bielefeld University, 33602 Bielefeld, Germany

⁴ The University of Bielefeld, Bielefeld, Germany

Correspondence should be addressed to Dustin Venini; d.venini@uq.edu.au

Received 8 December 2013; Revised 12 February 2014; Accepted 28 February 2014; Published 3 June 2014

Academic Editor: Arvid Herwig

Copyright © 2014 Dustin Venini et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

In visual search, some fixations are made between stimuli on empty regions, commonly referred to as “centre-of-gravity” fixations (henceforth: COG fixations). Previous studies have shown that observers with task expertise show more COG fixations than novices. This led to the view that COG fixations reflect simultaneous encoding of multiple stimuli, allowing more efficient processing of task-related items. The present study tested whether COG fixations also aid performance in visual search tasks with unfamiliar and abstract stimuli. Moreover, to provide evidence for the multiple-item processing view, we analysed the effects of COG fixations on the number and dwell times of stimulus fixations. The results showed that (1) search efficiency increased with increasing COG fixations even in search for unfamiliar stimuli and in the absence of special higher-order skills, (2) COG fixations reliably reduced the number of stimulus fixations and their dwell times, indicating processing of multiple distractors, and (3) the proportion of COG fixations was dynamically adapted to potential information gain of COG locations. A second experiment showed that COG fixations are diminished when stimulus positions unpredictably vary across trials. Together, the results support the multiple-item processing view, which has important implications for current theories of visual search.

1. Introduction

Researchers have long been intrigued by the fact that our rich and stable visual world is created from snapshot impressions gained during short fixations on different regions of the visual field. A common assumption is that we search the visual world through a series of fixations on objects or informative portions of objects. Interestingly, we also frequently make fixations between objects into empty regions of visual space. In previous studies, such fixations have been labelled *centre-of-gravity fixations*, *averaging saccades*, or the *global effect* [1–4]. Here, we will use the abbreviation *COG fixations* to refer to such fixations.

COG fixations were first discovered in a saccade task, where observers were instructed to make a fast eye movement to a predefined target stimulus [5]. An irrelevant distractor in the vicinity of the target frequently led to the eyes landing

at an intermediate location between the two stimuli [1, 5]. COG fixations occur only when the target and distractor were located quite near to one another, where the distance between the objects creates an angle of less than 30 degrees [2, 6–8]. Apparently, eye movements are occasionally targeted to the average of two stimulus positions rather than the precise target or distractor position.

Averaging of stimulus positions was initially attributed to the poor spatial resolution of an early saccade targeting mechanism that relies on distributed coding in a population of cells with large and overlapping receptive fields in the superior colliculus [2, 9–12]. In contrast to this bottom-up explanation, it was later noticed that fixating between stimuli may confer advantages in visual search or detection tasks, and hence, COG fixations could in part be strategic [13–15]. In particular, difficult search tasks with large numbers of distractors can potentially profit from COG fixations, as they

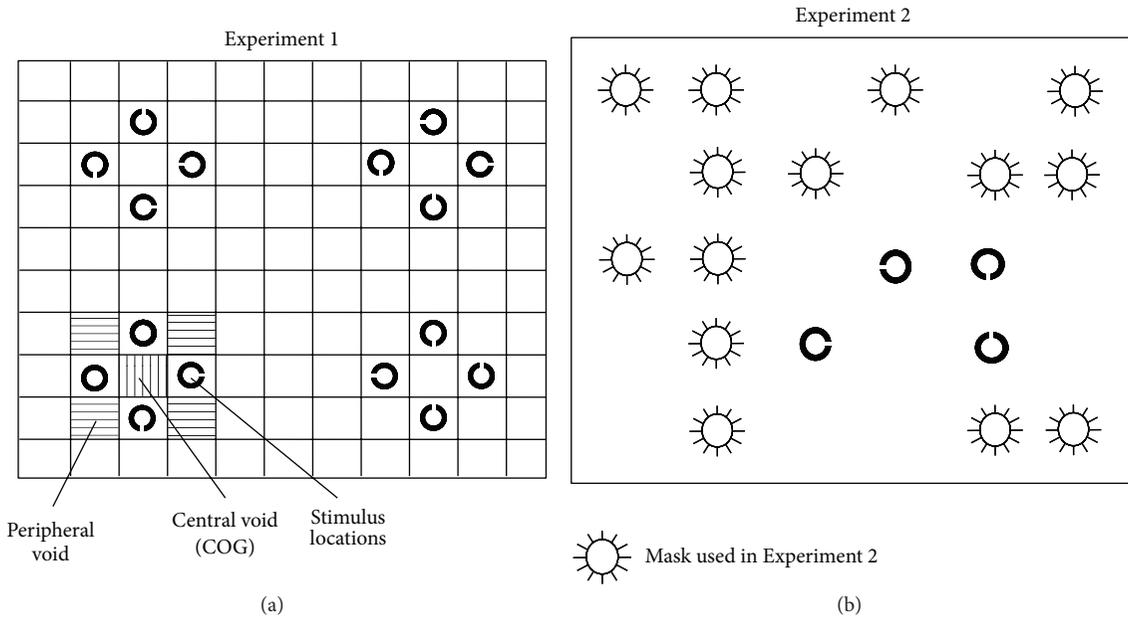


FIGURE 1: Example of the search displays used in Experiments 1 and 2. The grid (a) shows how the search display was partitioned for data analysis and was not visible in the experiment. In Experiment 1 (a), each cluster was partitioned into 4 stimulus regions (Landolt Cs), a central void region (marked by vertical lines), and 4 peripheral void regions (marked by horizontal lines). In Experiment 2 (b), a regular grid of same-sized squares was laid over the search display that contained 18 stimuli that were randomly distributed on 36 possible positions, resulting in equal numbers of stimulus regions and void regions.

may allow simultaneous processing of multiple stimuli during a single fixation.

In line with this contention, some studies found that COG fixations benefit task performance. For instance, investigating eye movement behaviour of chess experts and intermediate players in a check detection task, Reingold, Charness, Pomplun, and Stampe [16] found a large portion of eye fixations on squares not occupied by any chess pieces. Interestingly, experts showed significantly more COG fixations (~60%) than intermediate players (~40%) and clearly outperformed intermediate players. Reingold and colleagues [16] argued that COG fixations are a hallmark of more efficient perceptual encoding of chess configurations and thus can be viewed as a correlate for the ability to select and process multiple items in parallel.

Although the findings render it very probable that COG fixations can indeed be regarded as a correlate for more efficient perceptual encoding, the evidence for that claim is still quite indirect: firstly, because the comparisons relied on different groups of individuals that already differed in the central performance measure (experts versus novices) and second, because the effects of more efficient coding during COG fixations were not independently assessed. For instance, if COG fixations indeed allow for more efficient coding of stimulus configurations, the number of fixations on nearby stimuli and the dwell times of these stimulus fixations should be reduced. Such a result pattern would provide the most direct evidence that COG fixations enhance performance by allowing for more efficient coding of stimulus configurations.

2. Experiment 1

The aim of Experiment 1 was to test whether COG fixations can indeed serve as a correlate for more efficient encoding of visual stimuli, when participants do not differ in higher-order skills, and the task requires processing of abstract and unfamiliar stimuli. Observers in Experiment 1 had to search for a ring among 15 Landolt C distractors and to report with a button press whether the target ring was present or absent (50%). To test whether a higher proportion of COG fixations indeed reliably predict higher levels of visual search performance, we first correlated the observers' individual proportion of COG fixations with their performance in the visual search task (as measured by the mean response times; RTs). Secondly, to obtain independent evidence of the hypothesis that COG fixations allow processing of multiple stimuli in the vicinity, we assessed the effects of COG fixations on stimulus fixations in the same cluster of stimuli.

Stimulus displays consisted of 4 clusters of 4 stimuli that were arranged in a diamond configuration, one in each quadrant of the search display (see Figure 1 for an example of the stimulus display). Within each diamond cluster, there were 4 stimulus locations and 5 empty locations called *void* locations: the *central void location* was also called the "COG" location, and fixations into this location were labelled COG fixations. The four void locations at the corners of the configuration were called *peripheral void locations*, and the empty space between different clusters was labelled *outside locations* (as they were outside of the clusters).

If COG fixations indeed aid search by allowing for simultaneous processing of multiple items, then COG fixations should lead to a reduction of the number of stimulus fixations and/or their dwell times within the same cluster. Moreover, these reductions should be more pronounced for COG fixations than fixations into one of the peripheral void locations. This holds because the central location offers more optimal viewing conditions of the stimuli within the cluster, given that the resolution of stimuli dramatically decreases with increases of their distance from the fovea [17].

As an additional manipulation check, we compared the effects of COG fixations between a *narrow spacing condition* versus a *wide spacing condition*, in which the stimuli were located near versus far from the centre of the diamond. By the same logic (of decreasing resolution with an increase of distance), the wide spacing condition should show less of a benefit from COG fixations than the narrow spacing condition.

In addition, comparing wide versus narrow spacing conditions, and COG fixations with peripheral void fixations, also allowed a first assessment whether and to what extent COG fixations may be under strategic control. If the COG fixations are intentionally made to process multiple stimuli simultaneously, then we would expect less COG fixations in the wide spacing condition than in the narrow spacing condition and less fixations into peripheral void locations than the central void location. However, a corresponding result may still be consistent with a bottom-up account, which attributes COG fixations to automatic averaging of stimulus positions, because averaging is more likely to occur with a narrow spacing of stimuli [1–3].

The question of whether COG fixations are strategic was tested more directly, by including an additional time-limited, narrow spacing condition. In this condition, all search stimuli disappeared after 1,500 ms, rendering it impossible to select and process all 16 search stimuli individually in a serial manner. Hence, if COG fixations indeed promote simultaneous processing of multiple items, and the visual system can exploit this fact in the optimization of search performance, then we should observe more COG fixations in this condition than the standard (unlimited) narrow spacing condition.

2.1. Method

2.1.1. Participants. 20 naïve volunteers (15 females; mean age 22.9) with normal or corrected-to-normal vision took part in the experiments and were paid \$10 in compensation.

2.1.2. Apparatus. The stimuli were presented on a 17" flat-screen colour monitor. The experiment was controlled by the software "Presentation" (Neurobehavioral Systems) that was run on an Intel Duo 2 CPU 2.4 GHz computer. Eye movements were measured with a video-based eye tracker (EyeLink 1000, SR Research, Ontario, Canada) at 500 Hz. Participants were seated in a normally lit room, with their head resting against the eye tracker's chin rest and forehead support, and viewed the screen from a distance of 62 cm. For registration of manual responses, a standard USB keyboard was used.

2.1.3. Stimuli. Stimulus displays consisted of a regular array of search stimuli that either consisted of 16 black Landolt C stimuli (target absent trials) or 15 Landolt C stimuli and a target ring (diameter: 0.55°; line width: 0.09°; target present trials). All stimuli were presented against a white background and the Landolt Cs could have the gap oriented upwards, downwards, or to the right or left. The search stimuli were arranged in 4 diamond configurations of 4 × 4 stimuli, so that, within each cluster, there were a central region and 4 peripheral regions that were devoid of search stimuli (see Figure 1(a) for an example).

In the wide spacing condition, stimuli within a cluster had a distance of 7.85° (centre-to-centre), whereas in the narrow spacing condition, the distance between stimuli was 3.7° (centre-to-centre).

2.1.4. Design. The experiment consisted of 3 blocked conditions of a wide spacing condition, a narrow spacing condition, and a time-limited (narrow-spacing) condition whose order was varied randomly between participants. Each block contained 180 trials, and the position of the search target and target presence was varied randomly within each block. In the time-limited condition, presentation of the narrowly spaced search display was limited to 1,500 ms, so that observers could only make 4-5 fixations before the search display disappeared. In the other conditions, the search display remained visible until response. Observers were instructed to respond as fast as possible without making any errors and were given no specific instructions about their eye movements.

2.1.5. Procedure. Prior to each block, participants were given written instructions about the next block. Each trial started with the presentation of a small black fixation cross (0.23° × 0.23°). Participants had to fixate on the centre of the cross, and the search display was presented when the gaze was within 1.3° of the centre of the fixation cross, for at least 500 ms (within a time window of 2,000 ms). Otherwise, participants were calibrated anew (9-point calibration) and the next trial started again with the fixation control.

2.2. Analysis. For the analysis of fixations, each cluster was divided into regions of 9 equally sized squares, consisting of four stimulus regions, one central void region, and four peripheral void regions. The remaining areas above, below, and between individual clusters were defined as "outside" regions (see Figure 1). The *a priori* probabilities of selecting a stimulus versus the central void region versus a peripheral void region were 4:1:4 across all conditions (whereby the probability of selecting an outside region was much higher in the narrow spacing condition than in the wide spacing condition).

2.3. Results

2.3.1. Data. Trials with RTs <200 ms and >7,000 ms and wrong responses were excluded from all analyses, as were all trials where no fixations were recorded (<1%). Excluding all trials with manual errors removed an additional 17.5% of

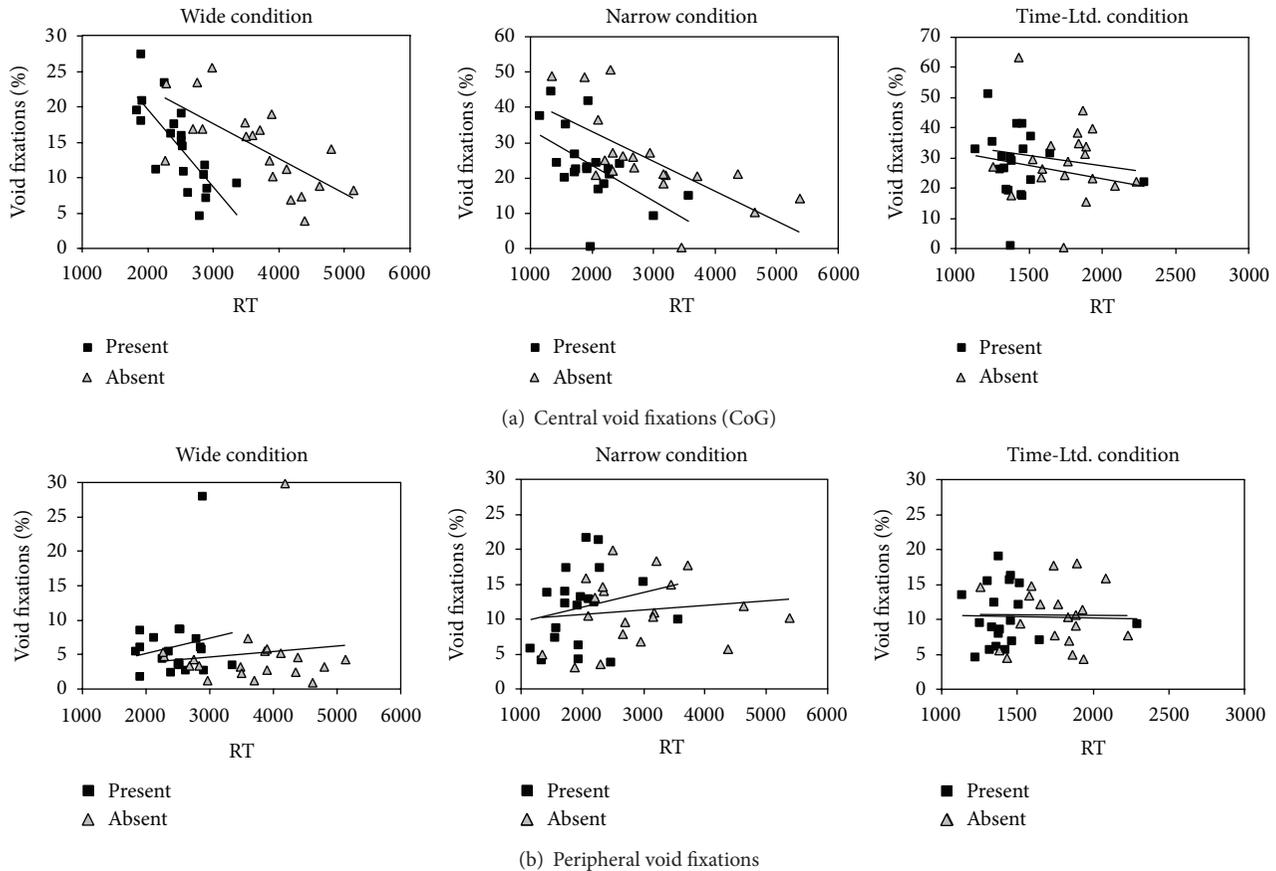


FIGURE 2: Effects of CoG fixations on search performance (RT), Experiment 1. Mean search times as a function of the proportion of void fixations in Experiment 1, depicted separately for each blocked condition (wide, narrow, and time-limited). Larger proportions of central void fixations were associated with shorter RT, both on target absent trials (black squares) and target present trials (grey triangles). Error bars depict ± 1 SEM and may be smaller than the plotting symbol.

trials (most of which because of poor performance in the time-limited condition). On average, data were based on 74 correct trials per cell (range: 29 to 100 data per cell). For the reported analyses, successive fixations in the same regions were counted as a single fixation; analyses counting them as two fixations yielded very similar results.

(I) *Effect of Void Fixations on Search Efficiency.* In a first analysis, we analysed mean RT as a function of the proportion of COG fixations and fixations made into a peripheral void region (see Figure 2). First, for COG fixations, the linear regression confirmed that RT systematically decreased with a higher proportion of COG fixations, both in the wide spacing condition (present: $F(1, 19) = 23.2, P < .001, R^2 = .56$; absent: $F(1, 19) = 16.5, P = .001, R^2 = .48$) and in the narrow spacing condition (present: $F(1, 19) = 7.8, P = .012, R^2 = .30$; absent: $F(1, 19) = 15.0, P = .001, R^2 = .45$). In the time-limited condition, the same trends remained nonsignificant (all $F_s < 1$), presumably because the limited presentation duration reduced the variance of the data (see Figure 2(a)).

The same analysis computed over the fixations into the peripheral void region did not show any significant effects on search efficiency (all $F_s < 1$). These results demonstrate

that COG fixations also benefit search performance in search among abstract and unfamiliar stimulus materials and in the absence of specific skills or expertise. Moreover, the finding that search was facilitated only by COG fixations and not peripheral void fixations is in line with the view that search benefits of void fixations depend on the information gain at the fixated location (see Figure 2(b)).

(II) *Effect of Void Fixations on Other Fixations in a Stimulus Cluster.* To test whether improved search performance with COG fixations can be attributed to the fact that multiple items were processed during the COG fixation, we next analysed whether and to what extent COG fixations reduced the mean number of fixations and/or the mean dwell times of fixations into the cluster. For this cluster-based analysis, the time-limited condition and target present trials were excluded because they lacked sufficient observations.

(a) *Number of Fixations.* The results of the first analysis confirmed that COG fixations significantly reduced the mean number of fixations into the same cluster. Figure 3(a) depicts the mean number of fixations observed with no void fixations versus peripheral or central void fixations, or both. A 2×4

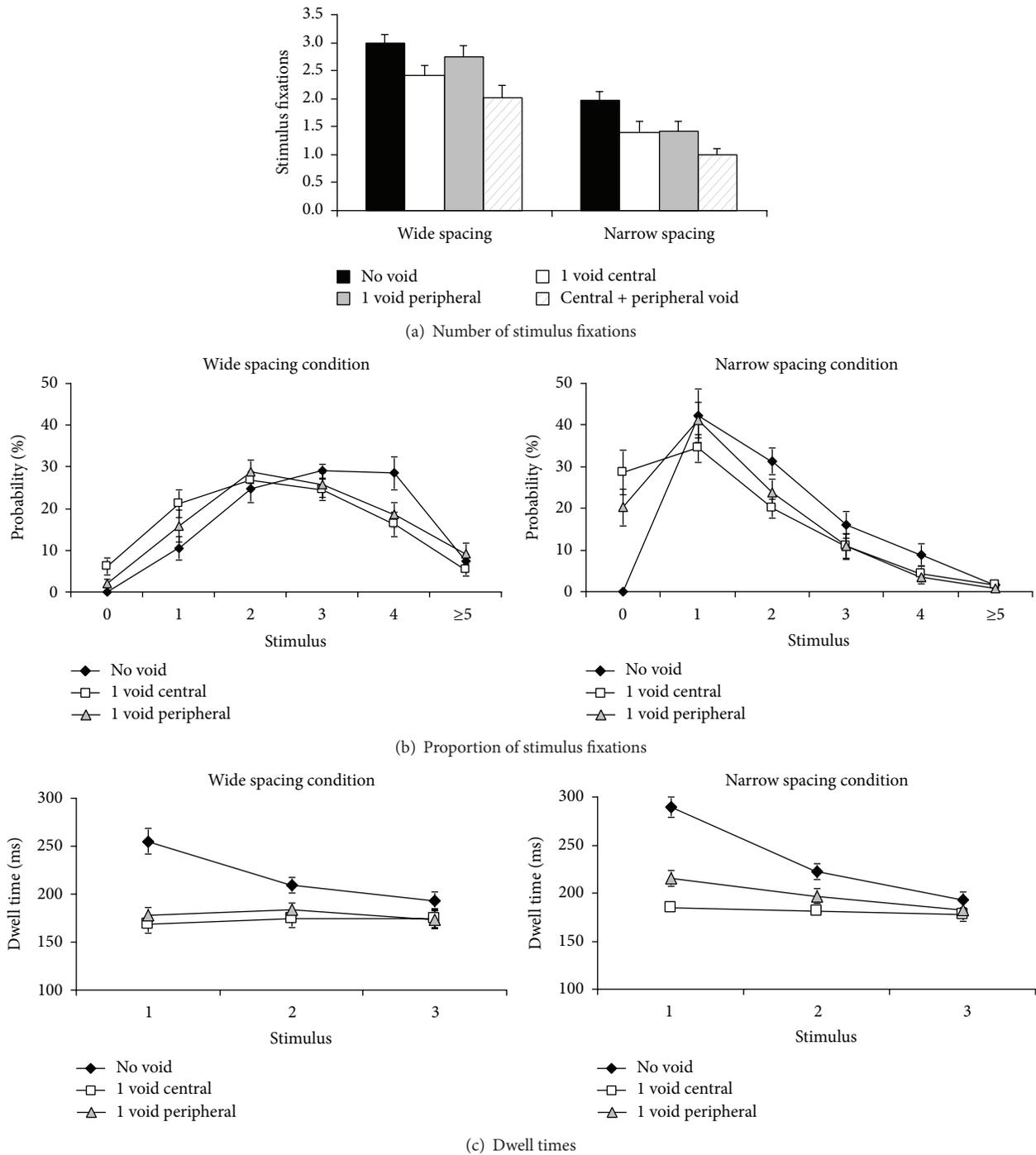


FIGURE 3: Effects of void fixations on stimulus fixations within a cluster. (a) The mean number of stimulus fixations within a cluster, depicted separately for instances in which there were no void fixations, one central or peripheral void fixation, and both central and peripheral void fixations into the cluster. Error bars depict ± 1 SEM and may be smaller than the plotting symbol. (b) The mean proportion of stimulus fixations within a cluster, depicted separately for instances in which 0, 1, 2, 3, 4, 5, or more stimulus fixations were made into a cluster. Results are depicted separately for the wide and narrow spacing conditions. (c) The mean dwell times of stimulus fixations within a given cluster, when observers had made 1, 2, or 3 stimulus fixations into a cluster, depicted separately for instances in which no void fixations, a central void fixation, or peripheral void fixations have been made into the cluster.

ANOVA comprising the variables spacing condition (narrow, wide) and fixated item (stimulus, central void, peripheral void, outside region) showed that there were more stimulus fixations in the wide condition than the narrow condition ($F(1, 18) = 35.8, P < .001, \eta_p^2 = .66$) and more stimulus fixations when no void fixations had been made ($F(3, 54) = 53.9, P < .001, \eta_p^2 = .75$; interaction: $F(3, 54) = 2.5, P = .093$). Stimulus fixations were most strongly reduced when both central and peripheral void fixations had occurred, to a lesser degree with a single central void fixation and to an even lesser degree with a single peripheral void fixation (see Figure 3(a)). Two-tailed t -tests showed that these differences were all significant (wide spacing: all $t_s > 2.8, P_s < .011$; narrow spacing: all $t_s > 3.7, P_s < .003$), except that the effects of peripheral and central void fixations did not differ in the narrow spacing condition ($t < 1$).

Figure 3(b) depicts the probability distribution of selecting 0, 1, 2, 3, 4, 5, or more stimuli within a cluster when there were no void fixations or a central or peripheral void fixation into the cluster. As shown in the figure, central void fixations mainly differed from peripheral void fixations by increasing the probability that observers made no stimulus fixations into the cluster (wide condition: $t(19) = 2.5, P = .024$; narrow condition: $t(19) = 2.4, P = .029$). In the wide condition, COG fixations also reduced the probability of making a single stimulus fixation into the cluster more than peripheral void fixations, although this difference just failed to reach significance ($t(19) = 2.0, P = .059$).

(b) *Dwell Times.* The same analyses were conducted to assess whether COG fixations would reduce the dwell times of stimulus fixations into the same cluster. Figure 3(c) depicts the mean dwell times of stimulus fixations, separately for instances in which one, two, or three stimulus fixations were made into a cluster, and as a function of whether there were no void fixations or a central or peripheral void fixation. As shown in the figure, COG fixations systematically reduced the dwell times of stimulus fixations within the same cluster. A 3×3 ANOVA comprising the factors number of fixations (1–3) and void fixations (no void fixation versus one central void condition versus one peripheral void fixation) computed over the data of the wide spacing condition showed significant main effects of both variables (number of fixations: $F(2, 20) = 37.0, P < .001, \eta_p^2 = .79$; void fixations: $F(2, 20) = 4.95, P = .039, \eta_p^2 = .33$) as well as a significant interaction between the variables, $F(4, 40) = 11.0, P < .001, \eta_p^2 = .52$. The same results were obtained in the narrow spacing condition (number of fixations: $F(2, 20) = 34.7, P < .001, \eta_p^2 = .72$; void fixations: $F(2, 20) = 21.5, P < .001, \eta_p^2 = .62$; interaction: $F(4, 40) = 31.8, P < .001, \eta_p^2 = .71$). As shown in Figure 3(c), void fixations significantly reduced the dwell times of stimulus fixations, whereby this effect was particularly strong when only one stimulus fixation had been made into the same cluster. Two-tailed t -tests showed that in the wide spacing condition, both central and peripheral void fixations significantly shortened dwell times when participants made 1, 2, or 3 stimulus fixations into

the cluster (all $t_s > 4.6, P_s < .002$); whereby the effects of COG fixations did not differ significantly from the effect of peripheral void fixations in the wide spacing condition. In the narrow spacing condition, a COG fixation significantly reduced the dwell times of stimulus fixations across all conditions (all $t_s > 3.1, P_s < .008$), and peripheral void fixations significantly reduced dwell times when observers made only 1 or 2 stimulus fixations into a cluster ($t_s > 5.0, P_s < .001$) but not when observers made 3 stimulus fixations ($t < 1$). In the narrow spacing condition, COG fixations reduced dwell times of stimulus fixations to a greater extent than peripheral void fixations when observers made one or two stimulus fixations ($t_s > 2.3, P_s < .033$), but not when 3 stimulus fixations were made into the cluster, $t < 1$.

The results listed above clearly show that an additional fixation into void regions reduced the number of stimulus fixations and the dwell times of these stimulus fixations in the same cluster, testifying to the fact that fixations into empty regions aided stimulus processing. An additional analysis was conducted to test whether dwell times of stimulus fixations are more strongly reduced by void fixations than stimulus fixations. To that aim we compared dwell times between clusters with two fixations in total (two stimulus fixations, or one stimulus fixation and one void fixation). The results showed that dwell times were shorter when a void fixation had occurred than when both fixations had been stimulus fixations. In the wide spacing condition, both central and peripheral void fixations resulted in significantly shorter dwell times than a stimulus fixation, $t_s > 2.5, P_s < .026$. In the narrow condition, only central void fixations shortened dwell times significantly more than stimulus fixations, $t(17) = 5.2, P < .001$, whereas peripheral void fixations did not shorten dwell times more than stimulus fixations, $t < 1$. Taken together, the findings show that void fixations affect stimulus processing more strongly than stimulus fixations.

(III) *Determinants of COG Fixations and Peripheral Void Fixations.* As mentioned above, the results so far support the view that the visual system can profit from fixations on empty locations, with the gain related to the possible information gain at a location. Can the visual system in addition strategically use void fixations to maximise such gains? If this is the case, then we would expect more COG fixations on the central void region than the peripheral void regions and more COG fixations in the narrow spacing condition than the wide spacing condition. This holds because, in these conditions, COG fixations have a higher potential information gain. However, corresponding results may still be consistent with a bottom-up account of COG fixations because of the underlying differences in the stimulus displays (wide versus narrow spacing) or the relative positions (central versus peripheral void regions exerting different bottom-up effects on eye movements). Hence, the most decisive evidence for a strategic account of COG fixations would be an increase of COG fixations in the time-limited condition compared with the (unrestricted) narrow spacing condition, which had the same stimulus displays.

Figure 4 depicts the results of the three analyses. In line with the predictions of a strategic account, the central void

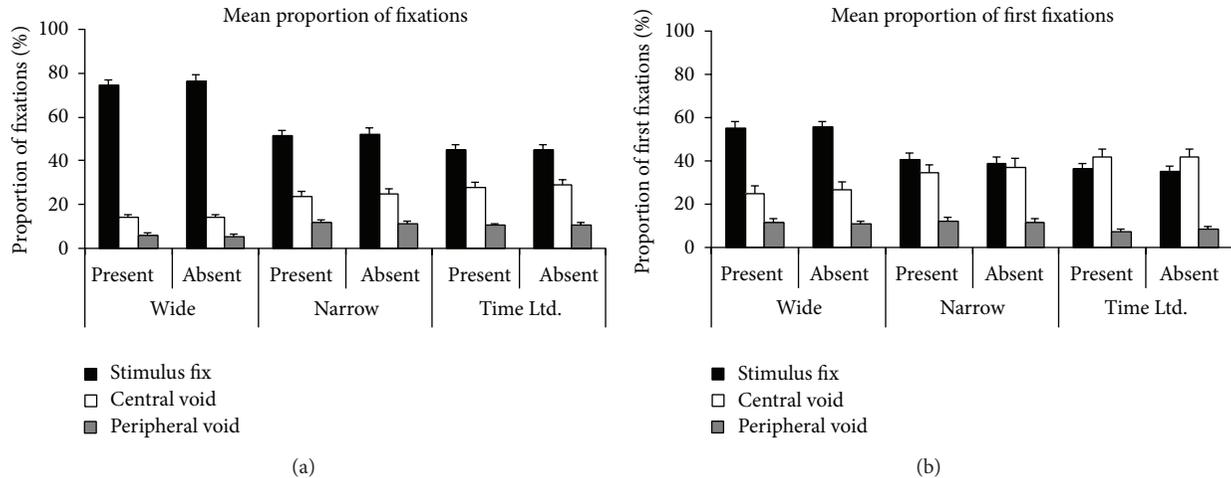


FIGURE 4: Determinants of CoG fixations and peripheral void fixations. The mean proportion of fixations (a) and mean proportion of first fixations (b) within a trial, depicted separately for the different conditions and different types of fixations (stimulus fixation versus central void fixation versus peripheral void fixation). Error bars depict ± 1 SEM and may not be visible when the SEM is very small.

region was more frequently selected in the time-limited condition than in the unrestricted narrow spacing condition, on both target present trials, $t(19) = 3.7, P = .002$, and target absent trials, $t(19) = 2.4, P = .025$ (see Figure 4(a)). These results indicate that the proportion of COG fixations was indeed strategically adapted to the task demands, indicating that we have at least partial top-down control over COG fixations.

Comparing the proportion of COG fixations across different regions and conditions showed that the central void region was selected more frequently than the peripheral void regions, on target present and absent trials and across all spacing conditions (all $t_s > 3.6$; all $P_s < .003$). Moreover, the proportion of COG fixations was higher in the narrow spacing conditions than in the wide spacing condition, on both target present and target absent trials (all $t_s > 5.4$; $P_s < .001$). These results demonstrate that the proportion of COG fixations was flexibly adapted to the task demands and the projected information gains.

An additional analysis was performed over the first fixations within a trial, to check whether the observed effects were present at an early stage of visual processing or whether they developed later during search (see Figure 4(b)). Contrary to the latter contention, selection of the central void region was disproportionately high in the first fixation within a trial—significantly higher than in the average proportion of fixations ($F(1, 19) = 81.1, P < .001, \eta_p^2 = .81$), and this was true for all spacing conditions and for target present and absent trials (all $t_s > 5.3, P_s < .001$). In line with the earlier results, a higher proportion of first fixations was made to the COG region rather than a peripheral void region, across all conditions (all $t_s > 2.8, P_s < .012$); the narrow and time-limited conditions showed significantly higher proportions of first COG fixations than the wide spacing condition (all $t_s > 2.2, P_s < .036$), and there were significantly or marginally significantly more first COG fixations in the time-limited condition than in the narrow spacing condition (present

trials: $t(19) = 3.5, P = .002$; absent trials: $t(19) = 1.9, P = .068$). Taken together, these results demonstrate that strategies to adapt COG fixations to the information gain of a condition or location were present at an early stage.

2.4. Discussion. The results of Experiment 1 support the view that COG fixations can be regarded as a correlate for multiple-item processing: first, COG fixations significantly benefited search performance, and second, COG fixations reliably reduced the number of stimulus fixations and their dwell times. Of note, fixations on the peripheral void regions did not enhance search efficiency and reduced stimulus fixations and their dwell times to a lesser degree than true COG fixations. These findings may constitute the best available evidence that multiple items were processed during a COG fixation.

In addition, the results demonstrated that COG fixations are to some degree under top-down control, as reflected by the results of the time-limited condition: when observers were forced to search quickly through the stimuli, the proportion of COG fixations increased significantly. These results are not predicted by a bottom-up account of COG fixations and indicate that COG fixations were strategically adapted to the task demands.

The results of the manipulation checks further corroborated these findings: more fixations were made into the highly informative central void region than the lesser informative, peripheral void regions, and more COG fixations were made in the narrow spacing condition than in the wide spacing condition. These results are consistent with the view that fixations into empty regions depend on the information content in a particular region, with their landing position and frequency being strategically adapted to optimise stimulus processing [16, 18, 19].

A possible complication for this interpretation is that COG fixations were frequently made at the beginning of the trial. Given that trials with short RT will have fewer fixations

TABLE 1: Correlations of RT with the proportion of trials with stimulus fixations, central void fixations, and peripheral void fixations.

	Wide spacing			Narrow spacing		
	Stim.	COG	Periph.	Stim.	COG	Periph.
Present trials	97.4%	65.5%	34.4%	91.4%	76.7	55.6%
Correl. (RT)	0.491*	-0.498*	0.223	0.532*	-0.220	0.581*
<i>P</i> value (Regr.)	0.028	0.025	n.s.	0.016	n.s.	0.007
Absent trials	100%	85.1%	42.2%	91.5%	76.7%	74.8%
Correl. (RT)	NA	-0.251	0.300	0.587*	-0.179	0.687*
<i>P</i> value (Regr.)	NA	n.s.	n.s.	0.007	n.s.	0.007

Note. Mean proportion of trials with one or more stimulus fixations, one or more COG fixations, and one or more peripheral void fixations; the correlation of each of these values with the participants' mean RT, depicted separately for the wide and narrow spacing conditions and present and absent trials. Asterisks indicate significant correlations, as per linear regressions that were computed separately over the RT and the proportion of trials with stimulus fixations, COG fixations, or peripheral void fixations, respectively (exact *P* values reported below). Bold font indicates negative correlations indicative of facilitation. Stim.: stimulus fixation; COG: central void fixation; periph.: peripheral void fixation.

overall, it is possible that trials with short RT had a higher proportion of COG fixations simply because trials with short RT have fewer fixations overall. To address this potential problem, we inspected entire trials according to whether they showed a COG fixation or not and computed the proportion of trials that had one or more COG fixations (by dividing the number of trials with COG fixation by the number of all trials). Analyses based on the proportion of trials with COG fixations are biased against finding facilitatory effects of COG fixations, because the probability of a COG fixation (or any kind of fixation) is lower when trial times are short (i.e., with short RT). This holds because fixations take time and, therefore, are usually positively correlated with RT.

As shown in Table 1, RT indeed correlated positively with stimulus fixations and peripheral void fixations. However, the reverse effect of a negative correlation was evident for central void (COG) fixations. That is, across all conditions, participants with a higher proportion of trials with COG fixations showed faster RT (see Table 1). The results of the RT regressions showed that this negative correlation was significant only on wide present trials, whereas the positive correlation between stimulus fixations and RT was always significant, and the positive correlation between peripheral void fixations and RT was significant for the narrow condition. This result was expected, considering the bias against finding a negative correlation.

Note that COG and stimulus fixations were collated independently of each other, thus allowing for the conclusion that a higher proportion of trials with COG fixations (and with or without stimulus fixations) result in shorter RT whereas a higher proportion of trials with stimulus fixations (and with or without COG fixations) result in longer RT. Taken together, the results support the notion that COG fixations benefit search—presumably, because a higher proportion of COG fixations (indirectly) indexes an observer's capacity for processing multiple items in parallel.

We also compared RT between trials in which the first fixation was made on a central or peripheral void region or on a stimulus. Three subjects had to be excluded from these analyses because of missing values. The wide condition showed shorter RT on present trials when the first fixation had been a COG fixation (2,284 ms) than when it had been a stimulus fixation (2,500 ms; $t(16) = 3.2$, $P = .006$) and shorter RT on absent trials when the first fixation had been a COG fixation (3,586 ms) than when it had been a stimulus fixation (3,691 ms; $t(16) = 2.1$, $P = .053$) or a peripheral void fixation (3,789 ms, $t(16) = 2.4$, $P = .029$). The narrow condition showed the same trends which, however, remained nonsignificant.

Despite the clear evidence that COG fixations benefit search, it could still be doubted that COG fixations are affected by top-down strategies. More COG fixations in the time-limited condition could also be due to saccades being elicited earlier, with the result that saccade endpoint positions were based on early sensory signals with a poor resolution that simply averaged over positions [2, 6, 7, 9, 11]. In this case, more COG fixations in the time-limited condition would be simply due to bottom-up limitations in the visual system and the fact that the time restrictions left no time to provide high-resolution information about the object position early on in saccade planning.

We tested this bottom-up explanation by inspecting whether the first saccades within a trial directed at a (central or peripheral) void region indeed started earlier (i.e., had shorter saccade latencies) than saccades directed at a stimulus. To ensure that the first saccades were not unduly influenced by the target, we limited the analyses to target absent trials and collapsed the data over correct and incorrect trials to yield sufficient observations. Figures 5(a)–5(c) depict the number of trials in which the latencies of the first saccades was short versus long (0–700 ms saccade latency, in bins of 15 ms), separately for stimulus, COG, and peripheral void fixations. As shown in Figure 5, COG fixations were not made visibly earlier than stimulus fixations. This rules out that COG fixations in the time-limited condition were due to bottom-up limitations that increased saccades into the centre of gravity because of poorly resolved sensory signals [2, 9]. Instead, in all conditions (wide, narrow, and time-limited), the earliest saccades directed either to a stimulus or the centre of gravity were elicited around 170–195 ms, independently of whether the conditions had time limitations. These results indicate that the higher proportion of COG fixations in the time-limited condition were due to a strategic adaptation to the task demands, with the COG location being targeted more frequently because it optimized the information gain.

Of note, Experiment 1 showed an unusually high number of COG fixations: previous visual search studies usually reported much lower proportions of COG fixations that were well below 20% [11, 12, 14]. In the previous literature, higher proportions of COG fixations seemed to be limited to studies using meaningful stimuli such as chess configurations or words that were embedded in a highly structured context [14, 20–23]. The present finding of high proportions of COG fixations especially in the first fixations (~50%) demonstrates that high proportions of COG fixations can be observed

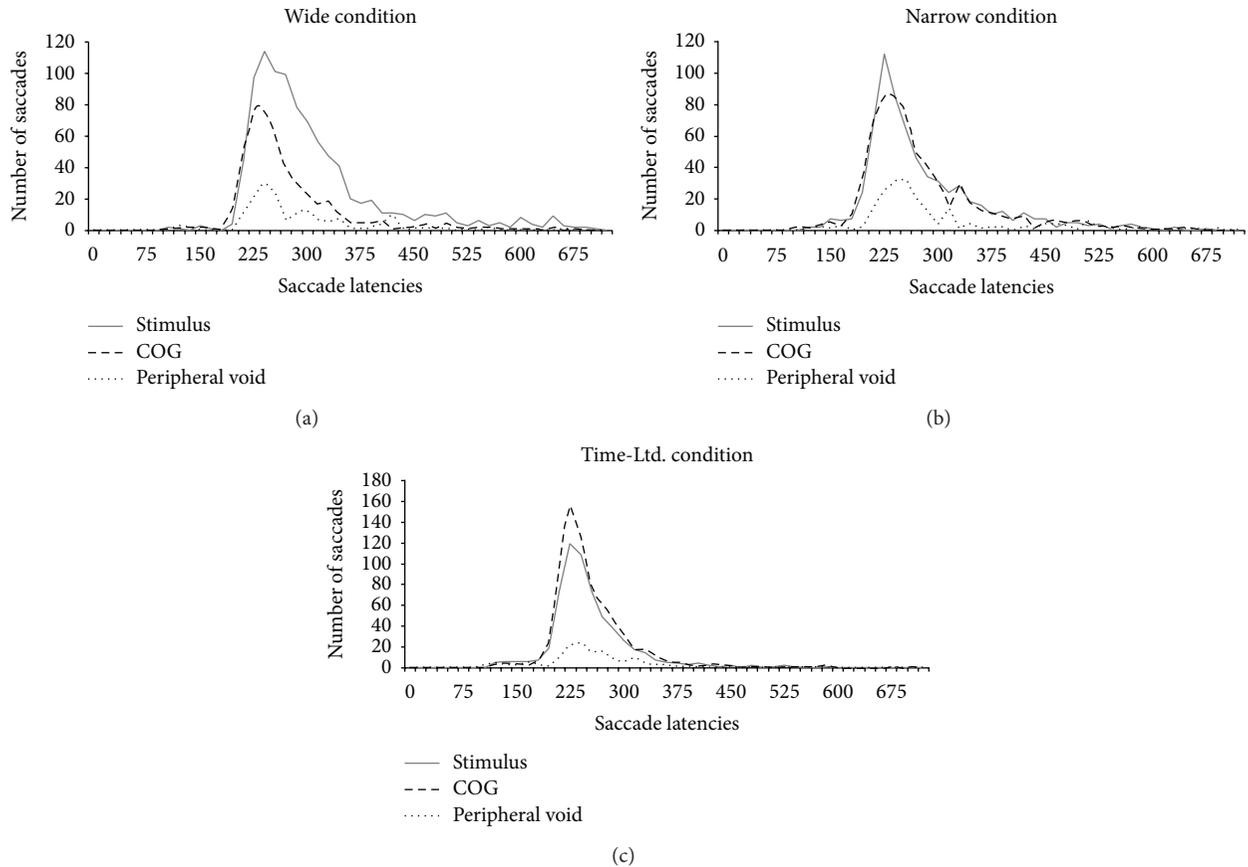


FIGURE 5: Fixations as a function of saccade latency. Number of fixations on a stimulus, central void region (COG), or peripheral void region as a function of saccadic latency, depicted separately for the wide and narrow spacing conditions and the time-limited narrow spacing condition.

with unfamiliar and abstract stimulus materials. Hence, the present findings show that expertise or higher-order cognitive skills such as reading or chess expertise are not necessary for observers to select COG locations.

It should be noted, however, that the stimuli in the present study were arranged in highly structured clusters. Experiment 2 was designed to test whether the same results could be obtained in unstructured displays, when the stimulus positions were unforeseeable.

3. Experiment 2

Experiment 2 was designed to test whether COG fixations would still aid search and show evidence for being strategic when the search stimuli are presented in unstructured and unforeseeable configurations. To that aim, we used the same stimuli and task in Experiment 2 as in the previous experiment; however, in Experiment 2, 18 Landolt Cs were distributed randomly over 36 possible locations in the search array. This allows for an equal number of grid regions to contain either a Landolt C or an empty space (see Figure 1(b) for reference). The viewing time was limited (to 5,500 ms) to encourage participants to adopt an efficient search strategy.

As in Experiment 1, we assessed whether COG fixations facilitate search by computing a regression over the mean

RTs with COG fixations as an independent variable. To test whether COG fixations observed in this task were strategic, we dynamically adapted the size of the viewable area around the observer's gaze location: all search stimuli (Landolt Cs) were initially masked with stimuli that had the same size as the search stimuli but did not convey any information about whether the location contained a target or a distractor. In different blocked conditions, a different proportion of search stimuli were unmasked within a gaze-contingent window that was continually centred at the observer's gaze, with the window unmasking either only a single stimulus (i.e., the fixated stimulus, *Z70 condition*), 2-3 stimuli (*Z150 condition*), 3-4 stimuli (*Z200 condition*), a whole quadrant (*Zoom320 condition*), or all stimuli (*free viewing condition*). If COG fixations are indeed under top-down control, the proportion of COG fixations should increase with the window size (i.e., the area of viewable search stimuli), because the possible information gain of COG fixation progressively increases with the window size. Hence, if participants can strategically use COG fixations to promote multiple-item processing, COG fixations should gradually increase along with an increase in window size. By contrast, if COG fixations are purely bottom-up, they should not be modulated by the potential information gain of between-item fixations and, thus, should not differ between the conditions because the masks did not alter the stimulus locations or their configuration.

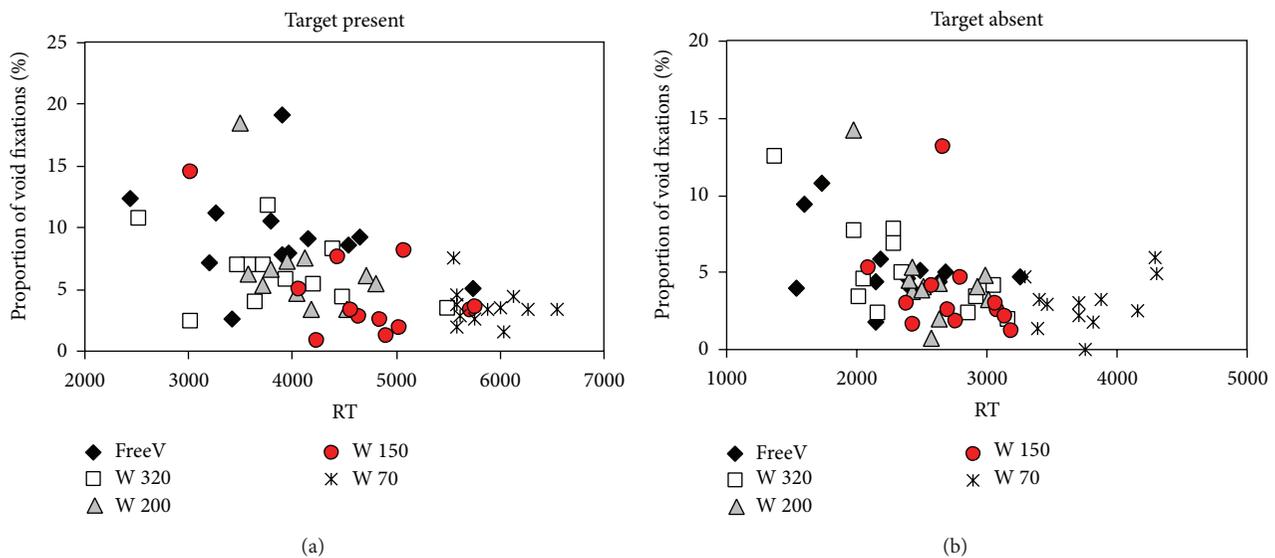


FIGURE 6: Effects of COG fixations on search performance (RT), Experiment 2. Mean individual search times as a function of the proportion of fixations into a void region, depicted separately for the free viewing condition (FreeV; black diamonds) and the 4 different restricted viewing conditions (W = window, with number specifying the size of the viewable area in pixels). As in Experiment 1, a higher proportion of void fixations is associated with shorter RT, both on target present trials (a) and target absent trials (b).

3.1. Method

3.1.1. Participants. Twelve new and naïve participants (nine females, mean age of 20.1) took part in Experiment 2 and were reimbursed with \$10 for their participation.

3.1.2. Stimuli, Design, and Procedure. The observers' task was to search for a closed target ring among distractor Landolt Cs (diameter: 0.83°) in an array of 18 stimuli that were randomly positioned on a 6×6 matrix ($20.3^\circ \times 20.3^\circ$; distance between stimuli: 4.1°). As in Experiment 1, observers had to report with a button press whether the target was absent or present (50%).

In the free viewing condition, all stimuli were visible from the start of the trial. In the restricted viewing conditions, only stimuli (Landolt Cs and target ring) within a specific distance around the fixation were visible, whereas all other stimuli were obscured by masks. The masks were circles with thin intersecting lines at the outlines and a small dot in the centre (see Figure 1(b), bottom). In the restricted viewing conditions, the size of the gaze-contingent window varied in different blocks between 70 pixels (1.9°), 150 pixels (4.2°), 200 pixels (5.5°), and 320 pixels (8.9°). Across all conditions, the search stimuli were presented for 5,500 ms, and participants completed 55 trials in each block. All participants were familiarised with the task by first completing 20 trials of the free viewing condition. After familiarisation, all participants first worked through the free viewing condition, after which they completed 4 blocks of the restricted viewing conditions, which were presented in random order.

3.2. Data. In Experiment 2, RTs longer than 10 s were excluded from all analyses ($<0.1\%$). Trials with wrong manual

responses (15.1%) were also excluded. Mean values were based on 27 trials per cell (range: 19 to 36 trials).

3.3. Results. Table 2 shows the effect of window size on the mean RT, error scores, dwell times, and fixation parameters. As can be seen in Table 2, both the mean RT and the number of stimulus fixations significantly decreased as the window size increased. To assess the effect of COG fixations on search performance, we computed a linear regression over the mean RT, with window size (1–5) and proportion of COG fixations as independent variables (see Figure 6). The analysis showed that both the proportion of COG fixations and the window size significantly modulated RT (present trials: $F(2, 59) = 39.4$; $P < .001$; $R^2 = .58$; COG fixations: $t = 3.0$; $P = .004$; window size: $t = 7.0$; $P < .001$; absent trials: $F(2, 59) = 31.8$; $P < .001$; $R^2 = .53$; COG fixations: $t = 2.9$; $P = .015$; window size: $t = 5.4$; $P < .001$). As in Experiment 1, search was significantly faster with a higher proportion of COG fixations, indicating that COG fixations facilitated search.

Table 2 shows that the proportion of COG fixations was higher for the first fixations on a trial than averaged over all fixations within a trial (compare Proportion void fix with Proportion of 1st void). This again raises the problem that short RT may have correlated with a higher proportion of COG fixations simply because COG fixations predominantly occurred early in the trial. To ascertain that COG fixations indeed aid search performance, we additionally computed the RT regression over the individual's mean proportion of trials with COG fixations. The results showed that narrowing the window size significantly decreased the proportion of trials with COG fixations ($F(4, 44) = 3.3$, $P = .034$). Moreover, a linear regression showed that a higher proportion of COG

TABLE 2: Experiment 2: effect of window size on eye movement parameters.

	Free V	Viewing condition				Effect of window size		
		Z 320	Z 200	Z 150	Z 70	<i>F</i>	<i>P</i>	η_p^2
RT								
Pres.	2267**	2381**	2585**	2748**	3763	35.9	<.001	0.76
Abs.	3809**	3860**	4127**	4696**	5877	50.4	<.001	0.82
Error								
Pres.	22.9	21.4	26.2	22.7	30.4	1.6	n.s.	
Abs.	3.4	2.2	1.8	1.0	3.7	1.7	n.s.	
Number of stim. fix.								
Pres.	6.1**	6.4**	6.8**	7.1**	9.6	15.5	<.001	0.058
Abs.	14.2*	14.0*	14.8*	16.4	16.7	5.0	.014	0.31
Number of void fix.								
Pres.	0.6**	0.4	0.5	0.3	0.4	3.7	.011	0.25
Abs.	0.8**	0.7*	0.6	0.6	0.5	3.3	.018	0.23
Dwell time								
Pres.	164**	171**	171**	185**	212	45.6	<.001	0.80
Abs.	168**	173**	177**	185**	219	48.6	<.001	0.81
Prop. stim. fix.								
Pres.	90.6**	93.2**	92.7	95.0	96.2	6.5	<.001	0.37
Abs.	94.5*	94.7	95.0	96.1	96.3	2.4	.062	(0.18)
Prop. void fix.								
Pres.	9.2**	6.4**	6.9*	4.5	3.6	9.5	<.001	0.47
Abs.	5.4**	5.2*	4.6	3.7	3.0	4.9	.002	0.31
Proportion of 1st stim.								
Pres.	81.8	82.3	82.2	90.4*	81.2	1.9	n.s.	
Abs.	81.2	84.9	83.7	86.6	80.5	1.5	n.s.	
Proportion of 1st void								
Pres.	18.2	17.7	17.8	9.2*	18.8	2.0	n.s.	
Abs.	18.8	15.1	16.0	13.4	19.5	1.6	n.s.	

* $P < .05$, ** $P < .01$ for the comparison to the narrowest zoom condition (Z70).

trials still led to significantly faster RT on absent trials, $F(1, 59) = 7.3$, $P = .009$, $R^2 = .11$, whereas the same trends on target present trial remained nonsignificant, $F < 1$. These results show that COG fixations facilitate search even in unstructured displays.

3.4. Discussion. The results of the second experiment showed that COG fixations can also serve as a correlate for search efficiency in visual search among unstructured displays, in which stimulus positions are unpredictable. These results reinforce the view that COG fixations facilitate processing of multiple items in the periphery.

Moreover, as in Experiment 1, the frequency of COG fixations was adapted to different viewing conditions, with progressively fewer COG fixations when the viewing area was

further limited and there were fewer opportunities to process multiple items during a fixation. These results indicate that COG fixations were at least to some extent under top-down control. Of note, a pure bottom-up account cannot account for the decrease of COG fixations with smaller window size, because the masks did not differ in saliency, size, or shape from the search stimuli. Hence, these effects have to be attributed to a strategic adaptation of COG fixations. In sum, the results of Experiment 2 indicate that COG fixations probably reflect strategic adaptations of eye movement behaviour that are controlled by the potential gains of COG fixations, even in unstructured visual search displays.

COG fixations were, however, much rarer in Experiment 2 than in the previous experiment, with only about 10% of all fixations being COG fixations and less than 20% of

first fixations being COG fixations, even in the free viewing condition. Although the results of Experiments 1 and 2 cannot be directly compared to each other because of the differences in stimulus size and density [3], the same observation has been made in several other studies [14–16, 21]. Together, these findings suggest that structured displays may be crucial for observing high rates of COG fixations, possibly, because in structured displays, the stimulus positions are foreseeable and allow preplanning eye movements. However, this possibility certainly warrants further investigation.

4. General Discussion

The present study yielded several interesting results. First, the results showed that COG fixations facilitate search by reducing the number of stimulus fixations and their dwell times within a cluster of stimuli. Second, the results showed that COG fixations were strategically adapted to different conditions, in that they were (a) more frequently made to locations with a higher potential information gain (central versus peripheral void locations), (b) more frequent in conditions that allowed for better viewing of stimuli in the vicinity (narrow spacing versus wide spacing in Experiment 1, larger area of visible search stimuli in Experiment 2), and (c) more frequently made in conditions that required an efficient selection strategy (i.e., time-limited condition in Experiment 1). In particular the latter results show that COG fixations in visual search are modulated by task demands, both in unstructured and structured displays. Thus, COG fixations reflect to some extent a strategic adaptation to maximise multi-item processing.

As a caveat, the view that COG fixations are modulated by task demands does not mean that the saccade endpoints are necessarily chosen voluntarily or chosen consciously by the observer. We use the terms top-down and strategic to point to a change in performance that is caused by the task (not the stimuli) and serves to optimise performance in the task, while permitting that such optimizations can be implicit and not consciously accessible (e.g., Becker, 2007). In addition, the present results can only show that COG fixations are modulated by top-down task demands and are in that sense strategic. This leaves open the possibility that the eye movement itself is generated as a bottom-up default option and that the saccade programme is only abandoned or executed depending on whether top-down demands favour or prohibit its occurrence [9, 11]. What the results show is that COG fixations are top-down modulated and strategic in the sense that their occurrences cannot be fully explained by bottom-up mechanisms.

As mentioned above, the view that COG fixations are not purely determined by an automatic averaging mechanism but are in part strategic has been proposed before [18]. However, the evidence for this view was not complete, as critical findings were based on comparing performance between different groups (e.g., experts versus novices). Alternatively or additionally, the tasks often involved familiar stimuli that required higher-order cognitive abilities such as chess expertise or reading skills [18, 20–24], and there was no

independent evidence for the view that COG fixations indeed foster multiple-item processing. The present study complements previous work by showing that COG fixations facilitate search by allowing for simultaneous processing of multiple items and that these findings generalise to observers with no specific expertise and to tasks and stimulus materials that are unfamiliar and do not require higher-order cognitive skills.

Of note, the present results leave open the possibility that COG fixations also depend to some extent on the stimulus conditions, as there were more COG fixations in the highly structured and foreseeable displays (Experiment 1) than the displays with random stimulus position (Experiment 2). In Experiment 1, stimulus clusters were always structured the same and the configuration did not change across trials. Hence, eye movements into void regions could be made either on the basis of the remembered positions of the void regions (from the last trial) or by applying the same algorithm for computing the saccade landing position across the four clusters. It is unknown whether COG fixations can be based on remembered saccade locations, and at a first glance, it may seem implausible that regions devoid of stimuli are memorised and can be used for saccade programming. However, in the present stimulus configurations, the central void region was always situated at the centre of a diamond, so that it could be targeted by encoding the global structure of the diamond and honing in on its centre. Presenting stimuli in a global structure may thus have had a dual facilitating effect of speeding on-line computations of saccade target positions and aiding memory-related processes of encoding the locations of void regions [15]. The present study cannot determine whether a higher proportion of COG fixations in Experiment 1 was due to the fact that the diamond configurations facilitated COG saccade programming or whether repeating the displays allowed executing COG saccades from memory. However, what is clear from the results is that the stimulus conditions play an important role in bringing about COG fixations, whereas the familiarity of the stimulus material and skill-related abilities are less decisive.

Moreover, the strong dependency of COG fixations on the information gain and strategic factors also questions the claims of current theories of eye movement control, that visual selection is largely determined by bottom-up saliency [25–27], or that COG fixations reflect bottom-up averaging of positions [2, 17]. Instead, the results highlight the importance of strategic factors in guiding the gaze [19].

Implications for Theories of Attention and Eye Movement Control. As mentioned above, the results of the present study support the view that multiple items are processed during a single fixation. This view is strongly supported by the two findings: first, the finding that observers frequently made only a single fixation into a stimulus cluster (see Figure 3(b)) and second, the finding that dwell times on stimulus fixations varied systematically with the number of stimulus fixations and void fixations into a cluster (see Figure 3(c)). These results strongly suggest that more often than not multiple items are selected and processed during a single fixation, including “normal”

stimulus fixations. To some researchers, these conclusions may not be surprising: several eye movement studies have already shown that observers typically do not select each and every stimulus present in the display, which already indicates that multiple-item processing occurs at least during some fixations [28]. However, in the analysis of eye movement data, it is typically assumed that each fixation has to be attributed to a single stimulus and, correspondingly, fixations between stimuli are usually either precluded from the outset (by defining areas of interest such that there are no gaps) or they are discarded as saccade errors [29, 30]. The results of the present study clearly reject this view. As shown in Experiment 2, even when COG fixations occur only infrequently, they significantly facilitate search. Moreover, in Experiment 1, COG fixations systematically altered the pattern of dwell times of stimulus fixations in the vicinity. These results highlight the importance of considering multiple items as the “unit of selection” in eye movement studies and suggest that excluding fixations on empty locations can falsify the results. This is perhaps an especially important point to consider for the analysis of dwell times. Of note, previous studies have often reported the rather puzzling finding that dwell times are impervious to stark modifications of the display, such as variations in the display duration or the number of items [31]. This has led to the view that that dwell times are relatively fixed and are determined prior to a trial, by a global estimate of how much processing will be required during each single fixation [31]. The results of Experiment 1 suggest that dwell times instead strongly depend on the number of fixations into a stimulus cluster, with systematically decreasing dwell times with increasing stimulus fixations. Moreover, a single void fixation can eliminate these differences and lead to dwell times that are largely unaffected by the number of stimulus fixations (see Figure 3(c)). These findings demonstrate that dwell times are strongly modulated by on-line processing demands [32], albeit the processing demands of a cluster of stimuli instead of a single stimulus. Previous failures to find on-line processing effects on dwell times may be rooted in the fact that fixations were mostly analysed with respect to a single stimulus instead of taking a restricted area of stimuli into account and analysing possible interactions between fixations into the cluster.

Taken together, the results of the present study provide new insights into how our common strategy of assigning fixations to single stimuli and excluding COG fixations can falsify the results and lead to wrong conclusions. In future studies, it may be worthwhile to consider the possibility of multiple-item processing during single fixations in the analysis of eye movement data and/or create stimulus conditions that preclude effective multiple-item processing. Considerations about adequate spacing between stimuli are also important to ascertain whether and to what extent visual search may be hampered by *crowding*—that is, limitations to discriminate the target in the periphery due to interference by nearby distractors [33].

In conclusion, we found that COG fixations lead to more efficient search and lower stimulus fixations and dwell times and that COG fixations diminish when stimulus positions unpredictably vary across trials. These results offer additional

support for the multiple-item processing view and demonstrate how the area between stimuli can be of strategic value in visual search.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgment

This research was supported by two Australian Research Council Grants (DP 110100588 and FT130101282) awarded to Stefanie I. Becker.

References

- [1] J. M. Findlay, “Global visual processing for saccadic eye movements,” *Vision Research*, vol. 22, no. 8, pp. 1033–1045, 1982.
- [2] J. M. Findlay, “Visual information processing for saccadic eye movements,” in *Spatially Oriented Behaviour*, A. Hein and M. Jeannerod, Eds., pp. 281–303, Springer, New York, NY, USA, 1983.
- [3] S. van der Stigchel and T. C. W. Nijboer, “The global effect: what determines where the eyes land?” *Journal of Eye Movement Research*, vol. 4, pp. 1–13, 2011.
- [4] F. Vitu, “About the global effect and the critical role of retinal eccentricity: implications for eye movements in reading,” *Journal of Eye Movement Research*, vol. 2, pp. 1–18, 2008.
- [5] S. Coren and P. Hoenig, “Effect of non-target stimuli upon length of voluntary saccades,” *Perceptual and Motor Skills*, vol. 34, no. 2, pp. 499–508, 1972.
- [6] C. Coeffe and J. K. O’Regan, “Reducing the influence of non-target stimuli on saccade accuracy: predictability and latency effects,” *Vision Research*, vol. 27, no. 2, pp. 227–240, 1987.
- [7] F. P. Ottes, J. A. M. van Gisbergen, and J. J. Eggermont, “Latency dependence of colour-based target vs nontarget discrimination by the saccadic system,” *Vision Research*, vol. 25, no. 6, pp. 849–862, 1985.
- [8] R. Walker, H. Deubel, W. X. Schneider, and J. M. Findlay, “The effect of remote distractors on saccade programming: evidence for an extended fixation zone,” *Journal of Neurophysiology*, vol. 78, pp. 1108–1119, 1997.
- [9] J. M. Findlay, “Saccadic eye movement programming: sensory and attentional factors,” *Psychological Research*, vol. 73, no. 2, pp. 127–135, 2009.
- [10] P. W. Glimcher and D. L. Sparks, “Representation of averaging saccades in the superior colliculus of the monkey,” *Experimental Brain Research*, vol. 95, no. 3, pp. 429–435, 1993.
- [11] J. M. Findlay and H. I. Blythe, “Saccade target selection: do distractors affect saccade accuracy?” *Vision Research*, vol. 49, no. 10, pp. 1267–1274, 2009.
- [12] E. McSorley and J. M. Findlay, “Saccade target selection in visual search: accuracy improves when more distractors are present,” *Journal of Vision*, vol. 3, no. 11, pp. 877–892, 2003.
- [13] P. He and E. Kowler, “The role of location probability in the programming of saccades: implications for “center-of-gravity” tendencies,” *Vision Research*, vol. 29, no. 9, pp. 1165–1181, 1989.

- [14] G. J. Zelinsky, "Using eye saccades to assess the selectivity of search movements," *Vision Research*, vol. 36, pp. 2177–2187, 1996.
- [15] A. Herwig, M. Beisert, and W. X. Schneider, "On the spatial interaction of visual working memory and attention: evidence for a global effect from memory-guided saccades," *Journal of Vision*, vol. 10, no. 5, article 8, 10 pages, 2010.
- [16] E. M. Reingold, N. Charness, M. Pomplun, and D. M. Stampe, "Visual span in expert chess players: evidence from eye movements," *Psychological Science*, vol. 12, no. 1, pp. 48–55, 2001.
- [17] G. J. Zelinsky, "TAM: explaining off-object fixations and central fixation tendencies as effects of population averaging during search," *Visual Cognition*, vol. 20, pp. 515–545, 2012.
- [18] N. Charness, E. M. Reingold, M. Pomplun, and D. M. Stampe, "The perceptual aspect of skilled performance in chess: evidence from eye movements," *Memory and Cognition*, vol. 29, no. 8, pp. 1146–1152, 2001.
- [19] J. Najemnik and W. S. Geisler, "Optimal eye movement strategies in visual search," *Nature*, vol. 434, no. 7031, pp. 387–391, 2005.
- [20] G. E. Legge, T. S. Klitz, and B. S. Tjan, "Mr. Chips: an ideal-observer model of reading," *Psychological Review*, vol. 104, pp. 524–553, 1997.
- [21] A. M. Jacobs, "Eye-movement control in visual search: how direct is visual span control?" *Perception and Psychophysics*, vol. 39, no. 1, pp. 47–58, 1986.
- [22] G. W. McConkie and K. Rayner, "The span of the effective stimulus during a fixation in reading," *Perception and Psychophysics*, vol. 17, no. 6, pp. 578–586, 1975.
- [23] K. O'Regan, "Saccade size control in reading: evidence for the linguistic control hypothesis," *Perception and Psychophysics*, vol. 25, no. 6, pp. 501–509, 1979.
- [24] H. Ojanpää, R. Näsänen, and I. Kojo, "Eye movements in the visual search of word lists," *Vision Research*, vol. 42, no. 12, pp. 1499–1512, 2002.
- [25] J. J. Clark, "Spatial attention and latencies of saccadic eye movements," *Vision Research*, vol. 39, no. 3, pp. 585–600, 2000.
- [26] L. Itti and C. Koch, "A saliency-based search mechanism for overt and covert shifts of visual attention," *Vision Research*, vol. 40, no. 10–12, pp. 1489–1506, 2000.
- [27] J. Theeuwes, A. F. Kramer, S. Hahn, and D. E. Irwin, "Our eyes do not always go where we want them to go: capture of the eyes by new objects," *Psychological Science*, vol. 9, no. 5, pp. 379–385, 1998.
- [28] D. E. Williams and E. M. Reingold, "Preattentive guidance of eye movements during triple conjunction search tasks: the effects of feature discriminability and saccadic amplitude," *Psychonomic Bulletin and Review*, vol. 8, no. 3, pp. 476–488, 2001.
- [29] S. I. Becker and G. Horstmann, "A feature-weighting account of priming in conjunction search," *Attention, Perception, and Psychophysics*, vol. 71, no. 2, pp. 258–272, 2009.
- [30] J. Shen, E. M. Reingold, M. Pomplun, and D. E. Williams, "Saccadic selectivity during visual search: the influence of central processing difficulty," in *The Mind's Eyes: Cognitive and Applied Aspects of Eye Movement Research*, J. Hyona, R. Radach, and H. Deubel, Eds., pp. 65–88, Elsevier Science, 2003.
- [31] I. T. C. Hooge and C. J. Erkelens, "Adjustment of fixation duration in visual search," *Vision Research*, vol. 38, no. 9, pp. 1295–1302, 1998.
- [32] S. I. Becker, "Determinants of dwell time in visual search: similarity or perceptual difficulty?" *PLoS ONE*, vol. 6, no. 3, Article ID e17740, 2011.
- [33] R. Rosenholtz, J. Huang, A. Raj, B. J. Balas, and L. Ilie, "A summary statistic representation in peripheral vision explains visual search," *Journal of Vision*, vol. 12, no. 4, article 14, 17 pages, 2012.

Research Article

The Bifixation Field as a Function of Viewing Distance

Philip M. Grove,¹ Alistair P. Mapp,² and Hiroshi Ono²

¹ School of Psychology, The University of Queensland, St. Lucia, QLD 4072, Australia

² Centre for Vision Research and Department of Psychology, York University, Toronto, ON, Canada M3J 1P3

Correspondence should be addressed to Philip M. Grove; p.grove@psy.uq.edu.au

Received 30 November 2013; Accepted 23 April 2014; Published 28 May 2014

Academic Editor: Gernot Horstmann

Copyright © 2014 Philip M. Grove et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Hering reported that the area over which he could bifixate a target was smaller at near convergence distances than far convergence distances and predicted that in extreme horizontal gaze positions, the temporally directed eye lags behind the nasally directed eye. We tested these predictions using a subjective index of eye position. Experiment 1 confirmed that the bifixation field was significantly smaller at near convergence distances. When bifixation broke down at the near distance, the nasally directed eye lagged behind the temporally directed eye for all observers. At the far distance, the nasally directed eye preceded the temporally directed eye for four of six observers. Experiment 2 also confirmed that the bifixation field was smaller at near convergence distances but the nasally directed eye always lagged behind the temporally directed eye at the limits of the bifixation field. We confirmed Hering's first prediction that the bifixation field is smaller at near convergence distances than at far ones. However, the majority of our results indicate that the nasally directed eye lags behind the temporally directed eye at the limits of the bifixation field, contrary to Hering's prediction. We conclude that the eyes drift toward their tonic state of vergence when fusion breaks.

1. Introduction

Binocular single vision and stereoscopic depth perception are critically dependent on precise coordination of the two eyes such that the left and right eyes' images fall on corresponding or nearly corresponding points in the two eyes. Bifixation refers to the images of fixated objects falling on the foveas in both eyes. The bifixation field refers to the total area over which the two eyes can accurately bifixate a target. Establishing bifixation on a target in the binocular visual field is achieved via binocular eye movements that typically involve both a version component and a vergence component. Version refers to a binocular eye movement in which both eyes rotate by an equal amount in the same direction. Vergence eye movements are those in which the two eyes rotate by an equal amount but in opposite directions. One subset of binocular eye movements involves a pure version movement with no vergence. Such a movement would trace an arc intersecting the centers of rotation in the two eyes and the fixation point. Another subset of binocular eye movements involves a pure vergence movement with no accompanying version. These movements trace parabolic arcs

intersecting the fixation point and the centers of rotation in the two eyes. All other binocular eye movements are combinations of version and vergence movements.

Tyler [1] argues that the role of vergence, in three-dimensional space perception, is similar to version eye movements in viewing a two dimensional scene. The general layout of a two dimensional scene is apparent without moving our eyes. However, we must change our gaze to foveate any details of the scene. Tyler describes the three dimensional case as follows:

The stereoscopic situation is analogous to perception of two-dimensional space with a high-acuity fovea controlled by lateral eye movements. It is clear that the general layout of objects in two-dimensional space is readily perceived across the 180 degree field without lateral eye movements. ... What the eye movements accomplish is detailed perception of a chosen part of the perceived scene. It seems reasonable to suppose that vergence movements serve the same role for the third dimension, bringing

regions of interest into the range of best disparity discrimination ([1] p. 283).

For Tyler, vergence is analogous to the commonly known function of version eye movements, the selection of small areas of the visual scene for detailed inspection with the fovea.

Hering [2] described the two eyes as a single mechanical and perceptual organ which he called the double eye. His theory, generally referred to as the law of equal innervation, accounts for how the eyes move together as a single mechanical organ. Hering's law is based on two putative kinds of innervation: one for the conjunctive (version) component of eye movements and one for the disjunctive (vergence) component of eye movements. Each type of innervation is equal in magnitude in the two eyes and binocular eye movements involve the pooling of the two types of innervation (see [3] for a more detailed discussion).

The pooling of version and vergence innervations has implications for the angular extent over which the two eyes can move together at different viewing distances. Specifically, the combination of version and vergence innervations relates to the change in size of the bifixation field as a function of viewing distance. To illustrate, consider the two eyes tracking a bifixated target into the periphery. At far convergence distances, where the visual axes (the visual axis is the line containing the point on which the eye is fixating, the optical nodal point of the eye, and the center of the fovea (Howard, 2012); a visual line is any straight line passing through the pupil and optical nodal point joining a distal object and a unique location on the retina) are nearly parallel (i.e., the eyes are converged at infinity), the vergence innervation is negligible relative to the version innervation. At near convergence distances, however, a large vergence innervation is required to maintain bifixation at the desired distance. Since the version and vergence innervations are congruent in the nasally directed eye and incongruent in the temporally directed eye, Hering predicted that the bifixation field should be smaller at near viewing distances, when the vergence innervation is large, than at far viewing distances, when the vergence innervation is small.

In support of his analysis above, Hering [2] made two critical observations. First, he measured the area over which each eye could move on its own by impressing a foveal afterimage on one eye when it was in primary position. Hering then moved his gaze away from primary position, attending to the afterimage. When he reached the extent to which he could move his eye in a given direction, he made a mark on a piece of glass indicating the location of the afterimage. Repeating this procedure for each eye, for near and far viewing distances, and for different directions of gaze, Hering mapped out a two-dimensional area over which he could direct the visual axis of each eye individually. The key observation was that the maximum horizontal excursion of a single eye was larger for far viewing distances than for near ones. Second, Hering reported that the area over which he could bifixate a target was relatively small compared to the combined areas over which each eye could move on its own.

Extending Hering's [2] observations and rationale, Mapp et al. [5] tested the prediction that the maximum

excursion of the left eye to the right and the right eye to the left is greater at far convergence distances than for near convergence distances. Importantly, Mapp et al. noted that in such extreme eye positions, it would be impossible to bifixate the target and speculated that the laws of equal innervation may only hold within the bifixation field. They suggested that a better test of Hering's hypothesis would be to examine the width of the bifixation area as a function of distance rather than the extreme position of the eyes.

Hering [2] also posited a mechanical and a structural factor influencing the extent of the bifixation field and the relative positions of the eyes when bifixation failed. The mechanical factor was that the medial recti play a more active role in moving the eyes because they are stronger muscles than the lateral recti. This speculation was later supported experimentally by Alpern and Ellen [6], Westheimer and Mitchell [7], and Yarbus [8]. Therefore, owing to the stronger medial recti, Hering predicted that, at the limits of the bifixation field, the nasally directed eye should overshoot the temporally directed eye. The structural factor Hering referred to was the restriction of the bifixation field due to facial structures such as the nose and orbital bones occluding the bifixated target to one eye in extreme gaze positions. This is a purely geometric constraint resulting from the optics of the eye and the protrusion of the nose and orbital bones.

In summary, the goal of this paper is to test three predictions derived from Hering's law of equal innervation. The first prediction is that the bifixation field is smaller for near convergence distances than for far distances, owing to increasingly incongruent vergence and version innervations at nearer viewing distances. The second prediction is that when bifixation breaks down, the nasally directed eye precedes the temporally directed eye, owing to the superior strength of the medial recti over the lateral recti. Third, we determine which boundaries of the bifixation field are imposed by facial structures. In Experiment 1, we test the first two predictions by examining the horizontal extent of the bifixation field for two convergence distances, using a stereoscopic apparatus which allows us to record eye signature information necessary to determine the relative positions of the eyes when bifixation breaks down. In Experiment 2, we extend these measurements to a 2D area in the frontoparallel plane to examine the spatial extent of the bifixation field for three convergence distances, testing all three predictions above. In anticipation, our data support the claim that the bifixation field is smaller at near convergence distances than for far distances, consistent with Hering's prediction, but only partially support the prediction that the nasally directed eye precedes the temporally directed eye at the limits of the bifixation field. Facial structures limit the extent of the bifixation field for moderate to long viewing distances.

2. Experiment 1

We measured the horizontal extent over which the eyes can move together and maintain bifixation for viewing distances of 32 cm and 125 cm. Second, we ascertained the relative position of the eyes at the limits of the bifixation field.

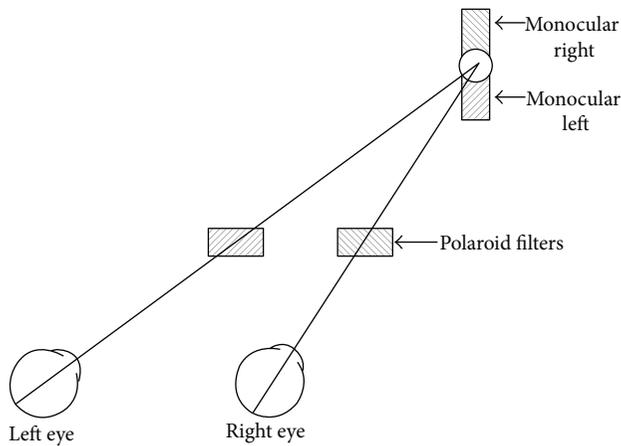


FIGURE 1: Illustration of the stimulus and the arrangement of the Polaroid filters in Experiment 1.

2.1. Method

2.1.1. Observers. There are six observers, four females and two males, from the Department of Psychology, York University participated. The observers ranged in age from 21 to 33 years with a mean age of 25.7 years. All had normal binocular vision and were experienced in psychophysical experiments. Those who required an optical correction wore contact lenses during the experiment.

2.1.2. Apparatus and Stimuli. The apparatus consisted of a motorized boom, suspended above the observer's head such that its centre of rotation was vertically aligned with the centre of rotation of either the right or the left eye. Two light-boxes, containing the stimuli, were positioned along the boom, at eye level, at viewing distances of 32 cm and 125 cm. Each stimulus consisted of a binocular dot, 0.6 degrees in diameter, flanked above and below by Nonius lines, 2.3 degrees long by 0.3 degrees wide. The Nonius lines were made visible to the right and left eyes via polarized filters such that one filter was placed in front of one of the Nonius lines and a complimentary filter was positioned before the appropriate eye. Figure 1 presents a schematic of the stimulus. Observers sat with their heads fixed by a bite-bar and they controlled the position of the boom via a joystick.

2.1.3. Procedure. The observers' task was to fixate the stimulus binocularly while either moving it away from their median plane (ascending trials) or moving it towards their median plane (descending trials) until it appeared misaligned (see Figure 2(b)) or aligned (see Figure 2(a)), respectively. The point at which the stimulus changed from appearing misaligned (aligned) to appearing aligned (misaligned) demarked the outer horizontal limit of the bifixation field. The angular position of the boom, with respect to the observers' median plane, at this limit, was recorded from a protractor attached to the boom. Additionally, the relative position of the eyes at the "breaking point" was determined by the observer's report of the position of (a) the upper half of

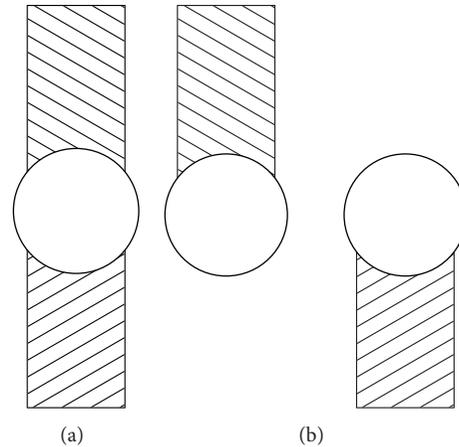


FIGURE 2: Appearance of the stimulus (a) within the bifixation field and (b) beyond the bifixation field.

the stimulus relative to the lower half and (b) the upper half of an afterimage induced with the eyes at the "breaking point" relative to the lower half.

Each observer performed a total of 92 trials, presented in four blocks of 23 trials each. Within each block, the limit of the horizontal bifixation field was measured 20 times at one convergence distance (32 cm or 125 cm) and one direction of gaze (rightward or leftward). Equal numbers of ascending and descending trials were presented randomly within each block and block order was randomized among observers. Three additional trials, at the end of each block, confirmed the relative position of the eyes at the "breaking point" as follows. With the observer's gaze at the limit of the bifixation field, an afterimage of the misaligned stimulus (see Figure 2(b)) was induced by a bright flash within the stimulus box. After receiving the afterimage, observers fixated a vertical line, in their median plane, and reported the position of the two components of the afterimage (the temporally and nasally directed eye's components) relative to the fixation line.

Figure 3 illustrates how the perceived relative position of the Nonius lines and afterimages indicates the relative position of the eyes when fusion breaks. The position of the stimulus and the eyes is given in the left panel of each quadrant. The associate perception is specified at the cyclopean eye in accordance with Wells [4] and Hering's [2] laws of visual direction and their modification by Mapp and Ono [9]. Stated briefly, Wells/Hering's laws state that a stimulus on the visual axes of the two eyes transfers to a common axis (cyclopean axis), which is a line passing through the intersection of the axes and a point midway between the eyes. Additionally, the angle between the visual axis and a monocular visual line transfers unaltered to the cyclopean eye. Consider the top left sector of Figure 3. The left half of this sector illustrates the stimulus and eye position and the right half illustrates the subjective perception. If in extreme leftward gaze the nasally directed right eye overshoots the temporally directed left eye, the right eye's visual axis precedes the binocular target. Therefore, the Nonius lines will appear to break such that the top (right eye's) Nonius line is to

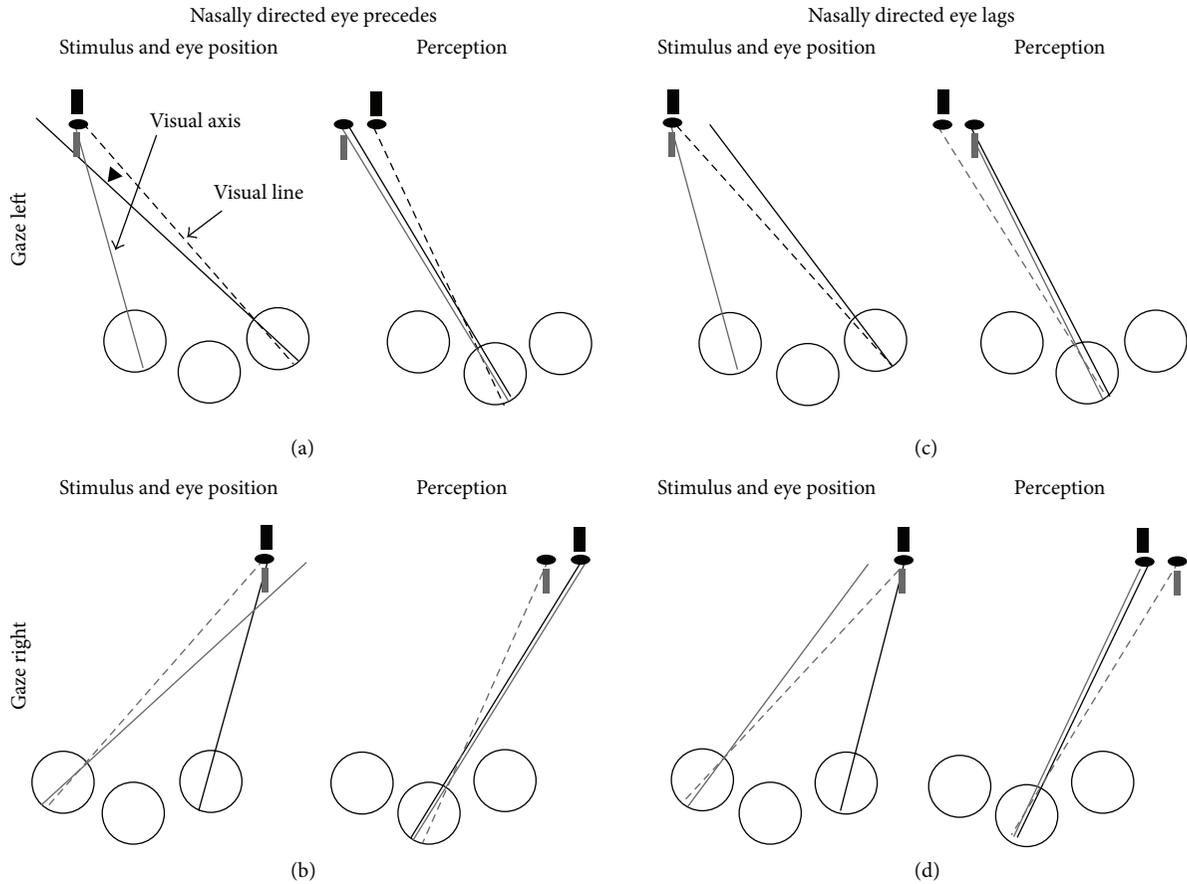


FIGURE 3: Predicted perceived Nonius/afterimage misalignments based on Wells [4] and Hering's [2] laws of visual direction. In (a) the nasally directed eye precedes the temporally directed eye with associated perception of Nonius lines or afterimages; (b) same as (a) but for rightward gaze; (c) the nasally directed eye lags the temporally directed eye in leftward gaze with associated perception of Nonius lines or afterimages; (d) same as (c) but for rightward gaze. See text for more details.

the right of the bottom (left eye's) Nonius line. The same perception is predicted if the nasally directed left eye precedes the temporally directed right eye in extreme rightward gaze, illustrated in the bottom left sector. Next, consider the top right sector. If in extreme leftward gaze the nasally directed right eye lags behind the temporally directed left eye, the right eye's visual axis lags behind the binocular target; the Nonius lines will appear to break such that the top (right eye's) Nonius line is to the left of the bottom (left eye's) Nonius line. The same perception is predicted if the nasally directed left eye lags behind the temporally directed right eye in extreme rightward gaze, illustrated in the bottom right sector.

2.2. Results

2.2.1. Width of the Bifixation Field. The mean width of the bifixation field, specified from the midpoint between the two eyes, was larger at 125 cm than at 32 cm for all but one observer (see Figure 4). The mean far-near difference between observers was 5.8° (SEM = 2.3°), $t(5) = 2.49$, $P < .05$, and $r^2 = 0.55$.

The mean position of the temporally directed eye (i.e., left eye to the left and right eye to the right) at the "breaking

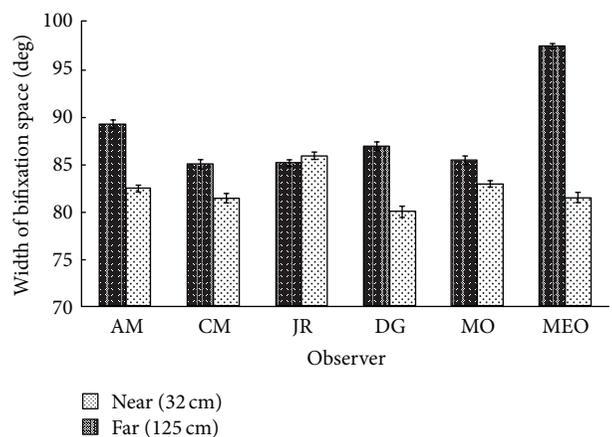


FIGURE 4: Mean width (±SEM) of the bifixation field as a function of convergence distance.

point" is illustrated in Figure 5. For all six observers, the temporally directed eye rotated to a greater extent when viewing the target at 125 cm than when viewing it at 32 cm. The overall mean far-near difference was 6.1° (SEM = 1.2°), $t(5) = 5.06$, $P < .01$, and $r^2 = 0.84$.

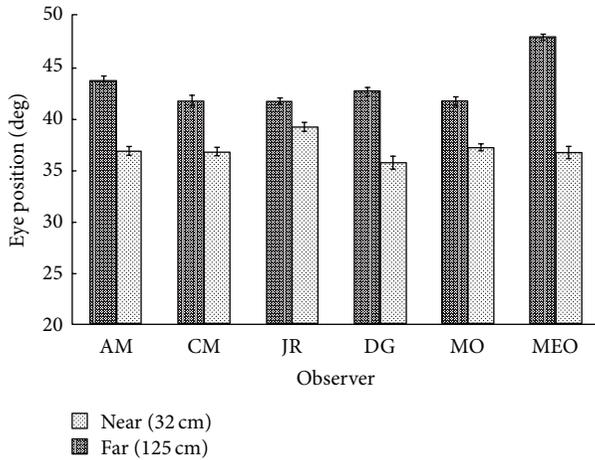


FIGURE 5: Mean position of the temporally directed eye (\pm SEM) at the limit of the bifixation field as a function of convergence distance.

2.2.2. The Relative Position of the Eyes at the Limit of the Bifixation Field. Based on the three afterimage trials at the end of each block, we determined the relative position of the eyes at the limit of the bifixation field. For all six observers, at both the 32 cm and the 125 cm convergence distances, the temporally directed eye maintained fixation on the target and the nasally directed eye broke fixation at the limit of the bifixation field. Moreover, the nasally directed eye lagged behind the fixation target for all six observers at the 32 cm convergence distance and it preceded the target for four of the six observers at the 125 cm convergence distance.

The data from Experiment 1 clearly support the prediction based on Hering's [2] law of equal innervation that the bifixation field is smaller at near viewing distances than at far viewing distances. However, the data indicating the relative position of the eyes at the limit of the bifixation field provided only partial support for Hering's prediction that the nasally directed eye precedes the temporally directed eye at the limit of the bifixation field.

The measurements in this experiment were limited to leftward and rightward eye movements in the horizontal plane of regard. In Experiment 2, we extended our investigation to match Hering's [2] measurements of the bifixation field over a 2D area.

3. Experiment 2

The purpose of this experiment is to address three issues about the spatial extent of the bifixation field. First, we measured the 2D area over which the eyes can move together and maintain bifixation. Second, we ascertained the relative position of the eyes at the limits of the bifixation field. Third, we determined the locations in the frontal plane where the bifixation field is limited by facial structures.

3.1. Method

3.1.1. Observers. There are four male observers, experienced in psychophysical experiments, one author (PG) and three

naïve observers participated. Observers ranged in age from 25 to 31 years with a mean age of 28.3 years. All reported normal binocular vision. Those who required an optical correction wore contact lenses during the experiment.

3.1.2. Apparatus and Stimuli. Stimuli were generated on a Macintosh power PC and displayed on a polarized rear projection screen, subtending 131 degrees horizontally and 102 degrees vertically at a 57 cm viewing distance. Two projectors, one for each eye's image, were fitted with orthogonally oriented polarizing filters. A complimentary pair of polarizing filters was placed in front of the observer's eyes. Observers sat with their heads fixed in a chin and forehead rest 57 cm in front of the display. Their responses were recorded via a trackball mouse. Stimuli consisted of a binocular dot flanked above and below by Nonius lines, visible to the right and left eyes, respectively. Additionally, binocular vertical lines flanked the dot on either side, positioned 0.9 degrees on either side of the centre of the binocular dot. These binocular flanking lines operationalized a specific criterion for successful/unsuccessful bifixation.

Right and left eye images were presented at one of three separations to simulate one of three viewing distance/vergence conditions: 57 cm (6.5 degree convergence) (these values are calculated assuming an interpupillary distance of 6.5 cm), 28.5 cm (13 degree convergence), and 10 cm (36 degree convergence). In the 57 cm condition, the actual distance of the display, the fixation stimulus, and the left and right eye's Nonius lines were positioned at the centre of the screen. To simulate a 28.5 cm viewing distance, the right eye's image was displaced 3.25 cm to the left of centre and the left eye's image was displaced 3.25 cm to the right of centre. To simulate a 10 cm viewing distance, the displacement was 15.2 cm for each eye's image (see Figure 6). Observers could move the stimulus along one of 12 radii (24 radii for observer PG) in the frontoparallel plane with a track ball. Upward movements on the trackball moved the stimulus away from the center of the display; downward movements on the trackball moved the stimulus towards the center of the display. Radii were at 30-degree intervals (15-degree intervals for observer PG) converging at the centre of the display. On a given trial, observers moved the stimulus away from or towards the centre of the display along one of these radii. An example is shown in Figure 7.

3.1.3. Procedure. Each trial began with the stimulus centred on the screen. For the convergence distances (28.5 and 10 cm), observers free-fused the stimulus by crossing their eyes until the binocular dot was fused and the Nonius lines were aligned. The fused stimulus was initially straight ahead of the observer. Observers then moved the stimulus slowly out from the centre along a randomly chosen radius. Observers became aware of which radius they were providing a measurement for after they moved the target. For the 57 cm viewing distance, the right and left eye's images were not separated; the observer simply fixated the binocular dot and moved the stimulus out from the centre.

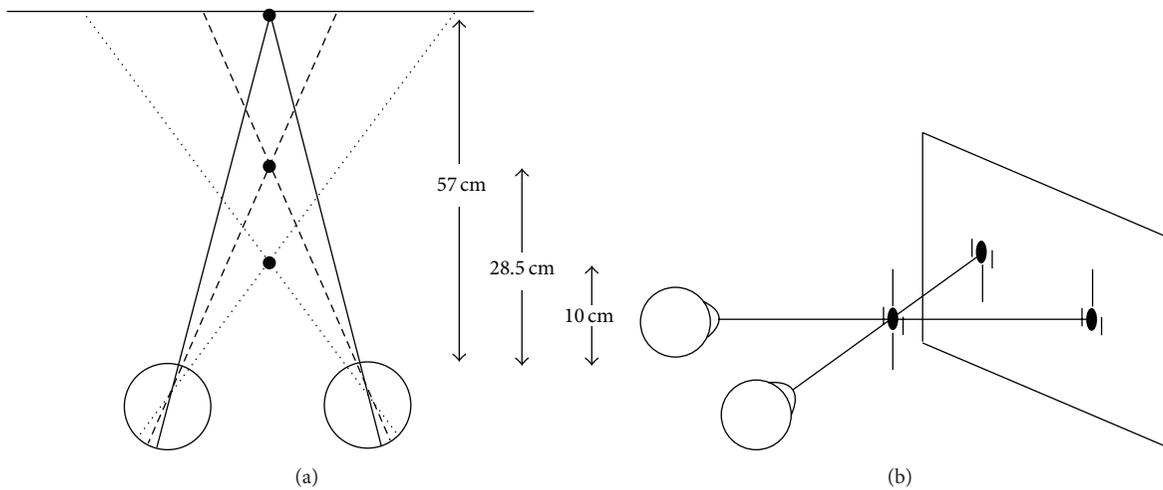


FIGURE 6: Illustration of the three vergence conditions in Experiment 1. Observers “free-fused” the fixation stimulus for the 28.5 and 10 cm distances. (a) Top view and (b) oblique view for one of the free-fused stimuli.

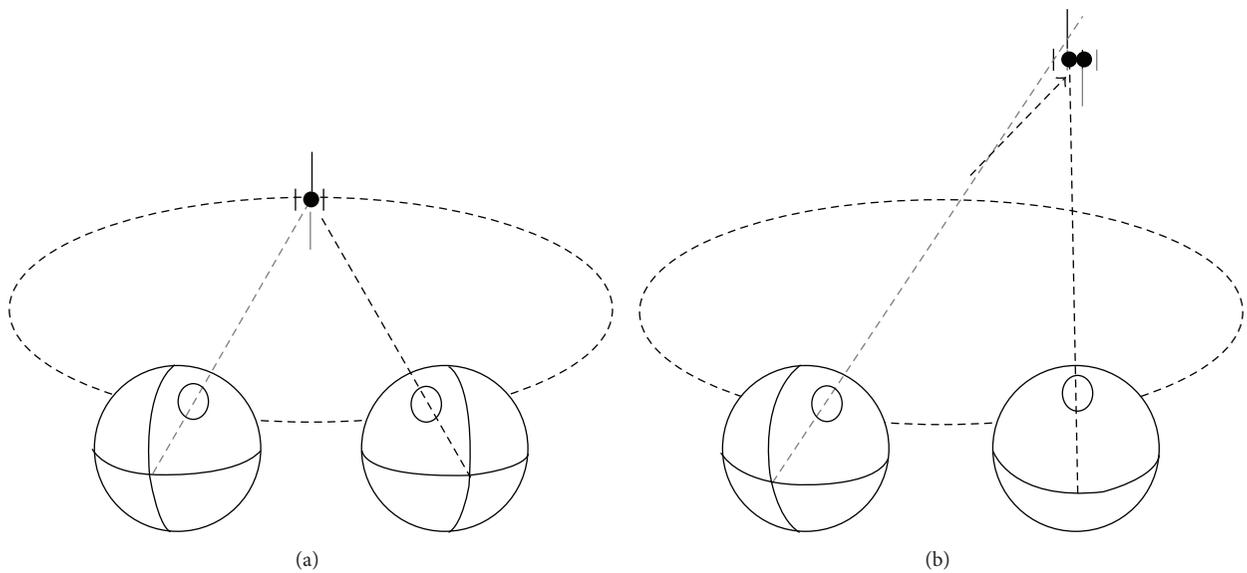


FIGURE 7: Illustration of the observers' task in Experiment 2. A typical ascending trial: after free-fusing the stimulus, observers moved it out along one of twelve radii until the Nonius lines were perceived as misaligned. Initial eye posture is shown in (a). Perception as the eyes reach the limit of the bifixation field is shown in (b). The black Nonius line was visible to the right eye; the grey Nonius line was visible to the left eye. Dashed circle represents an isovergence circle for reference.

Experimental runs were blocked according to convergence distance (10, 28.5, 57 cm) and the direction of adjustment (ascending/descending). Block order of convergence distance was varied across observers. Ascending and descending adjustment blocks alternated on each block of the experiment. On a given run in an ascending trial, observers moved the fused stimulus outward until the binocular dot appeared diplopic. Observers were instructed to move the stimulus out to the point where the Nonius lines became misaligned such that one of the Nonius lines was collinear with one of the flanking binocular lines. He then pressed

the mouse button indicating that location. In a given descending trial, the observer moved the stimulus outward until it was clearly diplopic and then moved it back towards the centre until the Nonius lines were subjectively aligned and indicated the position of the stimulus with a mouse click. All trials began with the stimulus straight ahead in order to allow observers to first free-fuse the stimulus and move it to the appropriate position for testing.

In all trials, observers indicated the relative positions of the Nonius lines when fusion broke by selecting one of three options presented on the display at the end of each trial.

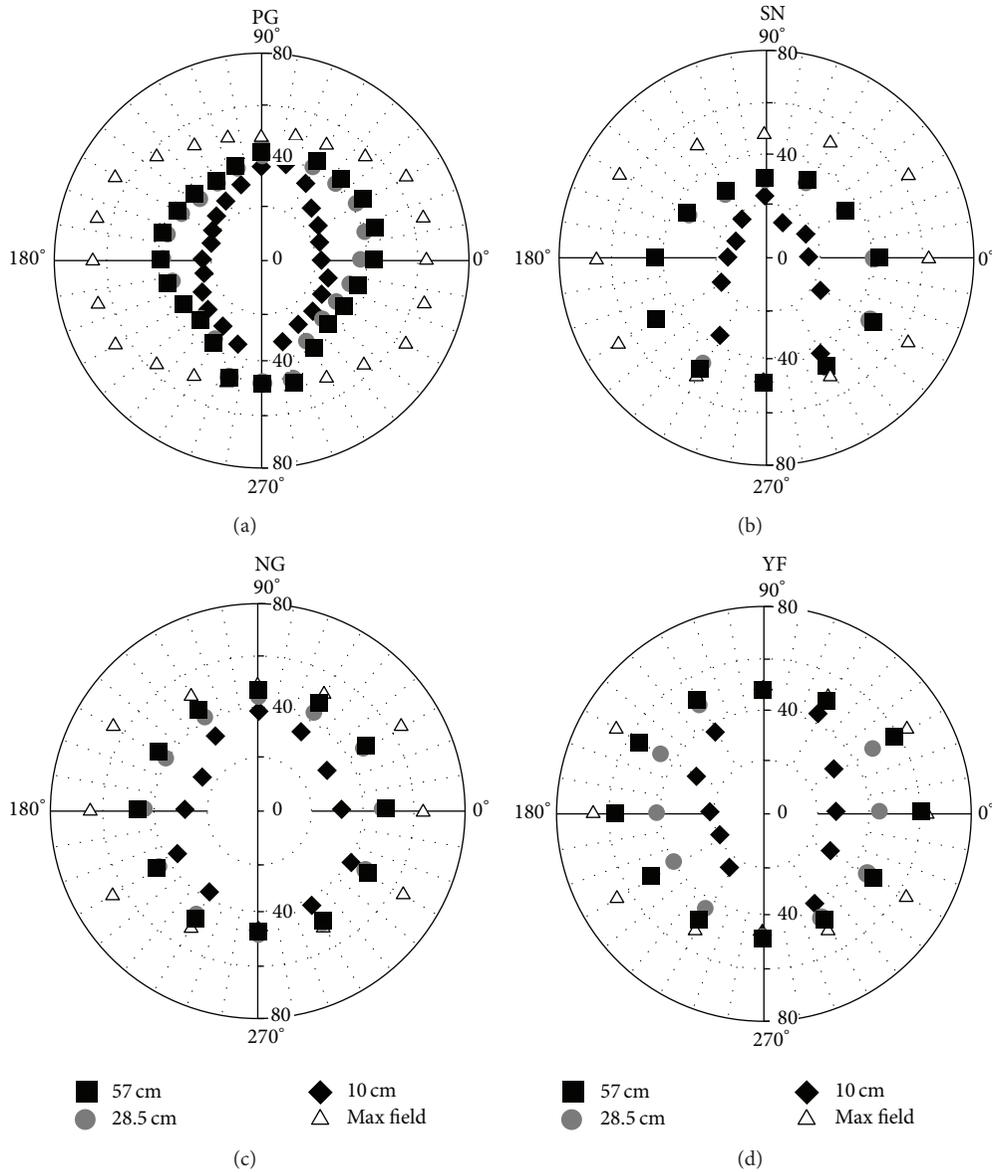


FIGURE 8: Individual polar plots of mean settings for “single to double” and “double to single” adjustments along each radius for three convergence distances. Closed symbols represent each simulated convergence distance. “Max field” refers to the extent of the stimulus display.

Observers reported whether the right eye’s (top) Nonius line appeared (a) to the left of the left eye’s (bottom) Nonius line, indicating that the nasally directed eye *lagged* behind the temporally directed eye, or (b) to the right of the left eye’s Nonius line, indicating that the nasally directed eye *preceded* the temporally directed eye; (c) some part of the stimulus was occluded by part of the observer’s face or border of the display. Figure 3 illustrates the relationship between perceived misalignment of the Nonius lines and the relative position of the eyes. Observers YF, SN, and NG completed 12 sessions (six in each direction: from single to double or double to single), each containing 36 trials for a total of 432 trials for each of these participants. In a given session, observers viewed each stimulus permutation once (three

vergence conditions X 12 radii). Observer PG completed 12 sessions (six in each direction), each containing 72 trials for a total of 864 trials (three vergence conditions X 24 radii).

3.2. Results

3.2.1. Polar Axes. Individual polar plots of the mean settings based on 12 observations, six for “single to double adjustments” and six for “double to single adjustments”, along each radius are illustrated in Figure 8. Closed squares represent mean adjustments for the 57 cm fixation distance, gray circles for the 28.5 cm convergence distance, and the black diamonds represent the 10 cm convergence distance condition. Open triangles denote the extent of the stimulus display and they

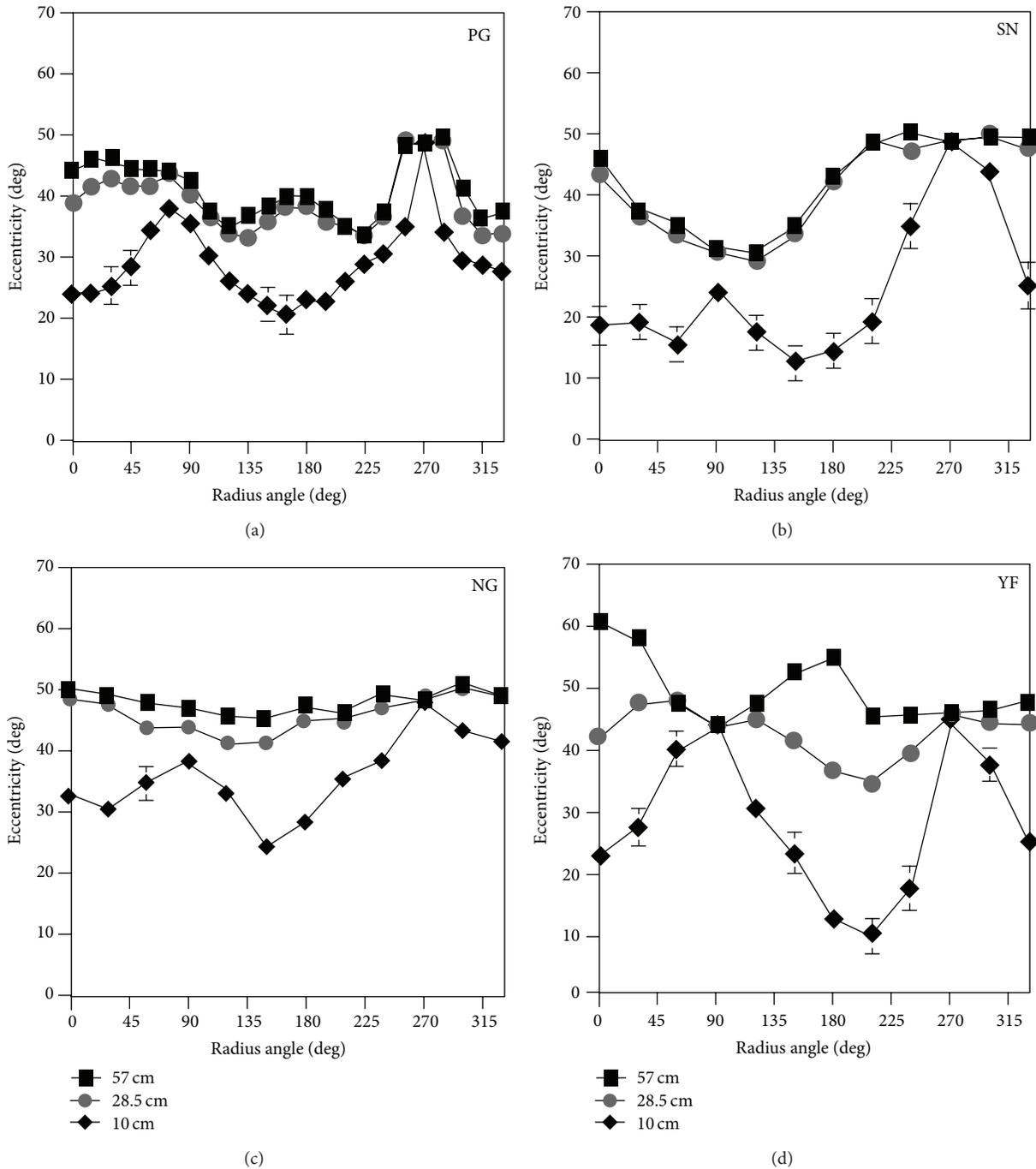


FIGURE 9: Individual Cartesian plots of the mean settings for “single to double” and “double to single” adjustments along each radius. Error bars represent ± 1 SEM.

are presented to indicate where, if ever, the bifixation field was limited by the dimensions of the display. This happened most frequently for the 270-degree radii and the two-adjacent radii. It is apparent from concentric distribution of the data as a function of convergence distance, for each of the four observers, that the angular extent of the bifixation field shrinks as the convergence distance is reduced. Moreover, the shape of the bifixation field at different convergence distances is defined by the distribution of the different data symbols.

This is most clearly defined for observer PG, who made observations on a larger sample of radii.

3.2.2. Cartesian Axes. Individual Cartesian plots are illustrated in Figure 9. These plots are provided to illustrate both the variability of the data (error bars = \pm SEM) and the radii for which differences in the angular extent of the bifixation field for different simulated convergence distances are at a maximum and minimum. It is clear from the graphs that the

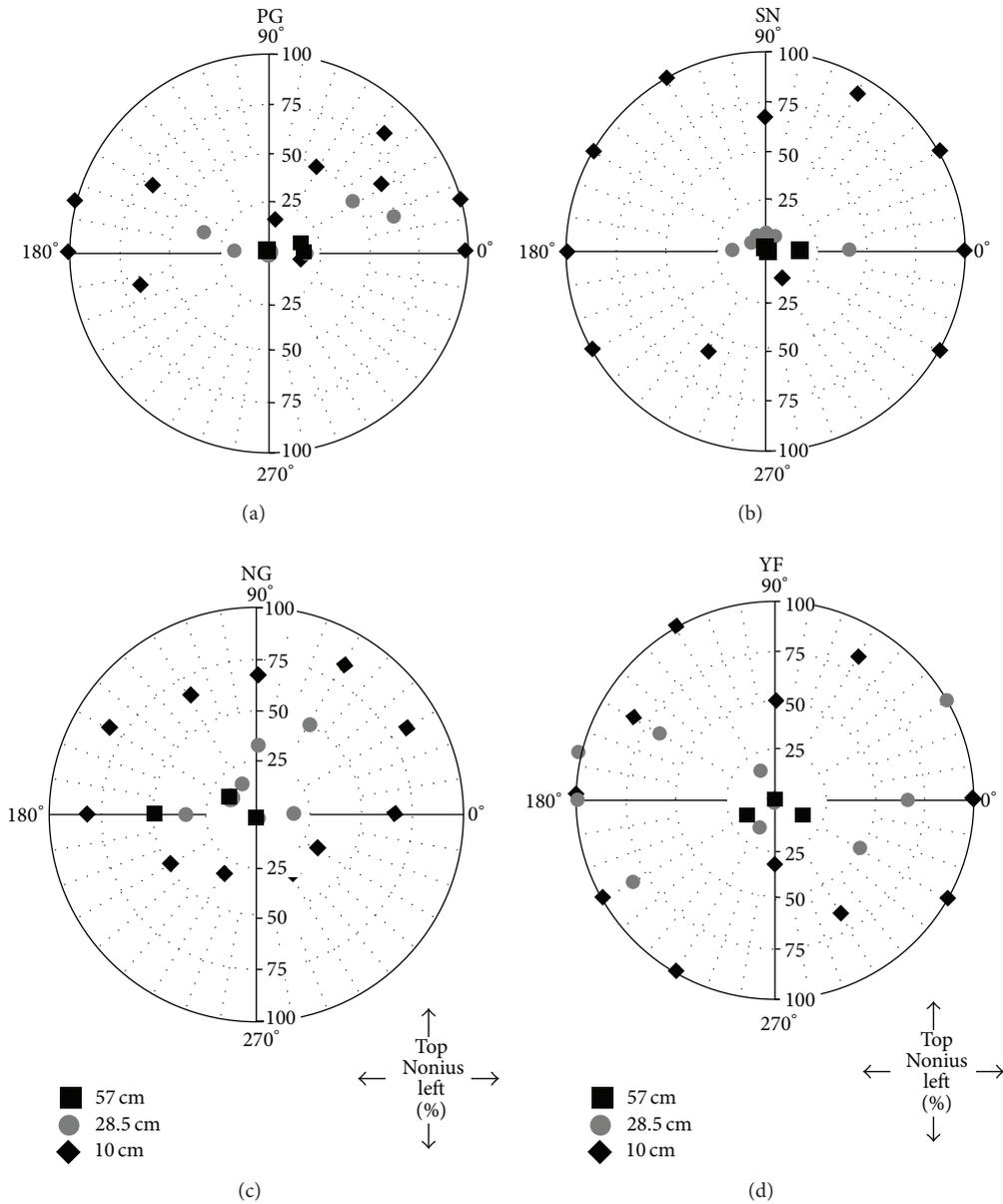


FIGURE 10: Individual polar plots indicating the percentage of trials; the Nonius lines appeared misaligned with the top line displaced towards the left for each radius. Percentage is plotted along vertical radii; radius angles are plotted around the circumference.

differences in the extent of the bifixation field are greatest at 0 and 180 degrees or along the horizontal meridian for each of the observers. The width of the bifixation field is clearly smaller at the 10 cm convergence distance than the 28.5 or 57 cm distances. The difference between the 28.5 and 57 cm distances are apparent for two observers (PG, YF) at 0 and 180 degrees, but less so for SN and NG. These data are consistent with the predictions based on Hering's [2] law of equal innervation. It is not surprising that the extent of the bifixation field converges for the three fixation distances at the 90-degree and 270-degree radii. Conjugate up/down eye movements have no version component and have a relatively constant vergence component.

3.2.3. *Nonius Data.* We next tabulated the percentage of trials which observers reported that the top Nonius line was to the left of the bottom Nonius line along each radius for each convergence distance. These data are illustrated on Polar axes in Figure 10. Each radius in these plots represents judgments made along each radius in the experiment. The distance away from the origin represents the percentage of trials which observers reported that the top Nonius line was seen to the left of the bottom Nonius line, indicating that the nasally directed eye lagged behind the temporally directed eye.

Despite being given a choice of three responses to describe their perception of the bifixation stimulus at the limit of the bifixation field, observers never reported that the top

Nonius line was seen to the right of the bottom Nonius line when fusion broke. Importantly, this indicates that the nasally directed eye never preceded the temporally directed eye in extreme binocular gaze positions for any of the convergence distances tested in this experiment, contrary to Hering's [2] prediction.

Inspecting the Nonius data more closely reveals another pattern. At the 57 cm convergence distance, with few exceptions, observers reported that the Nonius lines remained aligned until the stimulus was occluded to one eye. Trials for which the Nonius stimuli became misaligned before the stimulus was partially occluded to one eye, for this convergence distance, involved a near horizontal movement of the eyes, a radius close to 0 or 180 degrees. Nonius misalignment was reported at the 57 cm viewing distance along the 0-degree radius (an extreme rightward gaze) for observers PG and SN. Observers YF and NG reported Nonius misalignment for near extreme leftward movements of the eyes (210-degree radius for YF; 180-degree radius for NG). In the 10 cm convergence condition, however, the Nonius stimuli became misaligned before the stimulus was partially occluded to one eye in nearly all trials. The restriction of the bifixation field was most pronounced along radii close to 0 and 180 degrees. The 28.5 cm convergence condition yielded intermediate results with Nonius misalignment observed for near horizontal gazes and oblique gazes along radii close to horizontal.

Observers reported fewer incidences of Nonius misalignment for near vertical eye movements, involving radii close to 90 and 270 degrees. In fact, the limiting factor along the 270-degree radius was the size of the display. For this radius, all four observers were able to accurately track the target and maintain subjective Nonius alignment until it reached the edge of the display. Additionally, all four observers' data show a reduction in the percentage of "top Nonius left" responses near the 90-degree radius in the near vergence condition. For this and adjacent radii (particularly for observer PG) the stimulus was partially occluded by the observers' orbital bones or the top of the display.

The Nonius data are replotted in Figure 11 to illustrate the percentage of trials which observers reported; one eye's image became occluded by a facial structure in extreme gaze. When the viewing distance was 57 cm, observers were able to track the stimulus and maintain Nonius alignment until one eye's image was occluded by a facial structure on nearly 100% of the trials. This is illustrated by the closed squares distributed around the circumference of the graph for all observers. At the 28.5 cm viewing distance, observers were still able to track the stimulus to the point where one eye's image was occluded by a facial structure in many trials. This is illustrated by the distribution of gray circles near the outer edge of the polar graph. At the 10 cm viewing distance, however, all observers' bifixation broke down before the target reached the occlusion limits of the bifixation field. This is illustrated by the clustering of black diamonds near the centre of the polar graph. Observers were able to track the stimulus farther for near vertical eye movements, however, as illustrated by the scatter of closed diamonds along the 90 and 270 degree radii (and adjacent radii as well).

3.2.4. Statistical Analysis. The concentric distribution of the data points for the three viewing distances in Figure 8 indicates that the area of the bifixation field shrinks with near viewing distances. Figure 9, in addition, illustrates that the vertical extent of the bifixation field is nearly equal at all three viewing distances. This fits with Hering's [2] hypothesis because there is no version component and a fairly constant vergence component for up/down eye movements in the median plane. Figure 11 indicates that occlusion of one eye's image by facial structures was the limiting factor restricting the bifixation field for eye movements along radii on either side and including the 90-degree and 270-degree radii. Therefore, we performed paired *t*-tests on the individual data for near horizontal eye movements, using the overall mean of the 0, 30, 150, 180, 210, and 330-degree radii for observers SN, NG, and YF. For observer PG, used the mean of the 0, 15, 165, 180, 195, and 345-degree radii. We tested the differences in widths of the bifixation field between 57 and 28.5 cm and between 28.5 and 10 cm. This analysis revealed that the width of the bifixation field at 28.5 cm was significantly smaller than at 57 cm, $P < 0.001$, and the bifixation field at 10 cm was significantly smaller than at 28.5 cm, $P < 0.001$, for all observers. Lastly, it is statistically improbable that the settings of the three convergence distances be identically ranked for all four observers by chance. This was verified by Friedman's two-way analysis of variance by ranks, $P < 0.05$.

This experiment confirmed Hering's [2] prediction that the area over which the two eyes can move in concert, bifixating a target, is restricted both by viewing distance and the facial structures of the observer. Specifically, at short simulated viewing distances the bifixation field was markedly reduced relative to larger viewing distances. However, we found no support for the prediction that the nasally directed eye precedes the temporally directed eye at the limit of the bifixation field. We discuss the possible reason for this pattern of results in the next section.

4. Discussion

The first finding of this study was that the bifixation field is smaller for near viewing distances than for far. Experiment 1 showed this for measurements in the horizontal plane of regard. Experiment 2 expanded these measurements to map a 2D bifixation area similar to Hering's [2] mapping. Together, the experiments provide strong support for the first prediction based on the law of equal innervation.

The second finding was that, for most of our measurements, the relative position of the two eyes, at the limits of the bifixation field, was opposite to what Hering [2] predicted. In the near convergence distance condition (32 cm) of Experiment 1, all six participants reported that the nasally directed eye lagged the temporally directed eye, at the limit of the bifixation field, opposite to Hering's prediction. In the far condition (125 cm), two of the six participants reported that the nasally directed eye lagged the temporally directed eye, opposite to Hering, and four reported that the nasally directed eye preceded the temporally directed eye, consistent with Hering. In Experiment 2, all reports of the

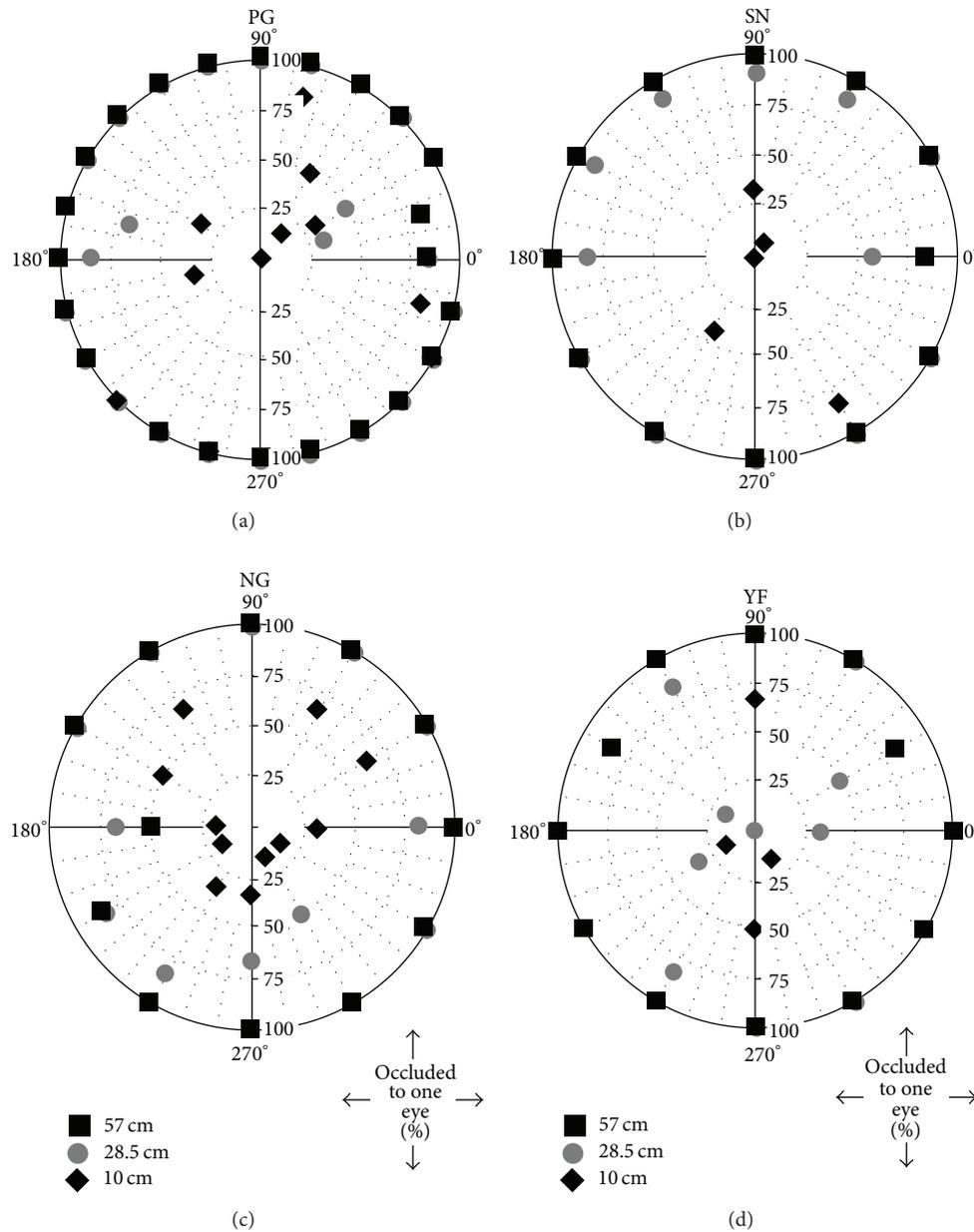


FIGURE 11: Individual polar plots indicating the percentage of trials; the fixation stimulus became occluded to one eye. Percentage is plotted along vertical radii; radius angles are plotted on the circumference.

relative position of the eyes at the limit of the bifixation field indicated that the temporally directed eye lagged the nasally directed eye. One possible reason for the nasally directed eye exclusively lagging the temporally directed eye in Experiment 2 is that the convergence distances spanned a relatively smaller range (10–57 cm). It is known that the typical resting vergence state of the eyes is approximately 1.2 m [10, 11], but there are considerable individual differences [12]. Therefore, it is possible that the eyes approach a resting state of vergence when fusion breaks at the limit of the bifixation field. This analysis is consistent with our results. The eyes diverged when fusion broke at the limit of the bifixation field in the near

condition in Experiment 1 and all the convergence distances in Experiment 2. That four of six observers' nasally directed eye preceded the temporally directed eye in the far condition of Experiment 1 is likely due to the fact that this viewing distance is close to the typical resting vergence distance. That is, the resting vergence distances may have been closer than 125 cm for four of the observers, but farther than 125 cm for the other two.

The possibility that subjects' eyes drifted towards their resting vergence posture at the limits of the bifixation field is consistent with Maddox's theory of vergence eye movements [13] (we thank an anonymous reviewer for pointing this

out). Maddox regarded vergence eye movements as having four additive components. The first component, he called tonic vergence, is similar in meaning to dark vergence or resting vergence as we have used above. Tonic vergence depends on the state of balanced tension in the rectus muscles and the spontaneous activity in the vergence control centre. Maddox's second component was reflex convergence which responds automatically to binocular disparity to correct any error between the to be fixated object and the intersection of the visual axes. The third component is accommodative-convergence, which is driven by the accommodative effort to maintain image sharpness. Contemporary research has shown that accommodation and convergence are dependent on one another as well as pupil diameter, known as the near triad [14]. Lastly, Maddox referred to voluntary convergence which was driven by the viewer's knowledge that a to be fixated object was nearer than the current point of intersection of the visual axes.

Two of Maddox's components are relevant to this report and we will address them in turn. As stated above, Maddox's concept of tonic vergence anticipated the modern concept of resting vergence or dark vergence, that is, the vergence state of the eyes in the absence of any fusible stimulus. One contemporary study by Francis and Owens [12] investigated dark vergence and showed that vergence drifted toward the dark vergence posture when the fusional stimulus was presented in the periphery but with the eyes converged on a central location. Specifically, when the peripheral fusional target was nearer in depth than the individual's dark vergence posture, convergence was beyond the target distance; when the fusional target was farther in depth than the individual's dark vergence distance, convergence was nearer than the target distance. Their report is consistent with our interpretation of the data reported here. Indeed, contemporary research, based on Maddox's theory, predicts the pattern of results we report here and would further predict that variations in the extent of the bifixation field as a function of viewing distance depends on the individual's dark vergence distance. To test this prediction, future experiments might measure the bifixation field for each participant at their dark vergence distance compared with nearer and farther viewing distances.

Considering the link between accommodation and vergence, Maddox's third component, the synergistic combination of accommodation, and convergence eye movements at near distances would be reduced or absent in older individuals with presbyopia (Herring law predicts that reduced accommodative vergence, resulting from presbyopia, would lead to an expansion, not reduction, of the bifixation field at near distances. Hering argued that the field is larger at far distances because the vergence component is smaller. Extending that logic to a weaker vergence component at near viewing distances, which is what happens with presbyopia, predicts that the bifixation field should be larger for older subjects relative to healthy young subjects). However, the participants in this study were significantly younger (maximum age: 33 years) than the typical onset age (40 years or older) of presbyopia and so we discount this as a contributing factor in our experiments. In Experiment 1, observers fixated on a real target presented at one of two

physical viewing distances but in Experiment 2 the stimuli were at the same physical distance (57 cm) in all conditions and the observers converged to the "virtual" distances of 28.5 and 10 cm, resulting in accommodation/vergence mismatch. We believe this mismatch is small, however, for at least two reasons. First, reduction of the bifixation field at the near viewing distances was observed in both experiments though the discrepancy between accommodation and vergence was only present in Experiment 2. Second, Owens and Leibowitz [15] reported that a fixation point is not an optimal accommodative stimulus. They reported that the accommodative response to a small luminous disk fixation stimulus is highly correlated with the individual's resting focus rather than the distance of the disc. Therefore, our fixation stimulus may not elicit a strong accommodation response and therefore the discrepancy between accommodation and vergence in Experiment 2 was small. We conclude that, in the context of the present study, accommodative convergence had a minimal impact on our results.

In addition to testing the specific predictions of Hering's [2] hypothesis, our data have practical implications for 3D media and virtual reality. The premise of a 3D display is that observers can be immersed in a virtual 3D environment defined mostly by binocular disparity. A major problem facing designers of this technology is the fact that users become fatigued and experience discomfort after prolonged use. Our data serve as another resource for display engineers requiring knowledge of the biological system when setting the parameters (such as display size and viewing distance) of their 3D systems.

The ability to discriminate the relative depth between two targets is the best when one of the targets is fixated. If an observer fixates a point, with symmetrical vergence, for example, their ability to discriminate small depth intervals deteriorates as the target stimuli are moved to eccentric locations away from the fovea. Ogle [16] showed that as targets with relative disparity were moved away from the fovea along the horizontal meridian, stereoacuity was degraded. Tyler [1] argues that this decrease in stereoacuity would occur if targets were moved out along any meridian (horizontal, vertical, or oblique) and is presumably a function of the increase in receptive field size with eccentricity.

Consider how removing a target display from the plane of fixation along an axis perpendicular to the frontoparallel plane affects our ability to discriminate small depth intervals within the display. Blakemore [17] varied the magnitude of the depth pedestal (absolute disparity or disparity between the two slit targets and the fixation point) of two slit targets such that they were positioned in front of or behind the fixation plane on any given trial. He found that stereothresholds increased as the discrimination targets were positioned further in front of the fixation point (crossed absolute disparity) or behind the fixation point (uncrossed absolute disparity). The angle of convergence was constant in Blakemore's study and the depth pedestal (absolute disparity) was introduced by horizontally shifting the stereo half images relative to the fixation point. Presumably, an equivalent degradation in stereoacuity would result from absolute disparities or depth pedestals, introduced by misconverging in front of or behind

the stimulus plane. Therefore, for optimal stereoscopic performance, stimuli should be positioned within the bifixation field to ensure that the targets are accurately fixated and absolute disparity is minimised.

5. Conclusion

We have presented data from two experiments supporting the prediction, from Hering's law of equal innervation that the bifixation field is smaller at near convergence distances than at far convergence distances. On the whole, our data are inconsistent with the prediction that the nasally directed eye precedes the temporally directed eye at the limit of the bifixation field, owing to its greater strength and the incongruent version and vergence components, present in the temporally directed eye. Our data are more consistent with the idea that the eyes drift towards their resting state when fusion breaks. At farther viewing distances, facial structures such as the nose and orbital bones contribute more to the restriction of the bifixation field than the differences in the component innervations. Lastly, since stereopsis is dependent on well-calibrated and precise vergence, a mapping of the bifixation field can inform 3D display engineers as they develop new displays that fill more and more of the visual field to ensure optimal performance and comfort.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

References

- [1] C. Tyler, "Sensory processing of binocular disparity," in *Vergence Eye Movements: Basic and Clinical Aspects*, C. M. Schor and K. J. Ciuffreda, Eds., pp. 199–295, Plenum Press, New York, NY, USA, 1983.
- [2] E. Hering, *The Theory of Binocular Vision*, Plenum Press, New York, NY, USA, edited and translated by B. Bridgeman & L. Stark, Original work published 1868, 1977.
- [3] H. Ono, "Hering's law of equal innervation and vergence eye movement," *American Journal of Optometry and Physiological Optics*, vol. 57, no. 9, pp. 578–585, 1980.
- [4] W. C. Wells, *An Essay Upon Single Vision with Two Eyes: Together with Experiments and Observations on Several Other Subjects in Optics*, Cadell, London, UK, 1792.
- [5] A. P. Mapp, H. Ono, and S. Saida, "Extreme eye position and Hering's law of equal innervation," *Canadian Journal of Psychology*, vol. 40, no. 3, pp. 251–262, 1986.
- [6] M. Alpern and P. Ellen, "A quantitative analysis of the horizontal movements of the eyes in the experiment of Johannes Mueller—I. Method and results," *American Journal of Ophthalmology*, vol. 42, no. 4, pp. 289–296, 1956.
- [7] G. Westheimer and A. M. Mitchell, "Eye movement responses to convergence stimuli," *Archives of Ophthalmology*, vol. 55, no. 6, pp. 848–856, 1956.
- [8] A. L. Yarbus, *Eye Movements and Vision*, Plenum Press, New York, NY, USA, translated by B. Haigh and edited by L. A. Riggs, Originally published 1965, 1967.
- [9] A. P. Mapp and H. Ono, "A restatement and modification of Wells—Hering's laws of visual direction," *Perception*, vol. 24, no. 2, pp. 237–252, 1995.
- [10] D. A. Owens and H. W. Leibowitz, "Oculomotor adjustments in darkness and the specific distance tendency," *Perception & Psychophysics*, vol. 20, no. 1, pp. 2–9, 1980.
- [11] S. K. Fisher, K. J. Ciuffreda, B. Tannen, and P. Super, "Stability of tonic vergence," *Investigative Ophthalmology and Visual Science*, vol. 29, no. 10, pp. 1577–1581, 1988.
- [12] E. L. Francis and D. A. Owens, "The accuracy of binocular vergence for peripheral stimuli," *Vision Research*, vol. 23, no. 1, pp. 13–19, 1983.
- [13] E. E. Maddox, *The Clinical Use of Prisms, and the Decentering of Lenses*, John Wright & Sons, Bristol, UK, 1893.
- [14] J. L. Semmlow and G. Hung, "The near response. Theories of control," in *Vergence Eye Movements: Basic and Clinical Aspects*, C. M. Schor and K. J. Ciuffreda, Eds., pp. 199–295, Plenum Press, New York, NY, USA, 1983.
- [15] D. A. Owens and H. W. Leibowitz, "The fixation point as a stimulus for accommodation," *Vision Research*, vol. 15, no. 10, pp. 1161–1163, 1975.
- [16] K. N. Ogle, "On the limits of stereoscopic vision," *Journal of Experimental Psychology*, vol. 44, no. 4, pp. 253–259, 1952.
- [17] C. Blakemore, "The range and scope of binocular depth discrimination in man," *The Journal of Physiology*, vol. 211, no. 3, pp. 599–622, 1970.

Review Article

Alterations of Eye Movement Control in Neurodegenerative Movement Disorders

Martin Gorges, Elmar H. Pinkhardt, and Jan Kassubek

Department of Neurology, University of Ulm, Oberer Eselsberg 45, 89081 Ulm, Germany

Correspondence should be addressed to Jan Kassubek; jan.kassubek@uni-ulm.de

Received 11 November 2013; Revised 27 March 2014; Accepted 14 April 2014; Published 18 May 2014

Academic Editor: Gernot Horstmann

Copyright © 2014 Martin Gorges et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

The evolution of the fovea centralis, the most central part of the retina and the area of the highest visual accuracy, requires humans to shift their gaze rapidly (saccades) to bring some object of interest within the visual field onto the fovea. In addition, humans are equipped with the ability to rotate the eye ball continuously in a highly predicting manner (smooth pursuit) to hold a moving target steadily upon the retina. The functional deficits in neurodegenerative movement disorders (e.g., Parkinsonian syndromes) involve the basal ganglia that are critical in all aspects of movement control. Moreover, neocortical structures, the cerebellum, and the midbrain may become affected by the pathological process. A broad spectrum of eye movement alterations may result, comprising smooth pursuit disturbance (e.g., interrupting saccades), saccadic dysfunction (e.g., hypometric saccades), and abnormal attempted fixation (e.g., pathological nystagmus and square wave jerks). On clinical grounds, videooculography is a sensitive noninvasive *in vivo* technique to classify oculomotor function alterations. Eye movements are a valuable window into the integrity of central nervous system structures and their changes in defined neurodegenerative conditions, that is, the oculomotor nuclei in the brainstem together with their directly activating supranuclear centers and the basal ganglia as well as cortical areas of higher cognitive control of attention.

1. Introduction

Eye movement assessment potentially provides a valuable window into the human central nervous system function and may help to obtain insights into the structure of complex forms of human behavior including attentional control [1, 2]. Furthermore, the study of oculomotor control in pathological conditions offers insight into the underlying neural mechanisms. Neurodegenerative movement disorders are frequently accompanied by a broad spectrum of oculomotor abnormalities since large parts of the human central nervous system contribute to the function of “vision” comprising visual areas, oculomotor areas, and associated visual memory structures including eye movement control [3]. A large part of knowledge about these higher oculomotor functions results from electrophysiological investigations in the monkey brain and functional imaging in humans by use of advanced test paradigms which have shown eye movement-related activity in several cortical and subcortical areas [4–6]. In addition, computer-based neuroimaging such as fiber tracking

by means of diffusion tensor imaging has depicted major pathways that are linked to oculomotor control and its changes in neurodegenerative movement disorders such as Huntington Disease (HD) [7, 8]. Oculomotor abnormalities in Parkinson's Disease (PD) have recently been reported to be associated with higher functional networks revealed by “task-free” intrinsic functional connectivity neuroimaging techniques [9]. The nature of the contribution of intrinsically interacting large-scale cortical functional networks to eye movements and their key to pathological dysfunction is currently being addressed in neuroimaging research.

Evidence for the need of intrinsically organized brain activity associated with visual input depends on the almost infinite visual information received by the human eye from the external environment [10]. Before guiding the eyes adequately in the orbit, a target of special interest in the visual scene needs to be determined, followed by target selection and by “programming” the oculomotor system in a coordinated manner to rotate the eye ball until the object is foveated. The entropy, a measure of information, of the visual

stream arriving at the human eye is about 10^{10} bits/s whereas only approximately 3,000,000 bits/s are leaving the retina due to the limited number of available axons of the optic nerve and finally less than 10,000 bits/s are believed to be under attentive scrutiny [11]. This complex system covers most of the human brain specific characteristics. Thus, the investigation of eye movements has been applied as an experimental tool over the past four decades and provides a unique opportunity to understand the functional integrity of brain structures both in the healthy brain and in pathological state. The latter include the broad variety of Parkinsonian Syndromes [5] and other neurodegenerative conditions such as amyotrophic lateral sclerosis [12], fronto-temporal lobar degeneration [13], and Alzheimer's disease [14]. Pathological conditions are of special interest to ophthalmologists, neurologists, and scientists in order to get insights into potential alterations of the complex oculomotor networks, including fundamental issues of human behavior comprising conflict resolution and free will [2].

Retinal structure is divided into the fovea centralis with ultimate vision in its center and the larger periphery (with markedly less visual acuity) so that humans have developed the ability to foveate or refoveate an object of interest in the visual field. Rotating the eye ball offers a somewhat more economical strategy to shift or to maintain an object of interest on the fovea than turning the whole head [15]. In general, eye movements are required to compensate small head movements to sustain stability of gaze, to accurately track moving objects in the visual surrounding smoothly [16], or to rapidly redirect the eye onto a new target [17] rather than scanning the environment [15]. Eye movements can be subdivided into two main classes: one class of movements comprises vestibuloocular reflexes, optokinetic nystagmus, fixation, and smooth pursuit eye movements (SPEM) [3]. As the second kind of eye movements, humans use saccades (old French "saquer," meaning "jerk") in order to perform conjugated, fast eye movements shifting the eye ball discontinuously in a stepwise manner onto a new target [17].

This review summarizes the fundamental mechanisms of eye movement control, considering healthy and pathological states of the brain. More specifically, we discuss the main features of the oculomotor phenotypes that are specific for different movement disorders and that can serve as model conditions to study how distinct brain areas contribute to eye movement control. In addition, we focus on fixational eye movements as presenting a continuous range from microsaccades to (pathological) square wave jerks (SWJ) [18]. Due to the particular role of eye movement alterations for the clinical and neuroscientific work-up of Parkinsonian syndromes, we will focus on movement disorders in this synopsis to emphasize the significance in assessing eye movement control to understand the respective pathophysiology. Together, our aim is to condense both the oculomotor dysfunctions in patients with neurodegenerative movement disorders and the underlying pathological mechanisms that result in the observed dysfunctional oculomotor behavior. Beyond the fact that oculomotor dysfunctions can be important for the purposes of clinical diagnosis, we discuss the potential functions and mechanisms of higher cortical contributions

to eye movement control, in particular by reviewing broad pathological spectrum of cognitive control in functional system-related neurodegenerative conditions.

2. Eye Movements during Attempted Visual Fixation in Health and Diseased States

During the absence of any (e.g., vestibuloocular) stimulus, healthy subjects are expected to withhold any unwanted considerable gaze shift maintaining the eyeball in its primary position. However, by performing attempted visual fixation of an unmoving target, conjugated small ($<1^\circ$), jerk-like, involuntary saccades (microsaccades) and slow conjugated drifts are near-instantly observed [19]. For clear vision in the sense of the highest spatial resolution, the perception of an object should be optimized by small saccadic eye movements rather than by holding the image completely steady upon the retina. Perfectly fixed images upon the retina cause sensor adaption (fading) due to the property of being designed for the highest motion responsiveness like other sensory systems [20]. Thus, in case of attempted fixation of stationary targets, microsaccades play an important role in counteracting visual fading by shifting the image on the retina back and forth in small portions of approximately 0.5 degrees. In addition, larger voluntary saccades or blinks are considered to also effectively overcome visual fading [21]. The generation of microsaccades depends on the target size whereas luminance appears to be of no effect in modulating microsaccades [20]. The dynamics vary during scanning the visual scene, and the frequency of microsaccade production tends to increase with more challenging visual tasks which require increased visual discrimination abilities [22]. The relationship between microsaccade amplitudes with respect to their peak velocities follows the main sequence in an approximately linear manner [23]. Microsaccades can be suppressed by precision demanding tasks (e.g., threading a needle) but cannot be voluntarily evoked [24].

With respect to their amplitude, larger microsaccades are termed as SWJ and also become evident during fixation [18]. SWJ are thought to have the same neural substrate as microsaccades and present as conjugated, rapid eye movements (preferentially in horizontal direction) that intrude accurate fixation. More specifically, both microsaccades and SWJ continuously shift the eyes away from the target and back onto it in an involuntary manner [25]. In pathological conditions, they mostly present abnormally large and frequent. However, preschool children may present with larger SWJ ($>1^\circ$) and less stable gaze holding [26] that rarely also occur in healthy adults but manifest more frequently in the elderly [19]. One diagnostic challenge rises from the large overlap of SWJ presentation between patients with movement disorders and healthy subjects [18].

Patients with neurodegenerative movement disorders frequently develop abnormal SWJ which frequently interrupt fixation, within the broad spectrum of oculomotor deficits [3, 27]. Since SWJ are believed to present as a continuous spectrum ranging from microsaccades to larger saccadic intrusions, the mechanisms generating SWJ appear to be

similar to those of microsaccades and share a common oculomotor network with the saccadic system. In addition, it is relevant for the characteristics of SWJ in movement disorders that SWJ generation appears to be similar in the healthy brain and in pathological state. Larger SWJ probably reflect internal “neural noise” in the saccadic control loops and in the superior colliculus that forms a major component for the release of saccades by triggering the saccadic pulse generator in the midbrain [25]. The “neural noise” is hypothesized to initiate a saccade away from the target, resulting in a position error that is counteracted by shifting the gaze back onto the target. The higher this “neural noise” is (e.g., in movement disorders due to an impaired triggering of the superior colliculus from the basal ganglia), the more prominent SWJ seem to occur. The cerebellum may contribute to abnormal SWJ in addition [28] if it is involved in the pathological process in cerebellar diseases and neurodegenerative Parkinsonian syndromes other than PD.

During impaired stationary fixation such as sustained abnormal eye oscillations (e.g., large SWJ), pathological nystagmus), patients may report that vision is becoming subjectively blurred [21]. In general, two clinical approaches to abnormal fixation need to be distinguished, on the one hand, the examination of the patient’s eye while the eye remains in primary position and on the other hand during the fixation in eccentric gaze holding [2]. In summary, abnormal oscillations of the eyes including pathological nystagmus and markedly large or frequent SWJ (beyond the aforementioned physiological fixation eye movements) account for a “red flag” symptom that should prompt further investigations with respect to differential diagnostic procedures [29]. The vast majority of these visual fixation signs are linked to dysfunctions of the central nervous system, in the absence of inaccurate vision, ophthalmologic diseases, or eye muscle affections.

3. Methods to Examine Eye Movements

Abnormalities during fixation can be investigated with Frenzel goggles or the ophthalmoscope by asking the patients either to hold their gaze steadily at the primary position or to shift their gaze towards eccentric positions. Frenzel goggles inspection of the patient’s fixation ability accounts for a sensitive instrument to address fixational dysfunction or nystagmus. Unlike the ophthalmoscope, Frenzel goggles are equipped with small lights illuminating the patient’s eyes and provide high-powered positive magnifying glasses (>+15 diopter) that disable the subject to adequately fixate any target in the visual field [30]. Hence, the examiner can detect abnormal SWJ and particularly pathological nystagmus since the absence of target fixation facilitates the manifestation of nystagmus forms that were attributed to peripheral vestibular impairment [31]. There are some drawbacks of these inspection methods. First, stimuli cannot be presented under specific conditions such as defined target positions. Second, the observations cannot be quantitatively characterized that is, metrics of saccadic accuracies, latencies with respect to stimulus onset, or determining peak eye velocities are not

possible. The latter parameter is of special interest since peak eye velocity obtained during saccade performance characterizes the main sequence that provides robust metrics to assess pathology in peak eye velocity [17].

To overcome these limitations, computer-based recording techniques are applied to quantify subtle alterations in eye movement control, that is, electrooculography, scleral search coil systems, and videooculography (VOG). The past decades have emerged easy manageable computer-based eye trackers with integrated software environment for both stimulus design and automated data analysis for laboratory and portable usage. Scleral search coil systems and VOG emerge as the most widely used techniques to quantify eye movements, although electrooculography is yet the only device allowing recordings with closed eyes. The VOG measurement offers the best compromise between easily tolerable, noninvasive measurement and spatial and temporal resolution but requires advanced calibration techniques to be able to accurately quantify oculomotor performance. In contrast, scleral search coil systems provide optimum spatial and temporal resolution and warrant no calibration approach due to the absolute calibration by default [32] but are invasive since they are based on tightly fixated “contact lenses” carrying orthogonal coils. Another reason for VOG having become popular is the improved electronic hardware with additional software packages including both stimulus design and eye movement recording analysis features. Moreover, modern VOG systems provide easier usage and high portability with the possibility to assess human gaze behavior outside a dedicated room and even under dynamic conditions by utilizing an additional head-mounted camera (e.g., [33]). Video-based eye trackers comprising one or two head mounted and adjustable infrared miniature cameras allow online measurements so that the recorded data can be visually inspected in real-time. Commonly, the systems operate at about 250 Hz temporal sampling frequency which is constrained by spatial resolution of the field of view.

Basal oculomotor network function (at brainstem/basal ganglia/cerebellar level) is usually tested by visually guided reactive saccades [17, 34, 35]. In this paradigm, subjects are asked to track a randomly “jumping” target as quickly and as accurately as possible. Smooth pursuit eye movements are elicited by requiring the subjects either to track a continuously moving target [36] or to track a sinusoidally oscillating target [37]. In order to assess attentional eye movement control as a correlate of the cognitive (cortical) top-down oculomotor pathway, delayed saccades and antisaccades are executed. Both conditions aim at investigating the subject’s ability to suppress the reflexive urge to shift their gaze towards a new suddenly upcoming target in the visual scene [38]. Figure 1 schematically illustrates two paradigms as an example for a cognitively demanding test.

4. Alterations of Eye Movement Control in Parkinsonian Syndromes

4.1. Parkinson’s Disease (PD). Parkinson’s Disease (PD) is the second most common neurodegenerative disorder with

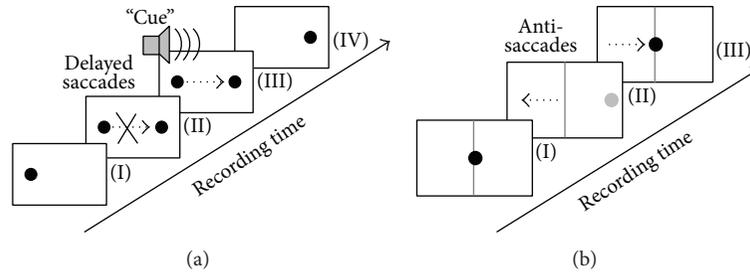


FIGURE 1: Illustration of cognitive demanding oculomotor tasks in order to assess attentional control. (a) In delayed saccades, subjects are asked to fixate the spot (I) and to withhold their gaze shift towards a new randomly appearing target (II) until an acoustic “cue” is sounded (III). The “run” is finished when the old target vanishes (IV). (b) The antisaccade task requires the subject to focus on the center position (I) until a new target (grey) presents randomly at either the right or the left eccentric position (II). The subject is immediately asked to shift the gaze to the contralateral half-plane (away from the target). The “run” is completed by shifting the gaze back onto the central position (III). Black dotted arrows illustrate the required gaze shift.

cardinal motor symptoms comprising hypokinesia, tremor, rigidity, and postural impairment, while a multitude of nonmotor conditions including cognitive decline as part of the disease process has become evident [39, 40]. Autopsy-controlled studies by Braak and coworkers [41–44] indicated that the pathological process of PD can be characterized as a six-stage ascending spreading scheme beginning in the lower brainstem (stages 1-2) towards mesencephalic structures including the basal ganglia (stages 3-4) and finally reaching the cortex (stages 5-6). These findings suggest that PD has a preclinical stage and a symptomatic stage as soon as patients display the aforementioned cardinal motor symptoms defining clinical onset not before stage 3. Only a few studies have systematically investigated oculomotor dysfunctions in asymptomatic subjects with gene mutations. Whereas saccadic hypometria and the problems in withholding unwanted gaze shifts (hyperreflexivity) are a hallmark of both early PD and symptomatic PARKIN mutation carriers, presymptomatic PARKIN mutation carriers revealed undistinguishable oculomotor performance compared to age-matched healthy controls [45]. PD patients presented with a lack of attentional control resulting in the disability to withhold unwanted gaze shifts which appears to manifest even in nondemented PD patients [9]. This can be tested by utilizing tasks such as delayed saccades [9, 37, 46] or antisaccades [47].

PD onset typically incorporates motor symptoms caused by dopaminergic nigrostriatal cell degradation in the basal ganglia which are critical in locomotion including eye movements. The substantia nigra pars reticulata tonically inhibits the superior colliculus (SC) via GABA-ergic projections, whereas pausing the inhibitory SC input provides a prerequisite for saccadic release [48]. The SC is an important visuomotor structure and plays a major role in triggering both voluntary and reflexive saccades [49]. Moreover, the SC projects to the cerebellum via the nucleus reticularis tegmenti pontis. The cerebellum contributes to saccadic control in optimizing saccade trajectory by increasing eye acceleration during saccade onset and controls the movement procedure in order to keep the eye on track [50]. Cerebellar pathology in

oculomotor function, however, typically cannot be observed in PD with very few exceptions (see below).

Unlike the basal ganglia, the SC remains intact until later stages in the pathological process [4], and both the SC and the striatum receive cortical input from the frontal eye fields (FEF), the supplementary eye fields, and the parietal eye fields [51]. Areas in the parietal cortex associated with oculomotor control beyond the parietal eye fields encompass superior and inferior parietal lobe and are a critical interface for attention and multiple sensory integration from visual and somatosensory modalities [52]. The supplementary eye fields contribute to target selection and visual search [53], and the FEF are critical in target selection of competing stimuli mediating their information to the SC and directly to the saccadic generator in the brainstem [54]. The striatum serving as the main input gate of the basal ganglia evaluates incoming and competing information for appropriate execution; however, with the putamen being the most affected area in PD, it remains to be discovered to what extent the PD pathology targets this mechanism [55]. The striatum gains also incoming streams from the dorsolateral prefrontal cortex which contributes to voluntary eye movements in the sense of inhibition control to prevent unwanted reflexive saccades [35]. As a part of the limbic system, the so-called cingulate eye field, located in the anterior cingulate cortex (which is involved in motivation, behavior, and executive control), contributes to saccade generation [56]. Guiding voluntary saccades requires several neural mechanisms within the framework of preemptive perception that manifests in activation in the cingulate eye field prior to the release of a saccade [55].

Deterioration of dopaminergically mediated pathways in the basal ganglia in PD leads to overactive SC inhibition preventing the SC to trigger the brainstem saccadic generator. This may contribute to saccadic hypometria, as depicted in Figure 2, and slowed initiation of voluntary saccades [57] such as reduced number of rapid alternating self-paced saccades where subjects are asked to shift their gaze as fast and as accurately as possible between to stationary targets [45]. In PD, deep brain stimulation of the subthalamic nucleus has

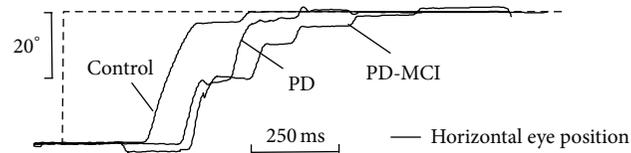


FIGURE 2: Visually guided horizontal reflexive saccade in a Parkinson's disease patient with mild cognitive impairment (PD-MCI) and a Parkinson's disease patient without cognitive impairment (PD), compared with an age-matched healthy control subject. Both PD patients presented with a considerable multistep sequence (saccadic hypometria) to shift their gaze onto the target (dashed-line). The videooculographically recorded data display the orthogonalized position for the cyclopean eye shown for the horizontal component (black lines). *x*-axis: acquisition time in seconds; *y*-axis: horizontal eye position in degrees.

undoubtedly positive effects in treatment of motor symptoms [58], but the improvement of oculomotor performance is still debated. Compensatory effects on the functional level of the SC mediated by the substantia nigra pars reticulata have been reported [59] yielding improved saccade initiation and inhibitory control but did not significantly prevent prosaccades during antisaccade condition [60]. In contrast, Pinkhardt et al. [35] did not observe enhanced reflexive saccade performance. One possible explanation of these discrepancies could result from the included patients' degree of motor impairment. Since motor performance worsens in the course of PD, it could be hypothesized that those patients investigated by Yugeta et al. [60] presenting with a unified Parkinson's disease rating scale III score [61] in the ranges of 6–44 (stimulation OFF state) and 1–24 (stimulation ON state) were less severely affected than those reported by Pinkhardt et al. [35] with an UPDRS III score in the ranges of 16–64 (OFF) and 5–62 (ON). This may lead to the assumption that the less advanced patient group exhibited more benefits from deep brain stimulation on saccadic performance than those presenting with higher UPDRS III scores which is probably associated with cortical involvement. This hypothesis is in line with the findings of MacAskill and coworkers [4] who attributed oculomotor dysfunctions in early and noncognitively impaired PD to “pure” basal ganglia disorder whereas the more widespread cortical involvement later in the course of PD [44] may result in malfunctioning cortical areas involved in saccadic control.

Terao et al. [6] proposed a possible task-related modulation within the basal ganglia resulting in oscillatory spike activity that may contribute to both “hyperreflexivity” and slowed initiation. Moreover, functional connectivity neuroimaging revealed that connectivity loss in the putamen versus the caudate nucleus follows the same gradient as dopamine depletion, indicating a decoupling of the putamen prior to the caudate nucleus [62]. Other imaging studies on functional integration in PD patients [63, 64] indicated widespread functional remapping that likely alters connectivity associated with oculomotor function. The nature of the cortical contribution of large-scale higher function networks to oculomotor control remains a promising issue in future studies.

SPEM provide an optimum strategy of maintained movement adaptation in a highly predictive manner and involve large parts of the brain cortex, comprising primary visual areas like the striate and extrastriate cortex as well as the FEF

and supplementary eye fields [16]. Likewise, the cerebellum is involved in performing pursuit and functions as a major hub after receiving the cortical efferents that are to be integrated in innervating the relays of the ocular motor neurons through the medial vestibular nucleus [50]. The easiest way to elicit SPEM is to ask a subject to track some continuously moving object in front of one's eyes. In the VOG, a sinusoidally oscillating target or an object moving with constant velocity can be presented. A quantitative measure of SPEM performance is the gain value describing the ratio of eye to target velocity. In patients with PD, SPEM are frequently interrupted or nearly abolished by anticipatory saccades resulting in a reduced pursuit gain [65], as depicted in Figure 3. This deficit already manifests early in PD and worsens with disease progression. Notably, even in advanced cases, the patients are fairly able to track the target smoothly whereas the episodes of performing SPEM exclusively shorten with more frequent saccadic intrusions [37]. Thus, the genuine SPEM system appears to be intact which raises the question of whether an executive dysfunction contributes to the characteristic anticipatory saccades during pursuit. For this fundamental issue, Pinkhardt et al. [35] suggested that accompanying extradopaminergic processes might cause SPEM impairment. Thus, a lack of inhibitory control which is closely linked to the higher functions located in the dorsolateral prefrontal cortex as well as the striatal projections [5] might explain these observations of dysfunctional SPEM. However, it remains an open issue to prove this hypothesis.

The mechanism of SWJ generation appears to be similar in PD patients and healthy controls, as indicated by Otero-Millan and coworkers [25]. Moreover, it was proposed that the characteristics of SWJ (such as frequency and amplitude) are linked to the internal neuronal noise level within the SC and the brainstem saccade generator. In pathological states such as PD, the saccade generator and the SC can be seen as a “neuronal noise amplifier” resulting in abnormal SWJ. In line with these findings, the SC might be triggered by an increase in FEF activity that compensates pathological increased inhibition of the SC from the substantia nigra pars reticulata [66].

In summary, PD patients present with a broad spectrum of disturbed oculomotor function comprising saccadic intrusions during SPEM, impaired inhibition control, and hypometric saccadic gains, while eye velocities used to be normal. Notably, these deficits manifest early in the disease course; however, they can be observed in the symptomatic

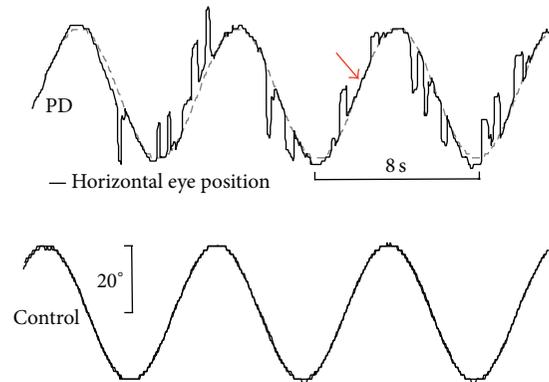


FIGURE 3: Horizontal smooth pursuit eye movements (SPEM) elicited by a sinusoidal oscillating spot ($f = 0.125$ Hz) and exemplified for a Parkinson's disease patient (PD, upper panel) and a representative age-matched healthy control (lower panel). The PD patient presents with severely affected SPEM, frequently interrupted by anticipatory saccades. Although SPEM is heavily impaired in PD, patients retained the ability to perform episodes of genuine smooth pursuit (arrow). For recording details, see Figure 2.

rather than in presymptomatic stages of familial PD cases. In general, as the disease progresses, the oculomotor disturbances develop their full spectrum. The combination of both, the observed oculomotor phenotype and autopsy-controlled findings in PD, may increase our understanding of eye movement control as (i) the oculomotor nuclei in the brainstem appear to be spared by the PD-associated pathological process and (ii) the oculomotor deficits may primarily reflect a lack of attentional control. In the clinical context, the quantitative objective measure of eye movements by means of VOG has the potential as a possible technical surrogate marker in PD [6, 67].

4.2. Multiple System Atrophy (MSA). MSA is a neurodegenerative disease characterized by autonomic and pyramidal dysfunction in addition to a broad spectrum of Parkinsonism presentations and cerebellar ataxia [68]. On neuropathological grounds, deterioration of nigrostriatal as well as olivopontocerebellar pathways contributes to the clinical phenotype of MSA [69] with the predominant Parkinsonian symptoms (MSA-P subtype) on the one hand and the predominant cerebellar dysfunction (MSA-C subtype) on the other hand. *Nota bene*, altered eye movements in MSA underlie both pathomechanisms [5]. In MSA-C, patients frequently present with typical cerebellar-type oculomotor signs comprising disturbed SPEM as well as downbeat, rebound, and gaze-evoked nystagmus [70]. Pathological nystagmus in the presence of Parkinsonism characterizes a unique identity for differentiating MSA from other Parkinsonian syndromes. In contrast, it is more difficult to distinguish MSA-P from PD because possible cerebellar symptoms mostly remain subtle; however, if present, they provide a “red flag” for MSA since cerebellar signs have not been reported in PD. Saccadic hypometria in MSA can be observed, with mildly or moderately inaccurate saccade amplitudes. MSA patients are principally able to generate normal saccade amplitudes, and peak eye velocities are unaffected in MSA compared to controls [37]. Reduced vertical eye velocities suggest in

almost all cases a diagnosis different than MSA or PD. Most MSA patients present with abnormally large SWJ. Disruptions of SPEM as consecutive, fine-stepped catch-up saccades emerge predominantly in MSA-C, while patients with MSA-P can present with a mixed picture of both catch-up saccades and anticipatory saccades. The latter type cannot be distinguished from those observed in PD patients [37]. MSA pathology involves the brainstem nuclei associated with smooth pursuit eye movements. In addition, MSA patients present with the disability to withhold unwanted gaze shifts suggesting an impaired executive control [37] although MSA patients show cognitive deficits only in the late stages of the disease [5]. This aspect is worth mentioning since MSA patients may manifest, like PD patients, an attention deficit that can be discovered by cognitively demanding tasks in VOG (e.g., antisaccades, see Figure 1). These observations call for further investigations in order to study higher function networks that may contribute to the pathological process in MSA resulting in disturbed eye movement control.

4.3. Progressive Supranuclear Palsy (PSP). Progressive supranuclear palsy (PSP) is characterized by Parkinsonism associated with signs like supranuclear gaze palsy, early falls, dysphagia, dysarthria, axially pronounced rigidity, and behavioral/cognitive impairment [71]. PSP can be subdivided into different subtypes that are characterized by their clinical course, most probably related to different patterns of pathological tau distribution in the brain. Apart from the “classical” PSP (Richardson Syndrome, PSP-RS), recent classifications subdivide clinical phenotypes including PSP-Parkinsonism (PSP-P), pure akinesia, progressive non-fluent aphasia, and corticobasal syndrome (CBS) [72, 73]. The eponymous supranuclear gaze palsy is a central element of all subtypes but is not present in all stages of all subtypes. The subtypes PSP-RS and PSP-P with the oculomotor hallmark of abnormally reduced vertical peak eye velocity are subsequently discussed. Oculomotor features might be diagnostically important as

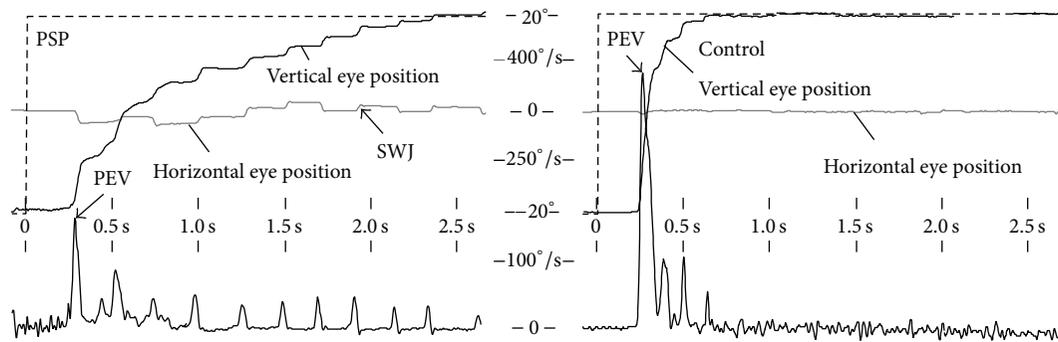


FIGURE 4: Videoculographic recordings depicting an upward visually guided reflexive saccade elicited in a sudden target jump ranging from -15 to $+15$ degrees in a patient with progressive supranuclear palsy (PSP, left panel) compared with an age-matched healthy control (right panel). The PSP patient reaches the target (dashed line) in a pathological multistep pattern, approximately 2.5 seconds (x -axis) after new stimulus appearance (black line, vertical gaze position, and y -axis) whereas the control's gaze shift is accomplished after about 600 milliseconds. Abnormal horizontal square wave jerks (SWJ) manifest in the orthogonalized horizontal eye position (gray line in the left panel), together with vertical saccades indicating a curved trajectory. In contrast, the horizontal eye position in the control subject (gray line in the right panel) exhibits no alteration. The lower row shows the corresponding vertical eye velocity (y -axis) computed by use of sample-by-sample differences of the vertical eye position signal. The PSP patient (left) fails in generating larger saccades resulting in a reduced peak eye velocity (PEV) compared with the control subject.

an early feature for PSP since definitive biomarkers remain to be defined yet, and subtle early clinical states of PSP may be indistinguishable from PD [74]. Slowing of saccades, particularly vertically, is caused by midbrain atrophy targeting burst neurons in the rostral interstitial nucleus of the medial longitudinal fasciculus that drives the extraocular eye muscles for vertical saccade generation [28]. Moreover, the omnipause neurons are required to suppress their firing while the burst neurons innervate the extraocular eye muscles to drive the saccade. A second inhibitory pathomechanism of the omnipause neurons is suggested to contribute to reduced peak eye velocity due to its interference with the burst neurons [5]. The dopaminergic nigrostriatal pathways and the superior cerebellar peduncle are reported to be involved in the pathological process resulting in prolonged latencies and (mostly subtle) cerebellar oculomotor signs, respectively [75].

Study of oculomotor dysfunctions both in PSP-RS and in PSP-P revealed a similar presentation comprising slowed vertical saccades, saccadic hypometria, prolonged latencies, and impaired pursuit eye movement [65]. In advanced stages, PSP patients are fairly disabled to generate large saccade amplitudes, preferentially vertical, as exemplified in Figure 4. When vertical saccades become slowed, horizontal saccade velocity remains intact until the pathological process also involves horizontal burst neurons resulting in reduced horizontal peak eye velocities [3, 76]. PSP patients also present with disrupted visual fixation when they attempt to fix their eyes upon stationary targets. Additionally, they present with more frequent, larger SWJ (with amplitudes up to 5°), slower saccades, and more horizontal SWJ compared to controls [77]. The phenomenon of considerably higher prevalence of horizontal SWJ in combination with larger amplitudes may give a clue for PSP although microsaccades are observed

preferentially in horizontal direction with increasing target size [24]. Two further explanations for the presence of abnormally large and frequent SWJ in PSP have been proposed: (i) since horizontal SWJ rate often increases during the release of vertical saccades, a SWJ coupling mechanism was suggested to enhance vertical saccade burst [13] and (ii) the decreased peak eye velocity and the resulting prolonged saccade duration may increase the probability that vision fades so that larger and more frequent SWJ could overcome visual fading in PSP [21, 28].

Remarkably, SPEM remain intact even in severely impaired PSP patients as long as a target is continuously moving in a predictive manner with low peak velocity and acceleration. This could be demonstrated when patients were asked to track a sinusoidal oscillating spot with low frequency [24]. With increasing stimulus frequency, the ability to perform SPEM considerably declines due to the disability to perform catch-up saccades to refoveate the target [37]. PSP is frequently accompanied by cognitive decline and frontal brain dysfunctions including executive deficits that can be demonstrated in cognitively demanding tasks such as the antisaccade condition in which the PSP patients often present with a limited ability to inhibit the visual "grasp" reflex in a sense of shifting the gaze towards the opposite target direction [28]. In addition, vergence eye movements are reported to be affected early in the PSP course and may also be associated with horizontal diplopia in some cases [78]. In summary, pathologically slowed vertical saccades' peak velocities are the eponymous hallmark of PSP. The PSP-associated damage involves midbrain structures including the saccadic burst generator in the brainstem that is responsible for the impaired (vertical) eye muscles innervation. Moreover, a hallmark of PSP is the early appearance of cognitive and behavioral deficits [79] that also manifest in oculomotor function by

means of a considerable lack of inhibitory control of saccades (e.g., tested by antisaccades).

5. Alterations of Eye Movement Control in Huntington's Disease

Autosomal dominant Huntington's disease (HD) is a progressive neurodegenerative disease, clinically presenting with a hyperkinetic movement disorder (chorea), cognitive decline, and behavioral symptoms [80]. The age of disease onset is predictable by the number of pathologically increased CAG repeats. Oculomotor deficits in patients with HD and presymptomatic gene carriers are reported to be one of the earliest signs [81]. They present as dysfunction of fixation ability [82], impaired initiation and inhibition of saccadic eye movements [83], impaired SPEM [2, 84], and decreased inhibition control in the sense of erroneously responding to novel stimuli [85–87]. Moreover, slowed saccades become prominent in both vertical and horizontal directions, latencies have been reported to be increased, and saccadic hypometria can be observed in HD like in other movement disorders [3]. Slowing of saccades is likely caused by midbrain atrophy, in particular in the pontine nuclei critical for the saccadic burst; however, the pathophysiology in oculomotor-related midbrain areas is ill-defined, so far [88].

Presymptomatic gene carriers show subtle cognitive and motor impairment due to striatal and cortical neuropathological changes that cause increased error rates during inhibition tests such as antisaccades [86] and likely reflect first clinical symptoms [7]. Reflexive saccades remain unaffected for a long time whereas both reflexive and voluntary-guided saccade performance decline with disease progression [89], since the structural connectivity between the frontal cortex and the caudate body seems to be particularly related to the control of voluntary-guided saccades [7, 86]. Difficulties in voluntarily initiating saccades in the presence of excessive saccadic intrusions during attempted fixation and a lack of inhibition control in the sense of withholding gaze shifts to new stimuli are apparently contradicting findings; a comprehensive explanation for this phenomenon in HD remains to be identified. HD-associated pathology appears to affect both the oculomotor nuclei "driving" the extraocular eye muscles and the attention system. The latter one is apparently involved already in presymptomatic HD.

6. Alterations of Eye Movement Control in Cerebellar Disorders

Cerebellar signs manifest in many neurodegenerative movement disorders such as MSA and in the heterogeneous group of hereditary spinocerebellar ataxia. One prominent feature is cerebellar ataxia with impaired body posture; in addition, patients present with dysarthria, dysmetria, and dysdiadochokinesia [90]. Cerebellar dysfunctions in eye movement control frequently manifest in a variety of symptoms including the spectrum of pathological nystagmus, dysmetric saccades, abnormally large SWJ, postsaccadic drift

as a consequence of pulse-step-mismatch, mildly slowed saccades, and a disturbed pursuit in the sense of corrective saccades interrupting SPEM [3, 16, 28, 37, 50, 88]. These deficits become pronounced in advanced cases, while many patients present with less dominant oculomotor abnormalities in early stages. In order to detect these symptoms, VOG is helpful beyond pure visual inspection. Oculomotor dysfunctions have been characterized by the genetically defined spinocerebellar ataxia subtypes [88]; for a comprehensive review, see [2]. Only a few studies investigated presymptomatic spinocerebellar ataxia gene carriers in contrast to HD. For spinocerebellar ataxia type 2 presymptomatic patients, a relation between CAG repeats, estimated time to disease onset, and decreased peak eye velocity has been reported [91]. Together, these VOG findings in cerebellar dysfunction mirror the cerebellar contribution to the oculomotor system, that is, refinement of saccade guidance, the adaptive strategy to perform perfect smooth pursuit, and the ability to hold the eye in a steady position. To our knowledge, the role of the cerebellum in attentional oculomotor control remains incompletely defined yet and might be a promising issue for future investigations.

7. Summary

In the absence of definitive biomarkers, VOG holds promise for a complementary noninvasive tool to characterize the oculomotor phenotype of distinct disease entities within the spectrum of neurodegenerative diseases. In the course of neurodegenerative disorders, disease-specific brain structures get systematically damaged. Hence, the resulting clinical condition might be considered as an investigational model for the contribution of functional components to eye movement control. *In vivo* examination of the oculomotor system offers a valuable window into altered brain function in the pathological state of movement disorders. Thus, we can learn about the contribution of different functional systems that may interfere with the way we direct our attention in the visual scene. In addition, oculomotor control covers large portions of the whole brain that appear to be decomposable into two major subdivisions: (i) the oculomotor nuclei responsible for the innervation of the six extraocular eye muscles and (ii) the much more complex network of higher cognitive control that is strongly associated with visual attention.

The investigation of eye movements may become important to clinicians in the context of differential diagnostics of movement disorders such as in distinguishing between Parkinsonian syndromes or to uncover a possible cerebellar contribution to pathological processes. VOG provides a sensitive noninvasive *in vivo* method to detect alterations in oculomotor function in patients with neurodegenerative movement disorders. Malfunctioning oculomotor control appears to have some characteristic feature that can give clues to be attributed uniquely to the subtype of the movement disorder. More specifically, other neurodegenerative types of Parkinsonian syndromes can be differentiated from PD early in the course. One should keep in mind that some of the Parkinsonian-associated hallmarks such as slowed

eye velocities could also manifest in other neurodegenerative (nonmovement) disorders, resulting in the necessity for careful interpretation of VOG results in the light of the clinical presentation. Particular aspects such as SWJ or larger intruding eye movements may provide motivation for future investigations (possibly together with functional brain imaging studies [9, 92]) to increase our understanding of the functional pathoanatomy of these neurodegenerative conditions.

Notably, attentional dysfunction in oculomotor control mostly presents early in the course of neurodegenerative movement disorders even while no obvious cognitive deficits exist. This finding prompts the notion that even a subtle pathology of cortical networks may cause a broad variety of oculomotor alterations. To further investigate the complex nature of visual attention and the way we direct or withhold our gaze, it might be safe to assume that we can learn much from pathological conditions related to specific functional systems. This approach offers the possibility to refine our existing models of human oculomotor networks whose functional interaction may be considered an essential framework for higher functions such as visual attention.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

The authors would gratefully acknowledge Professor Dr. Wolfgang Becker and Dr. Reinhart Jürgens.

References

- [1] M. E. Goldberg and M. F. Walker, "The control of gaze," in *Principles of Neural Science*, A. J. Hudspeth, J. H. Schwartz, T. M. Jessell, S. A. Siegelbaum, and E. R. Kandel, Eds., pp. 894–916, McGraw-Hill, New York, NY, USA, 5th edition, 2013.
- [2] R. J. Leigh and D. S. Zee, *The Neurology of Eye Movements*, Oxford University Press, New York, NY, USA, 4th edition, 2006.
- [3] T. J. Anderson and M. R. MacAskill, "Eye movements in patients with neurodegenerative disorders," *Nature Reviews Neurology*, vol. 9, no. 2, pp. 74–85, 2013.
- [4] M. R. MacAskill, C. F. Graham, T. L. Pitcher et al., "The influence of motor and cognitive impairment upon visually-guided saccades in Parkinson's disease," *Neuropsychologia*, vol. 50, no. 14, pp. 3338–3347, 2012.
- [5] E. H. Pinkhardt and J. Kassubek, "Ocular motor abnormalities in Parkinsonian syndromes," *Parkinsonism & Related Disorders*, vol. 17, no. 4, pp. 223–230, 2011.
- [6] Y. Terao, H. Fukuda, A. Yugeta et al., "Initiation and inhibitory control of saccades with the progression of Parkinson's disease—changes in three major drives converging on the superior colliculus," *Neuropsychologia*, vol. 49, no. 7, pp. 1794–1806, 2011.
- [7] S. Klöppel, B. Draganski, C. V. Golding et al., "White matter connections reflect changes in voluntary-guided saccades in pre-symptomatic Huntington's disease," *Brain*, vol. 131, part 1, pp. 196–204, 2008.
- [8] S. F. Neggers, R. M. Diepen, B. B. Zandbelt, M. Vink, R. C. Mandl, and T. P. Gutteling, "A functional and structural investigation of the human fronto-basal volitional saccade network," *PLoS ONE*, vol. 7, no. 1, article e29517, 2012.
- [9] M. Gorges, H. P. Müller, D. Lule, A. C. Ludolph, E. H. Pinkhardt, and J. Kassubek, "Functional connectivity within the default mode network is associated with saccadic accuracy in Parkinson's disease: a resting-state fMRI and videooculographic study," *Brain Connectivity*, vol. 3, no. 3, pp. 265–272, 2013.
- [10] M. E. Raichle, "Two views of brain function," *Trends in Cognitive Sciences*, vol. 14, no. 4, pp. 180–190, 2010.
- [11] C. H. Anderson, D. C. Essen, and B. A. Olshausen, "Directed visual attention and the dynamic control of information flow," in *Encyclopedia of Visual Attention*, L. Itti, G. Rees, and J. Tsotsos, Eds., Elsevier/Academic Press, 2004.
- [12] C. Donaghy, M. J. Thurtell, E. P. Piore, J. M. Gibson, and R. J. Leigh, "Eye movements in amyotrophic lateral sclerosis and its mimics: a review with illustrative cases," *Journal of Neurology, Neurosurgery & Psychiatry*, vol. 82, no. 1, pp. 110–116, 2011.
- [13] S. Garbutt, A. Matlin, J. Hellmuth et al., "Oculomotor function in frontotemporal lobar degeneration, related disorders and Alzheimer's disease," *Brain*, vol. 131, part 5, pp. 1268–1281, 2008.
- [14] Z. Kapoula, Q. Yang, J. Otero-Millan et al., "Distinctive features of microsaccades in Alzheimer's disease and in mild cognitive impairment," *Age*, vol. 36, no. 2, pp. 535–543, 2014.
- [15] G. L. Walls, "The evolutionary history of eye movements," *Vision Research*, vol. 2, no. 1–4, pp. 69–80, 1962.
- [16] K. Fukushima, J. Fukushima, T. Warabi, and G. R. Barnes, "Cognitive processes involved in smooth pursuit eye movements: behavioral evidence, neural substrate and clinical correlation," *Frontiers in Systems Neuroscience*, vol. 7, article 4, 2013.
- [17] W. Becker, "The neurobiology of saccadic eye movements. Metrics," *Reviews of Oculomotor Research*, vol. 3, pp. 13–67, 1989.
- [18] S. Martinez-Conde, J. Otero-Millan, and S. L. Macknik, "The impact of microsaccades on vision: towards a unified theory of saccadic function," *Nature Reviews Neuroscience*, vol. 14, no. 2, pp. 83–96, 2013.
- [19] R. V. Abadi and E. Gowen, "Characteristics of saccadic intrusions," *Vision Research*, vol. 44, no. 23, pp. 2675–2690, 2004.
- [20] S. Martinez-Conde, S. L. Macknik, and D. H. Hubel, "The role of fixational eye movements in visual perception," *Nature Reviews Neuroscience*, vol. 5, no. 3, pp. 229–240, 2004.
- [21] S. Martinez-Conde, S. L. Macknik, X. G. Troncoso, and T. A. Dyar, "Microsaccades counteract visual fading during fixation," *Neuron*, vol. 49, no. 2, pp. 297–305, 2006.
- [22] J. Otero-Millan, X. G. Troncoso, S. L. Macknik, I. Serrano-Pedraza, and S. Martinez-Conde, "Saccades and microsaccades during visual fixation, exploration, and search: foundations for a common saccadic generator," *Journal of Vision*, vol. 8, no. 14, article 21, pp. 1–18, 2008.
- [23] S. Martinez-Conde, S. L. Macknik, X. G. Troncoso, and D. H. Hubel, "Microsaccades: a neurophysiological analysis," *Trends in Neurosciences*, vol. 32, no. 9, pp. 463–475, 2009.
- [24] M. B. McCamy, A. Najafian Jazi, J. Otero-Millan, S. L. Macknik, and S. Martinez-Conde, "The effects of fixation target size and luminance on microsaccades and square-wave jerks," *PeerJ*, vol. 1, article e9, 2013.
- [25] J. Otero-Millan, R. Schneider, R. J. Leigh, S. L. Macknik, and S. Martinez-Conde, "Saccades during attempted fixation in

- parkinsonian disorders and recessive ataxia: from microsaccades to square-wave jerks," *PLoS ONE*, vol. 8, no. 3, article e58535, 2013.
- [26] E. Kowler and A. J. Martins, "Eye movements of preschool children," *Science*, vol. 215, no. 4535, pp. 997–999, 1982.
- [27] F. Rosini, P. Federighi, E. Pretegianni et al., "Ocular-motor profile and effects of memantine in a familial form of adult cerebellar ataxia with slow saccades and square wave saccadic intrusions," *PLoS ONE*, vol. 8, no. 7, article e69522, 2013.
- [28] A. L. Chen, D. E. Riley, S. A. King et al., "The disturbance of gaze in progressive supranuclear palsy: implications for pathogenesis," *Frontiers in Neurology*, vol. 1, article 147, 2010.
- [29] J. Kassubek, "Diagnostic procedures during the course of Parkinson's disease," *Basal Ganglia*, 2014.
- [30] D. S. Zee, "Ophthalmoscopy in examination of patients with vestibular disorders," *Annals of Neurology*, vol. 3, no. 4, pp. 373–374, 1978.
- [31] A. Serra and R. J. Leigh, "Diagnostic value of nystagmus: spontaneous and induced ocular oscillations," *Journal of Neurology, Neurosurgery & Psychiatry*, vol. 73, no. 6, pp. 615–618, 2002.
- [32] T. Eggert, "Eye movement recordings: methods," *Developments in Ophthalmology*, vol. 40, pp. 15–34, 2007.
- [33] E. Schneider, T. Villgrattner, J. Vockeroth et al., "EyeSeeCam: an eye movement-driven head camera for the examination of natural visual exploration," *Annals of the New York Academy of Sciences*, vol. 1164, pp. 461–467, 2009.
- [34] H. Kimmig, K. Haussmann, T. Mergner, and C. H. Lucking, "What is pathological with gaze shift fragmentation in Parkinson's disease?" *Journal of Neurology*, vol. 249, no. 6, pp. 683–692, 2002.
- [35] E. H. Pinkhardt, R. Jürgens, D. Lule et al., "Eye movement impairments in Parkinson's disease: possible role of extradopaminergic mechanisms," *BMC Neurology*, vol. 12, article 5, 2012.
- [36] C. Helmchen, J. Pohlmann, P. Trillenber, R. Lencer, J. Graf, and A. Sprenger, "Role of anticipation and prediction in smooth pursuit eye movement control in Parkinson's disease," *Movement Disorders*, vol. 27, no. 8, pp. 1012–1018, 2012.
- [37] E. H. Pinkhardt, J. Kassubek, S. Sussmuth, A. C. Ludolph, W. Becker, and R. Jürgens, "Comparison of smooth pursuit eye movement deficits in multiple system atrophy and Parkinson's disease," *Journal of Neurology*, vol. 256, no. 9, pp. 1438–1446, 2009.
- [38] M. P. van den Heuvel and H. E. Hulshoff Pol, "Exploring the brain network: a review on resting-state fMRI functional connectivity," *European Neuropsychopharmacology*, vol. 20, no. 8, pp. 519–534, 2010.
- [39] K. R. Chaudhuri, P. Odin, A. Antonini, and P. Martinez-Martin, "Parkinson's disease: the non-motor issues," *Parkinsonism & Related Disorders*, vol. 17, no. 10, pp. 717–723, 2011.
- [40] A. Park and M. Stacy, "Non-motor symptoms in Parkinson's disease," *Journal of Neurology*, vol. 256, supplement 3, pp. 293–298, 2009.
- [41] H. Braak and K. del Tredici, *Neuroanatomy and Pathology of Sporadic Parkinson's Disease*, vol. 201 of *Advances in Anatomy, Embryology and Cell Biology*, Springer, Berlin, Germany, 2009.
- [42] H. Braak, K. del Tredici, U. Rub, R. A. de Vos, E. N. J. Steur, and E. Braak, "Staging of brain pathology related to sporadic Parkinson's disease," *Neurobiology of Aging*, vol. 24, no. 2, pp. 197–211, 2003.
- [43] H. Braak, C. M. Müller, U. Rub et al., "Pathology associated with sporadic Parkinson's disease—where does it end?" *Journal of Neural Transmission. Supplement*, no. 70, pp. 89–97, 2006.
- [44] H. Braak, U. Rub, E. N. Jansen Steur, K. del Tredici, and R. A. de Vos, "Cognitive status correlates with neuropathologic stage in Parkinson disease," *Neurology*, vol. 64, no. 8, pp. 1404–1410, 2005.
- [45] B. Machner, C. Klein, A. Sprenger et al., "Eye movement disorders are different in Parkin-linked and idiopathic early-onset PD," *Neurology*, vol. 75, no. 2, pp. 125–128, 2010.
- [46] E. H. Pinkhardt, H. Issa, M. Gorges et al., "Do eye movement impairments in patients with small vessel cerebrovascular disease depend on lesion load or on cognitive deficits? A video-oculographic and MRI study," *Journal of Neurology*, vol. 261, no. 4, pp. 791–803, 2014.
- [47] D. P. Munoz and S. Everling, "Look away: the anti-saccade task and the voluntary control of eye movement," *Nature Reviews Neuroscience*, vol. 5, no. 3, pp. 218–228, 2004.
- [48] O. Hikosaka and R. H. Wurtz, "The basal ganglia," *Reviews of Oculomotor Research*, vol. 3, pp. 257–281, 1989.
- [49] P. Sauleau, P. Pollak, P. Krack et al., "Subthalamic stimulation improves orienting gaze movements in Parkinson's disease," *Clinical Neurophysiology*, vol. 119, no. 8, pp. 1857–1863, 2008.
- [50] A. Kheradmand and D. S. Zee, "Cerebellum and ocular motor control," *Frontiers in Neurology*, vol. 2, article 53, 2011.
- [51] S. van Stockum, M. R. MacAskill, D. Myall, and T. J. Anderson, "A perceptual discrimination task results in greater facilitation of voluntary saccades in Parkinson's disease patients," *European Journal of Neuroscience*, vol. 37, no. 1, pp. 163–172, 2013.
- [52] R. Ptak and R. M. Muri, "The parietal cortex and saccade planning: lessons from human lesion studies," *Frontiers in Human Neuroscience*, vol. 7, article 254, 2013.
- [53] B. A. Purcell, P. K. Weigand, and J. D. Schall, "Supplementary eye field during visual search: salience, cognitive control, and performance monitoring," *The Journal of Neuroscience*, vol. 32, no. 30, pp. 10273–10285, 2012.
- [54] S. E. Bosch, S. F. Neggers, and S. van der Stigchel, "The role of the frontal eye fields in oculomotor competition: image-guided TMS enhances contralateral target selection," *Cerebral Cortex*, vol. 23, no. 4, pp. 824–832, 2013.
- [55] S. Yerram, S. Glazman, and I. Bodis-Wollner, "Cortical control of saccades in Parkinson disease and essential tremor," *Journal of Neural Transmission*, vol. 120, no. 1, pp. 145–156, 2013.
- [56] B. Gaymard, S. Rivaud, J. F. Cassarini et al., "Effects of anterior cingulate cortex lesions on ocular saccades in humans," *Experimental Brain Research*, vol. 120, no. 2, pp. 173–183, 1998.
- [57] U. P. Mosimann, R. M. Muri, D. J. Burn, J. Felblinger, J. T. O'Brien, and I. G. McKeith, "Saccadic eye movement changes in Parkinson's disease dementia and dementia with Lewy bodies," *Brain*, vol. 128, part 6, pp. 1267–1276, 2005.
- [58] M. S. Okun, "Deep-brain stimulation for Parkinson's disease," *The New England Journal of Medicine*, vol. 368, no. 5, pp. 483–484, 2013.
- [59] M. H. Nilsson, M. Patel, S. Rehncrona, M. Magnusson, and P. A. Fransson, "Subthalamic deep brain stimulation improves smooth pursuit and saccade performance in patients with Parkinson's disease," *Journal of NeuroEngineering and Rehabilitation*, vol. 10, article 33, 2013.
- [60] A. Yugeta, Y. Terao, H. Fukuda et al., "Effects of STN stimulation on the initiation and inhibition of saccade in Parkinson disease," *Neurology*, vol. 74, no. 9, pp. 743–748, 2010.

- [61] S. Fahn, R. L. Elton, and UPDRS Development Committee, "The unified Parkinson's disease rating scale," in *Recent Developments in Parkinson's Disease*, pp. 153–163, 293–304, Macmillian Healthcare Information, Florham Park, NJ, USA, 1987.
- [62] C. D. Hacker, J. S. Perlmutter, S. R. Criswell, B. M. Ances, and A. Z. Snyder, "Resting state functional connectivity of the striatum in Parkinson's disease," *Brain*, vol. 135, part 12, pp. 3699–3711, 2012.
- [63] K. T. O. Dubbelink, D. Stoffers, J. B. Deijen, J. W. Twisk, C. J. Stam, and H. W. Berendse, "Cognitive decline in Parkinson's disease is associated with slowing of resting-state brain activity: a longitudinal study," *Neurobiology of Aging*, vol. 34, no. 2, pp. 408–418, 2013.
- [64] A. Tessitore, F. Esposito, C. Vitale et al., "Default-mode network connectivity in cognitively unimpaired patients with Parkinson disease," *Neurology*, vol. 79, no. 23, pp. 2226–2232, 2012.
- [65] E. H. Pinkhardt, R. Jürgens, W. Becker, F. Valdarno, A. C. Ludolph, and J. Kassubek, "Differential diagnostic value of eye movement recording in PSP-parkinsonism, Richardson's syndrome, and idiopathic Parkinson's disease," *Journal of Neurology*, vol. 255, no. 12, pp. 1916–1925, 2008.
- [66] A. G. Shaikh, M. Xu-Wilson, S. Grill, and D. S. Zee, "Staircase" square-wave jerks in early Parkinson's disease," *British Journal of Ophthalmology*, vol. 95, no. 5, pp. 705–709, 2011.
- [67] T. Blekher, M. Weaver, J. Rupp et al., "Multiple step pattern as a biomarker in Parkinson disease," *Parkinsonism & Related Disorders*, vol. 15, no. 7, pp. 506–510, 2009.
- [68] K. Ubhi, P. Low, and E. Masliah, "Multiple system atrophy: a clinical and neuropathological perspective," *Trends in Neurosciences*, vol. 34, no. 11, pp. 581–590, 2011.
- [69] T. Hasegawa, T. Baba, M. Kobayashi et al., "Role of TPPP/p25 on α -synuclein-mediated oligodendroglial degeneration and the protective effect of SIRT2 inhibition in a cellular model of multiple system atrophy," *Neurochemistry International*, vol. 57, no. 8, pp. 857–866, 2010.
- [70] T. Anderson, L. Luxon, N. Quinn, S. Daniel, C. D. Marsden, and A. Bronstein, "Oculomotor function in multiple system atrophy: clinical and laboratory features in 30 patients," *Movement Disorders*, vol. 23, no. 7, pp. 977–984, 2008.
- [71] A. C. Ludolph, J. Kassubek, B. G. Landwehrmeyer et al., "Tauopathies with parkinsonism: clinical spectrum, neuropathologic basis, biological markers, and treatment options," *European Journal of Neurology*, vol. 16, no. 3, pp. 297–309, 2009.
- [72] I. T. Armstrong, M. Judson, D. P. Munoz, R. S. Johansson, and J. R. Flanagan, "Waiting for a hand: saccadic reaction time increases in proportion to hand reaction time when reaching under a visuomotor reversal," *Frontiers in Human Neuroscience*, vol. 7, article 319, 2013.
- [73] D. R. Williams, R. de Silva, D. C. Paviour et al., "Characteristics of two distinct clinical phenotypes in pathologically proven progressive supranuclear palsy: Richardson's syndrome and PSP-parkinsonism," *Brain*, vol. 128, part 6, no. 6, pp. 1247–1258, 2005.
- [74] D. R. Williams and I. Litvan, "Parkinsonian syndromes," *Continuum*, vol. 19, no. 5, Movement Disorders, pp. 1189–1212, 2013.
- [75] D. W. Dickson, R. Rademakers, and M. L. Hutton, "Progressive supranuclear palsy: pathology and genetics," *Brain Pathology*, vol. 17, no. 1, pp. 74–82, 2007.
- [76] S. Marx, G. Respondek, M. Stamelou et al., "Validation of mobile eye-tracking as novel and efficient means for differentiating progressive supranuclear palsy from Parkinson's disease," *Frontiers in Behavioral Neuroscience*, vol. 6, article 88, 2012.
- [77] J. Otero-Millan, S. L. Macknik, A. Serra, R. J. Leigh, and S. Martinez-Conde, "Triggering mechanisms in microsaccade and saccade generation: a novel proposal," *Annals of the New York Academy of Sciences*, vol. 1233, no. 1, pp. 107–116, 2011.
- [78] A. Hardwick, J. C. Rucker, M. L. Cohen et al., "Evolution of oculomotor and clinical findings in autopsy-proven richardson syndrome," *Neurology*, vol. 73, no. 24, pp. 2122–2124, 2009.
- [79] R. G. Brown, L. Lacomblez, B. G. Landwehrmeyer et al., "Cognitive impairment in patients with multiple system atrophy and progressive supranuclear palsy," *Brain*, vol. 133, no. 8, pp. 2382–2393, 2010.
- [80] F. O. Walker, "Huntington's disease," *The Lancet*, vol. 369, no. 9557, pp. 218–228, 2007.
- [81] S. L. Hicks, M. P. Robert, C. V. Golding, S. J. Tabrizi, and C. Kennard, "Oculomotor deficits indicate the progression of Huntington's disease," *Progress in Brain Research*, vol. 171, pp. 555–558, 2008.
- [82] W. Becker, R. Jurgens, J. Kassubek, D. Ecker, B. Kramer, and B. Landwehrmeyer, "Eye-head coordination in moderately affected Huntington's disease patients: do head movements facilitate gaze shifts?" *Experimental Brain Research*, vol. 192, no. 1, pp. 97–112, 2009.
- [83] T. H. Turner, J. Goldstein, J. M. Hamilton et al., "Behavioral measures of saccade latency and inhibition in manifest and premanifest Huntington's disease," *Journal of Motor Behavior*, vol. 43, no. 4, pp. 295–302, 2011.
- [84] J. Fielding, N. Georgiou-Karistianis, J. Bradshaw et al., "Impaired modulation of the vestibulo-ocular reflex in Huntington's disease," *Movement Disorders*, vol. 19, no. 1, pp. 68–75, 2004.
- [85] T. Blekher, S. A. Johnson, J. Marshall et al., "Saccades in presymptomatic and early stages of Huntington disease," *Neurology*, vol. 67, no. 3, pp. 394–399, 2006.
- [86] J. Fielding, N. Georgiou-Karistianis, and O. White, "The role of the basal ganglia in the control of automatic visuospatial attention," *Journal of the International Neuropsychological Society*, vol. 12, no. 5, pp. 657–667, 2006.
- [87] S. S. Patel, J. Jankovic, A. J. Hood, C. B. Jeter, and A. B. Sereno, "Reflexive and volitional saccades: biomarkers of Huntington disease severity and progression," *Journal of the Neurological Sciences*, vol. 313, no. 1–2, pp. 35–41, 2012.
- [88] J. Kassubek and E. H. Pinkhardt, "Neuro-ophthalmological alterations in patients with movement disorders," in *Uncommon Causes of Movement Disorders*, N. Gálvez-Jiménez and P. Tuite, Eds., pp. 306–315, Cambridge University Press, Cambridge, UK, 1st edition, 2011.
- [89] C. V. Golding, C. Danchavijitr, T. L. Hodgson, S. J. Tabrizi, and C. Kennard, "Identification of an oculomotor biomarker of preclinical Huntington disease," *Neurology*, vol. 67, no. 3, pp. 485–487, 2006.
- [90] A. Dürr, "Autosomal dominant cerebellar ataxias: polyglutamine expansions and beyond," *The Lancet Neurology*, vol. 9, no. 9, pp. 885–894, 2010.
- [91] L. Velazquez-Perez, C. Seifried, M. Abele et al., "Saccade velocity is reduced in presymptomatic spinocerebellar ataxia type 2," *Clinical Neurophysiology*, vol. 120, no. 3, pp. 632–635, 2009.
- [92] S. D. Jamadar, J. Fielding, and G. F. Egan, "Quantitative meta-analysis of fMRI and PET studies reveals consistent activation in fronto-striatal-parietal regions and cerebellum during anti-saccades and prosaccades," *Frontiers in Psychology*, vol. 4, article 749, pp. 1–15, 2013.

Research Article

Selective Age Effects on Visual Attention and Motor Attention during a Cued Saccade Task

Wendy E. Huddleston, Brad E. Ernest, and Kevin G. Keenan

Department of Kinesiology, University of Wisconsin-Milwaukee, PT-PAV 350, P.O. Box 413, Milwaukee, WI 53201-0413, USA

Correspondence should be addressed to Wendy E. Huddleston; huddlest@uwm.edu

Received 6 December 2013; Revised 19 March 2014; Accepted 22 April 2014; Published 12 May 2014

Academic Editor: Stefanie I. Becker

Copyright © 2014 Wendy E. Huddleston et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Objective. Visual information is often used to guide purposeful movement. However, older adults have impaired responses to visual information, leading to increased risk for injuries and potential loss of independence. We evaluated distinct visual and motor attention contributions to a cued saccade task to determine the extent to which aging selectively affects these processes. *Methods.* Nineteen healthy young (18–28 years) and 20 older (60–90 years) participants performed a cued saccade task under two conditions. We challenged motor attention by changing the number of possible saccade targets (1 or 6). *Results.* Older adults had difficulty in inhibiting unwanted eye movements and had greater eye movement inaccuracy in the hard condition when compared to the younger adults and to the easy condition. Also, an inverse relation existed between performance on the visual and motor components of the task in older adults, unlike younger adults. *Conclusions.* Older adults demonstrated difficulty in both inhibiting irrelevant saccade targets and selecting correct saccade endpoints during more complex tasks. The shift in relations among attention measures between the younger and older participants may indicate a need to prioritize attentional resources with age. These changes may impact an older adult's ability to function in complex environments.

1. Introduction

Most people depend heavily on visual cues to guide purposeful movement within the environment. Some older adults respond more slowly than younger adults to changes in the environment [1–4], negatively affecting functional independence and leading to increased risk of injuries related to traffic accidents or falls [5, 6]. These age-related declines in response to the environment may be due to changes in cognitive processes such as attention. Attentional processes contribute to each stage of a visually guided movement, particularly the selection of visual information relevant to the current task [7–9] and the selection of the correct motor plan to successfully perform the action [10–13]. The component, or components, of a visually guided task at which the effects of age-related declines in attention most significantly alter function [2, 14–16], is under debate. For example, deficits in both visual processing [17, 18] and motor control [2, 19] have been reported in older adults. Separate basic tests of visual perception (line length discrimination) as well as motor

function (timed finger tapping) illustrate modality-specific declines in older adults [2].

Performance declines in older adults are oftentimes attributed to decreased processing speeds [20, 21]. The Processing-Speed Theory posits that cognitive acts are more difficult for older adults because it simply takes longer to perform all aspects of the task. This increase in time required for processing leads to diminished performance because either the activity is time-limited, or the increased time for processing each component in serial tasks prevents information from early steps still being available for later steps. However, increases in reaction time associated with both the visual and motor systems together do not fully explain deficits noted in a choice reaction time task [2]. Attentional deficits may also contribute to slowing of responses. Thus, in addition to age-related generalized slowing [21, 22], specific declines in executive function, such as attention, may subsequently explain observed declines in the control of eye movements [23, 24] in complex situations (but not in simple scenarios; see [19, 25]).

Other theories of cognitive aging may further explain declines in attentional processes involved in visuomotor tasks. Some older adults have difficulties processing task conditions or requirements as described by the Task Context Theory [26, 27]. Context, in this case, is described as relevant information to the task at hand such as the goal of the movement or specific instructions. Top-down, or voluntary, attentional processes require contextual information to correctly select information required for successful completion of the task. Impaired maintenance of context due to age may lead to an inability to correctly or efficiently select information necessary for successful and timely completion of the task, such as to move the eyes to a correct location at the correct time [23, 24]. The complementary view to older adults having difficulty selecting relevant task information is the inability to inhibit irrelevant information (Inhibitory Deficit Theory). Older adults tend to have difficulty suppressing information irrelevant to the current task [28, 29], which then leads to cognitive decline. Inhibition of irrelevant information is critical for controlling access to the focus of attention, deleting irrelevant information from attention and working memory stores, and suppressing or restraining planned, but inappropriate, responses [29]. Although the physiological mechanisms behind the two theories differ, behavioral predictions from both are typically similar.

Much evidence suggests that older adults have difficulty making the correct selection of task-related information and/or suppressing all unnecessary information [14, 17–19, 30–33]. For example, older adults demonstrate greater slowing in reaction times with an increase in the number of choices for reach targets in a visual pop-out task [34] and have failed to follow precues regarding which effector (left or right hand) to use [35]. Also, when healthy older participants are asked to specifically attend to a salient visual cue to guide movement, either error rates increase compared to a simple reaction time task [36] or movement speed decreases compared to younger adults [37]. However, in these studies the visual cue to guide movement “pops out” via a rapid onset or a significant difference in cue appearance. Visual cues that significantly differ in appearance or onset typically have a strong involuntary attention saliency signal. One question remaining unanswered is how older adults respond to changes in the complexity of the motor task when the target of action is no more visually salient than distractors, minimizing any involuntary capture of attention. In complex environments, such as driving, the ability to voluntarily select visual information and initiate correct movements is critical for successful goal-directed actions. The correct selection of a motor plan, via attention-mediated mechanisms, may play a critical role in preventing driving accidents, which might in turn increase functional independence in older adults. In this case, top-down attentional factors related to task context determine the salience of the desired movement. A task in which the targets are no more salient than the distractors may have more ecological validity related to older adults functioning within the home, driving, or avoiding falls in the community.

It is critical to understand the nature of the decline in endogenous visually guided movements in older adults so as

to develop approaches to maximize functional independence within this population. Thus, the purpose of the current study was to explicitly evaluate visual and motor domains of attention contributing to a cued saccade visuomotor task to identify which attentional components show an interaction effect between age and motor attentional load. In younger adults, increasing the attentional load during a cued saccade task in either the visual or motor domain negatively impacted performance within that specific domain without affecting the opposite one, indicating a functional dissociation of the two processes in this age group [38]. The unique aspect of the present experiment is the use of measures to separately assess different attention domains in older adults.

As in our previous study [38], participants performed saccades to one of six peripheral targets based on a centrally located cue. Younger and older adults performed the task with two levels of motor attention load under vigorous temporal constraints, all while maintaining constant visual perceptual task demands across conditions (six cue letters were used in both motor load conditions). We increased the motor attention load by changing the number of possible saccade targets from 1 to 6. In the hard condition (i.e., 6 possible saccade targets), participants had to select the correct target and inhibit other incorrect targets in a time-sensitive manner (six cue letters mapped to six different targets). In the easy condition, participants only performed a saccade to one location regardless of the visual cue and thus did not have to inhibit selection of incorrect targets (six cue letters mapped to one common target) yet still would have to select the single correct targets. We presented the cue letters at a fast rate (4 per second) to press the temporal constraints of the task. Using this paradigm, we tested the hypothesis that older adults would have greater difficulty than younger adults when more irrelevant information (more choices in saccade targets) was available during the hard condition. We could explicitly test predictions made by three theories of cognitive aging (Task Context Theory, Inhibitory Deficit Theory, and Processing-Speed Theory) by evaluating several dependent measures including visual attention errors (incorrectly perceiving the cue letter either by missing a cue or by perceiving one when one was not shown), saccade target selection errors (initially performing saccades to an incorrect target and then self-correcting), saccade endpoint accuracy and variability, and reaction time. All three theories of cognitive aging would predict an age effect for visual attention errors, with older adults performing worse on that component of the task. However, we did not anticipate any condition effect in visual attention errors as we did not manipulate visual attention load across conditions, and due to our previous findings in younger adults [38]. We also predicted that older adults would respond more slowly (based on the Processing-Speed and the Task Context Theories) and make more saccade target selection errors, and these age differences would increase in the hard condition (based on the Task Context and Inhibitory Deficit Theories). Our last prediction was that older adults would be as accurate and reliable as younger adults in saccade endpoint accuracy and variability in the easy condition, but not in the hard condition as predicted by the Task Context Theory and the Inhibitory Deficit Theory.

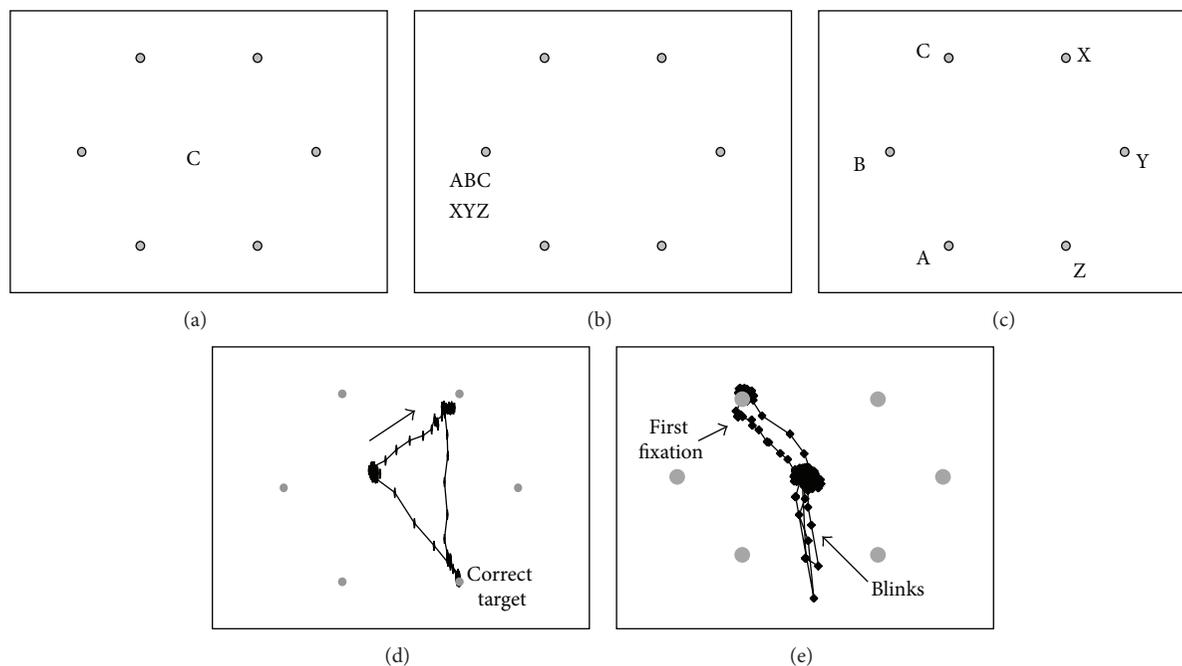


FIGURE 1: Stimulus and task. (a) The stimulus as seen by the participant. The central letter (“C” in this figure) changed every 250 ms. (b) An example of stimulus-response mapping for the easy condition. In this case, the participant would perform a saccade to the middle left location whenever any of the 6 target letters were shown. The mapping was not present during the data collection and the mapping changed for every set of 12 trials. (c) An example of stimulus-response mapping for the hard condition in which each cue letter was mapped to a unique peripheral target. (d) An example of a participant making a target selection error. The participant initially selected an incorrect target (top right) and then made a correction to the correct bottom right location. In this case the participant correctly identified the cue letter (“Z”) and recalled the correct mapping (bottom right) but chose an initially incorrect target. (e) A correct trial illustrating saccadic eye movement. In this case, the participant made an initial saccade in the correct direction and then further corrected to the target location prior to returning gaze to the central letter stream. During this trial, the participant overshot in the horizontal direction and undershot in the vertical direction during the initial saccade.

Preliminary data have been previously presented elsewhere [39].

2. Materials and Methods

Younger and older participants performed a cued saccade task to identify the effects of task difficulty and age on visual and motor attentional abilities. For the current study, we define visual attention as the selection of task-relevant cue letters from all distractors, a definition consistent with others [7–9]. Motor attention has been previously described as involving the selection of movement target, trajectory, and effector [40]. Because effector selection (the eyes) was determined by the task and did not change over the course of the experiment, we define motor attention as the selection of the correct saccade target and associated accuracy [10–13, 41]. In this experiment we challenged motor attention by changing the number of possible saccade targets between the easy and hard task conditions. We were particularly interested in potential age-related changes in performance when motor attention was challenged in the hard task condition.

2.1. Participants. Twenty healthy older adults (60–90 years, 9 females, 4 left-handed) and 20 healthy young adults (18–28

years, 11 females, 4 left-handed), with normal or corrected-to-normal vision, completed the study. One younger adult could not achieve greater than 50% accuracy during training on the cued saccade task and so all data from this participant were removed from analysis. All participants provided written informed consent as approved by the University of Wisconsin-Milwaukee Institutional Review Board. Exclusion criteria included an inability to sit comfortably for extended periods, self-report of diseases of the eye, and neurological or musculoskeletal conditions that would affect task performance. All participants lived independently within the community.

2.2. Equipment. We recorded eye movement with an infrared R6 Remote Optics Eye Tracking System (Applied Science Laboratories, Bedford, MA) at 120 Hz. Eye tracking data were collected with a personal computer (DELL, Austin, TX). Participants completed a full-field 9-point eye tracking calibration routine prior to testing.

2.3. Stimulus and Task. The stimulus and task have been described previously [38, 42]. We created and presented the visual stimuli using Presentation software (Neurobehavioral Systems, Albany, NY). The stimulus (Figure 1) consisted of

six peripheral targets (13° eccentricity). In the center of the monitor, a rapid serial visual presentation (RSVP) of random letters (subtending $1.2 \times 1.8^\circ$ visual angle) occurred at 4 Hz (marked by “C” in Figure 1(a)). Participants performed saccades as quickly and as accurately as possible to one of six peripheral target locations based on cue presentation of “A,” “B,” “C,” “X,” “Y,” or “Z” in the RSVP stream of letters. For example, if “B” was presented, the participant was instructed to look as quickly and as accurately at a predetermined peripheral target location and then focus his or her attention (and gaze) back to the RSVP stream of letters to await the next trial. Participants were instructed to make corrective saccades until they looked at the correct target. If a target letter was not presented, participants continued to focus centrally on the RSVP stream of letters. Target letters were randomly presented no closer than six seconds apart within each set. The duration between cue letter presentations was considered to be a single trial. Each cue letter was presented 2 times, for a total of 12 trials per set. Distractor letters consisting of the remaining letters of the alphabet were shown between target letter presentations. Prior to each set of 12 trials, each participant was shown a mapping between cue letter and target location (Figures 1(b) and 1(c)). This mapping changed for every set of trials and differed between the easy and hard task conditions. An “easy” mapping cued the participant to perform a saccade to a single location when any of the six cue letters were presented (Figure 1(b)). A “hard” mapping instructed the participant to perform a saccade to a different location for each of the cue letters presented (Figure 1(c)). By changing the number of possible saccade targets from one to six between conditions, we manipulated motor attention load. It is important to note that visual attention load remained constant between the two task conditions as the number of target cues was always six, and the six peripheral saccade targets remained on the screen (even when no cue letter was mapped to them in the easy condition). Participants were able to study the mapping for as long as they wished and were tested to confirm knowledge of the correct target location mapping prior to starting each set of trials. Participants completed three sets of 12 trials for each condition. Prior to collecting experimental data, participants trained on the task until they were able to achieve 75% of letter identification (1–3 sets of 12 trials for all participants).

2.4. Data Analysis. Eye tracking data collected during the cued saccade task were segmented into individual trials using custom software (BloomTech, Richfield, WI) written in LabVIEW (National Instruments, Austin, TX). Each trial was segmented into the central fixation, the first saccade, and the first fixation for further analysis. Data were collapsed across target locations within each condition. Trials in which eye movement data were lost or in which blinks occurred during the first saccade or subsequent fixation were removed from analysis.

Dependent variables assessed visual or motor attention. The dependent measure for the visual attention domain included the visual attention error rate. We calculated the visual attention error rate by adding the false positive rate

and the miss rate together. We summed the values from these two types of errors, as the denominators were slightly different for each rate as described below. We determined a false positive occurred when a participant performed a saccade to a minimum of 75% of the distance to any peripheral target without cue letter having been presented within 1500 ms prior to the saccade. The false positive rate was calculated by dividing the number of false positives by the total number of trials plus the number of false positives. The false positive rate was calculated in the manner described above because a false positive essentially added a trial to the participant’s experience. To not account for the false positives in the denominator of the equation would have falsely inflated the error rate. The miss rate was calculated by dividing the number of trials in which participants missed target letters (participant did not perform a saccade within 3000 ms of cue letter presentation) by the total number of trials. Conversely, we did not take into account the false positives when calculating the miss rate because then the score would have been artificially deflated. Twelve target letters were presented in a single run and we wanted the miss rate to represent the percentage of target letters missed.

Motor attention dependent measures included the target selection error rate, reaction time, first saccade endpoint accuracy relative to target, and within-participant saccade endpoint variability. Target selection error rates, indicating faulty motor planning, were calculated based on the number of times participants initially performed a saccade to an incorrect target but then made a correction to the appropriate location (Figure 1(d)). When making target selection errors, participants correctly identified the cue letter but initially selected the incorrect target. In this case, the perceptual portion of the task was done correctly, but the early stages of motor planning were executed incorrectly. It is important to note that these errors are not an issue of working memory, as the participant was able to ultimately perform a saccade to the correct location. When calculating the target selection error rate, the number of trials in which the initial saccade target selection was incorrect was divided by the total number of trials in which the perceptual portion of the task was performed correctly. Reaction time and saccade endpoint accuracy were calculated based on the first saccade endpoint after the cue was presented (Figure 1(e)). Reaction time was calculated separately for correct trials and for trials in which a trajectory selection error occurred. Saccade endpoint accuracy and variability were only calculated for correct trials. Saccade endpoint accuracy is primarily dependent on visual perception of the saccade target and motor planning [43]. Sensory input regarding target location was stable throughout the current experiment as the saccade targets were present at all times during the experiment; thus we considered saccade endpoint accuracy to reflect motor planning. Saccade endpoint accuracy was calculated for the horizontal and vertical directions separately in degrees of visual angle by computing the horizontal and vertical distance between the center of mass of the first endpoint and the coordinates of the correct target location. Overshoot for all of the targets was considered a positive error, and undershoot was considered negative. This analysis allowed us to quantify the direction of

TABLE 1: Means and standard deviations (in parentheses) for younger and older participants in the easy and hard cued saccade task conditions.

Dependent measure	Younger		Older	
	Easy	Hard	Easy	Hard
Visual attention error rate (%)	10.22 (3.36)	7.52 (3.61)	40.42 (3.52)	39.56 (3.27)
Target selection error rate (%)	0 (0)	30.72 (20.22)	1.84 (2.36)	44.69 (15.62)
Reaction time (ms)	568.50 (78.42)	735.79 (132.91)	773.79 (142.03)	902.33 (191.17)
Saccade endpoint accuracy (°)	2.58 (1.08)	2.86 (1.07)	2.81 (0.934)	3.41 (0.882)
Saccade endpoint variability (°)	1.69 (1.00)	1.79 (0.799)	1.60 (0.586)	1.78 (0.715)

the error. Additionally, we calculated an absolute error vector to quantify the magnitude of saccade endpoint accuracy. We calculated the root mean square distance (in degrees of visual angle) between the first fixation and the actual target location using the horizontal and vertical error values described above. We also investigated the within-participant variance of saccade endpoint accuracy by taking the within-participant standard deviation of the accuracy. Small standard deviations would be interpreted as consistent motor planning.

A mixed-model 2×2 repeated measures ANOVA was used to identify condition (within participants) and age (between participants) differences, along with possible interactions for all dependent measures. Where effect size could be calculated, either a partial eta-squared (h_p^2) or a Cohen's d -value is reported in the results. Statistical analysis was performed using SPSS 19.0 (SPSS Inc, Chicago, IL). The level of significance for all statistical tests was set at 0.05.

3. Results

All dependent measures demonstrated significant age effects for the easy and hard conditions. Means and standard deviations for all measures from both younger and older participants and across conditions are presented in Table 1.

3.1. Motor Attention Domain. Significant age effects were observed for target selection error rates, reaction time, saccade endpoint accuracy, and saccade endpoint variability.

3.1.1. Target Selection Errors. We had hypothesized that if older adults had difficulty suppressing the irrelevant saccade targets, the largest effects of task condition would be seen in the target selection error rate and not in measures of saccade endpoint accuracy or reaction time. Participants in both age groups did not make many target selection errors when only one saccade direction was required for the task (easy condition), although even in this condition older adults made slightly more errors (2%). However, older adults made 14% more target selection errors than their younger counterparts when the number of possible saccade targets increased between conditions (condition main effect $F(1, 37) = 162.980, P < 0.001, h_p^2 = 0.815$; age main effect $F(1, 37) = 7.361, P = 0.010, h_p^2 = 0.166$; condition \times age interaction $F(1, 37) = 4.433, P = 0.042, h_p^2 = 0.107$; Figure 2(a)). This increase in the initial target selection error rate in older adults was not related to working memory as participants

did ultimately perform a saccade to the correct location even though peripheral letters were not present during data collection (Figure 1(d)). These results are consistent with older adults having more difficulty suppressing irrelevant saccade targets, and/or more difficulty determining task context, after the visual cue was identified than the younger participants.

3.1.2. Saccade Endpoint Accuracy. We also wanted to determine the level of difficulty older adults had with the selection of the correct saccade path. We predicted that older adults would be as accurate and consistent as younger adults in selecting saccade targets in the easy condition, but not in the hard condition. When evaluating the overall magnitude of the error of the first saccade endpoint, all participants made greater errors in the hard condition than the easy condition ($F(1, 37) = 5.459, P = 0.025, h_p^2 = 0.129$; Figure 2(b)). Interestingly, the main effect of age was not significant ($F(1, 37) = 2.310, P = 0.137, h_p^2 = 0.059$; age \times condition interaction $F(1, 37) = 0.488, P = 0.717, h_p^2 = 0.019$). However, post hoc analysis showed that the effect of task difficulty on saccade endpoint accuracy was driven by significantly worse saccade endpoint accuracy by the older adults in the hard condition compared to the easy condition (one-tailed paired t -test $t(19) = 1.939, P = 0.034, d = 0.720$) and worse accuracy of the older adults compared to the younger adults in the hard condition (one-tailed t -test $t(37) = 1.754, P = 0.044, d = 0.560$). Older adult accuracy in the easy condition was no different than the performance of the younger adults, showing that the mechanics of performing the saccade did not contribute to the change in accuracy in the hard condition. Also, we attribute changes in accuracy between task conditions in older adults to changes in motor attention rather than visual attention as visual attention load did not change. Although older adults were less accurate in the hard condition, they were no more variable in their saccade trajectories when compared to younger participants ($F(1, 37) = 0.049, P = 0.825, h_p^2 = 0.001$). Also, no effect of task difficulty was present in saccade endpoint variability ($F(1, 37) = 0.763, P = 0.388, h_p^2 = 0.020$; age \times condition interaction $F(1, 37) = 0.071, P = 0.792, h_p^2 = 0.002$).

3.1.3. Reaction Time. In this task, only the number of possible saccade targets changed between task conditions; thus changes in reaction time (the time between cue presentation and the initiation of eye movement) would presumably be due to motor planning differences. We predicted that older adults

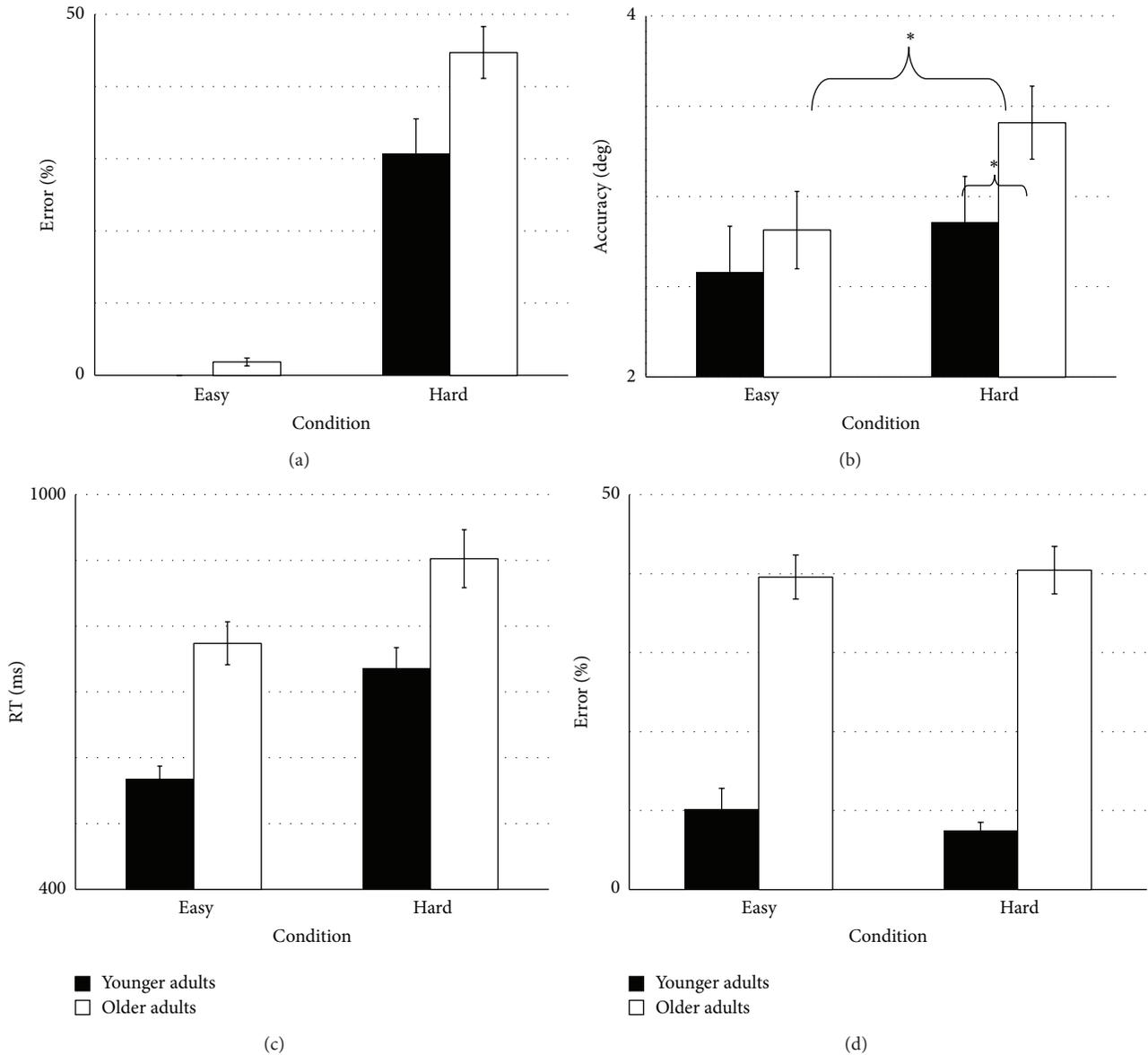


FIGURE 2: Effects of task condition and age on performance. (a) Both younger and older participants made more target selection errors in the hard condition compared to the easy condition. The older participants also made more target selection errors than their younger counterparts. (b) Mean magnitude of the saccade endpoint accuracy error relative to the target location. (c) Reaction time. Both main effects of condition and age were significantly different with no significant interaction present. (d) Older participants made significantly more visual perception errors (misses and false positives) than the younger participants in both conditions (represented along x -axis). All data are presented as mean \pm SEM.

would respond more slowly, and these age differences would be enhanced in the hard condition. In both age groups, reaction times for correct trials were significantly longer in the hard condition ($F(1, 37) = 38.201, P < 0.001, h_p^2 = 0.508$; Figure 2(c)), with older adults being significantly slower than the younger adults in both the hard and easy conditions ($F(1, 37) = 22.706, P < 0.001, h_p^2 = 0.380$; age \times condition interaction $F(1, 37) = 0.655, P = 0.423, h_p^2 = 0.017$).

We then calculated within-participant reaction time differences between the easy and hard conditions. In the easy task condition, participants knew the correct saccade location

without having to identify specific letter cues (e.g., “A” versus “B”). The participant would simply make the saccade when any target letter was identified. Thus, the reaction time in this scenario mostly reflects the time for visual perception and saccade execution. In the hard condition, the correct target letter had to be specifically identified (i.e., not only that a target letter was shown, but rather which target letter was shown), the correct mapping applied, and the correct target selected. The longer reaction time in the hard condition reflects the additional components to the visuomotor task. If true, subtracting the easy condition reaction time from

the hard condition reaction time would provide an index of the temporal cost for the additional steps. No significant differences existed between the younger and older participants on this index (younger: 167 ± 135 ms, older: 128 ± 161 ms; two-tailed Student's t -test $t(37) = -0.810$, $P = 0.423$, $d = 0.262$). A lack of a difference is most consistent with the Inhibitory Deficit Theory, which would predict no differences in RT between age groups.

We also compared reaction times between correct and incorrect trials for the two age groups to determine the extent to which participants of different ages may have used different strategies between successful and unsuccessful trials. Participants could have used a strategy of making an indiscriminant first saccade and then apply the stimulus-response mapping to eventually gaze at the correct target location. In this scenario, participants would have faster reaction times on incorrect trials. Conversely, correct trials could represent trials with high confidence of the mapping, leading to faster reaction times on the correct trials. Neither the younger adults (correct: 715 ± 101 ms, incorrect 673 ± 129 ms; paired two-tailed t -test $t(17) = 1.632$, $P = 0.121$, $d = 0.362$), nor the older adults (correct: 902 ± 192 ms, incorrect 844 ± 169 ms; paired two-tailed t -test $t(19) = 1.795$, $P = 0.086$, $d = 0.321$) demonstrated a significant difference in reaction times between correct and incorrect trials, indicating participants simply chose the incorrect target on error trials without employing different cognitive strategies.

3.2. Visual Attention Domain. All three theories of cognitive aging would predict an age effect for visual attention errors, with older adults performing worse on that component of the task. However, we did not anticipate any condition effect in visual attention errors as we did not manipulate visual attention load across conditions. Participants had to identify the same six letters regardless of the number of saccade targets, while the six peripheral targets remained present at all times. Thus, we did not anticipate any effect of condition on the visual attention error rate, which was consistent with our results ($F(1, 37) = 0.225$, $P = 0.638$, $h_p^2 = 0.006$). However, an effect of age was present. Older adults made 29% more errors in visual perception in the easy condition and 33% more errors in the hard condition than the younger adults ($F(1, 37) = 48.374$, $P < 0.001$, $h_p^2 = 0.567$; Figure 2(d)) with no significant interaction present (age \times condition interaction $F(1, 37) = 0.858$, $P = 0.360$, $h_p^2 = 0.023$). This age difference was not due to differences in visual acuity as all participants had to correctly identify the letters prior to the start of the study. Rather, the temporal constraints placed on the identification of the letters made identification difficult for the older participants. The types of errors made by older adults were also consistent across the two task conditions. Older adults made $5.49\% \pm 8.16\%$ false positives in the hard condition and $6.95\% \pm 10.26\%$ false positives in the easy condition (compared to younger adults with false positive rate of $0.79\% \pm 1.66\%$ in the hard condition and $1.94\% \pm 3.10\%$ in the easy condition). Older adults missed cue letters $34.94\% \pm 18.01\%$ of the time in the hard condition and $32.6\% \pm 14.01\%$ of the time in the easy condition (compared to 6.73%

TABLE 2: Relations among measures of attention for younger and older participants.

	VAE	VAE	VAE	VAE
VAE	—	0.426	0.041	-0.172
TSE	-0.452*	—	0.481*	-0.456*
SEA	0.165	0.229	—	-0.325
RT	0.577**	-0.625**	-0.194	—

Note. Correlations for younger participants ($n = 19$) are presented above the diagonal, and correlations for older participants ($n = 20$) are presented below the diagonal (VAE: visual attention errors (misses and false positives); TSE: target selection errors; SEA: saccade endpoint accuracy; and RT: reaction time).

*Correlation is significant at $P < 0.05$ (2-tailed).

**Correlation is significant at $P < 0.01$ (2-tailed).

$\pm 6.63\%$ in the hard condition and $8.29 \pm 9.32\%$ in the easy condition for younger adults).

3.3. Relations among Measures of Attention. Although we first considered each dependent measure individually to assess the relative contributions of distractor suppression, processing speed, and correct target selection to performance on the cued saccade task in younger and older adults, we were also interested in how these measures related to one another. In younger adults, increasing the attentional load during a cued saccade task in either the visual or motor domain negatively impacted performance within that specific domain without affecting the opposite one, indicating a functional dissociation of the two processes in this age group [38]. We performed correlations among the dependent measures separately for the younger and older participants to identify potential relations between the measures and the extent to which these relations differed by age group (Table 2). Age positively correlated with visual attention errors ($r = 0.519$ and $P = 0.019$) and reaction time ($r = 0.448$ and $P = 0.048$) in the older participant group. In this group, reaction time positively correlated with visual attention errors (false positives and misses; Table 2, below the diagonal); thus older participants who were more accurate in identifying cue letters also had the shortest reaction times. Conversely, older participants with the shortest reaction times had the highest target selection error rates (Table 2, below the diagonal). Visual attention errors and target selection errors were negatively correlated. This was an interesting finding because, in younger adults, target selection errors and visual attention errors were unrelated (Table 2, above the diagonal). The younger adults did not show a strong relation between visual attention errors and reaction time as the older adults did, but younger participants did show a strong relation among motor attention measures. Young participants who made fewer initial saccade target selection errors were also more accurate in saccade endpoints (Table 2, above the diagonal). Also in this group, changes in target selection error rate positively correlated with reaction time. In sum, the relations among dependent measures varied greatly between younger and older performers and may shed some light on alternate strategies used by the different age groups.

4. Discussion

The present study evaluated visual and motor attention contributions to a cued saccade task, under temporal constraints, while varying motor attention load. Although the use of a cued saccade task to evaluate visual and motor attention is not new [44, 45], the approach of comparing and contrasting measures representing both visual and motor domains across age groups, to our knowledge, is novel. Typically, the visual component of the task covaries with motor components of the task, which may confound interpretation of results. In the present experiment, the visual attention load was maintained across both conditions so that any changes in performance could be attributed to changes in attention-mediated motor planning. We found that older adults demonstrated difficulty in both inhibiting irrelevant saccade targets and selecting correct saccade endpoints, but not slower processing, when the task was more complex.

4.1. Inefficient Selection of Task-Relevant, and Inhibition of Irrelevant, Motor Information by Older Adults. Behaviorally, it is oftentimes difficult to discern difficulties in selecting relevant information versus inhibiting irrelevant information. We had hypothesized that in the hard condition older participants would have proportionally greater difficulty in the motor component of the task than the younger participants (i.e., significant age by condition interaction), consistent with modality-specific difficulties in older adults [2, 36, 46] and in support of the Context Processing [26] and Inhibitory Deficit [29] Theories. This finding was observed in target selection errors and saccade endpoint accuracy. Few participants of any age made target selection errors in the easy condition in which one common saccade target was required for all six cue letters. However, older adults made significantly more incorrect initial saccades than the younger participants in the hard condition. This decrement in performance cannot be attributed to working memory errors or to difficulty in encoding task context, as older participants ultimately performed a saccade to the correct peripheral target after the initial incorrect saccade. However, this difficulty in initially selecting the correct saccade by the older adults could be attributed to difficulty in inhibiting saccades to incorrect targets [19, 29, 47]. Electrophysiological evidence in macaque has shown that as a decision to move to a particular location is made, activity coding the selected target increases and the activity related to the unselected movement decreases [48, 49]. This phenomenon has also been observed in the perceptual decision-making literature regarding saccade selection [50]. A number of authors have shown a parallel priming of motor responses during the sensory component of a task [51–53]. Presumably this preprocessing of movement contingencies allows for more efficient timing of movements. Difficulty in inhibiting undesired actions in older adults is robust, affecting arm reaching movements as well [37].

Changes in saccade endpoint accuracy between the easy and hard conditions also differed between young and old participants. We did not expect to find age-related differences in saccade endpoint accuracy in the easy condition, as older adults are as accurate as younger adults in simple saccade

tasks [19, 25]. However, older adults had a significant decline in accuracy in the hard condition compared to the easy condition, and compared to the younger adults in the hard condition. Thus, when compared to younger adults, older adults have more difficulty with motor planning and execution when multiple movement options are available. Older adults may function better in less complex environments with fewer task components to attend [3, 4, 14].

4.2. Generalized Slowing in Older Adults. We had also predicted an age by condition effect in reaction time, which was not the case. Older adults were slower than younger adults in both conditions; however no interaction was present, a result consistent with others [34]. The presence of a generalized slowing of responses in older adults supports the Processing-Speed Theory of cognitive aging [20]. Correlations between age and reaction times for the older adults were 0.45 for both task conditions, similar to other reported relations between age and various speeded responses [54]. Assuming the easy condition represents a simple reaction time task (one response), the “cost” of having six choices for younger adults was not significantly different than the easy condition with one movement choice. Contrary to our results, Godefroy et al. [2] found a difference in “decisional cost” between younger and older adults between a simple and choice reaction time task. We may not have observed this effect due to the slower performance of the older adults on the easy condition. Older adults could have used two different strategies for the two conditions. They may have chosen accuracy over speed in the easy condition [55], yet chose speed over accuracy in the hard condition. In this case, reaction times for older adults might not significantly change between conditions as we found in the present study, yet target selection errors and saccade endpoint accuracy would be affected. The lack of difference in reaction times between the easy and hard conditions in the older adults may have also been due to the older adults not “preparing” for the upcoming saccade while waiting for the cue presentation in the easy condition. In this condition, the saccade was always to the same location regardless of the cue, so preparing the motor system for a saccade to the single target location would have been a useful strategy. Younger adults may have “preset” the motor system to make the single saccade and then focused on identifying when a cue target letter was shown, irrespective of which cue was shown. Parallel preparation of responses during the accumulation of sensory information occurs in young participants [51, 53, 56]. Older adults may have instead focused on perceiving the cue letter prior to considering the correct saccade direction, with a cost of longer reaction times. In tasks in which participants are correctly pre-cued for the effector to use or future location of a stimulus most of the time, older adults typically do not “use” this pre-cue information, leading at times to great accuracy than younger adults [35], but also to longer reaction times [2, 14, 17, 32, 35].

The increase in visual attention errors with age also supports the view of a general slowing of mental processing as a component of cognitive aging. We attribute the differences

in visual perception errors between younger and older participants to difficulty in visual information processing rather than to declines in visual acuity. All participants were able to correctly identify target letters during training when no time constraints were imposed. Speed of visual perception has been shown to be similar between younger and older age groups based on evoked resting potentials [18]. Cerella [57] tested young and old participants on letter identification (4 possible letters) at various eccentricities and letter sizes. Older adults had less than a 10 ms delay in letter recognition with letters presented in the center of the screen, using letters slightly smaller than the ones used in the present study. For both age groups in that study, however, identification took longer than 250 ms. In our study, each target letter was only shown for 250 ms. In younger participants, a similar task with four cue letters can be performed with rapid serial visual presentation (RSVP) durations as low as 50 ms with less than 40% errors and in the same task at 125 ms RSVP durations with less than 10% visual perception errors [38]. We piloted the current experiment in three older adults at shorter RSVP times prior to data collection, and none of the participants were able to perform the task with letter presentation durations less than 250 ms. This need for slowing of the central RSVP may be indicating an inability to ignore other letters while attempting to identify the cue letter, or longer letter durations needed for information processing to identify the letter [2]. Older adults have more misses and false positives (both measures accounted for in our visual perception error rate) when performing a dual task when compared to younger participants [14], supporting the premise that older adults have difficulty inhibiting extraneous information.

4.3. Modality-Specific Changes Associated with Aging. Consistent with the notion of modality-specific slowing, previous studies have reported weak correlations between sensory and motor measures of performance in older adults [2, 36]. In the current study, we observed inverse or weak correlations between our visual and motor dependent measures. Older adults who performed best on the visual component of the task performed the worst on target selection for the initial saccade following cue letter presentation, which was the opposite for younger adults. Younger participants who performed best on the visual component of the task also performed the best on initial saccade target selection, although this relation was not significant. Two possibilities exist to explain these age differences. In younger adults, challenging one attentional system (visual or motor) has no effect on the other [38], indicating separate modality-specific attentional resources. However, in older adults, the inverse relation between performances on the visual component of the task versus target selection errors could be interpreted as evidence for shared attentional resources in this population. Older adults may allocate attentional resources differently to specific systems (e.g., visual, motor) as a compensation mechanism. Diminished attentional selection would negatively affect a person's ability to inhibit the noncue letters in the visual component of the task (temporal distractor suppression) and the incorrect targets in the motor component of the task.

A second possible explanation for the inverse relationship in the older adults may be due to slower processing speeds for selecting the correct visual cue and the correct application of the stimulus-response mapping. Temporal constraints of the task (250 ms duration of letter presentation in the RSVP) may have limited the overall time to complete a trial. This would have forced participants who spent more time to correctly perceive the cue letter to have to more rapidly select the correct saccade target, which may have led to more target selection errors. Conversely, other older participants may have made a more rapid decision on the presented cue letter, leading to more perceptual errors, but allowing for more time to select the correct target. In support of the second alternative, older adults had a positive correlation between visual perception errors and reaction time. Also, older participants who potentially took longer to select the visual cue, leading to greater visual attention errors, also had longer reaction times on correct trials.

5. Conclusions

The motor attention load-specific slowing in older adults suggests an attentional capacity issue related to the distribution of attentional resources across visual and motor modalities. In older adults, the consequences of increased motor planning complexity (e.g., increasing the number of possible saccade targets) are difficulty inhibiting unwanted movements and decreased eye movement accuracy. These changes may have an impact on an older adult's ability to function in a complex environment and may inform the development of effective techniques to maximize functional independence. Our results highlight the contributions of three different theories of cognitive aging on changes to attentional processes. Further study is required to fully assess the effect of potential differences in attentional capacity in younger and older adults on visuomotor tasks.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

References

- [1] B. U. Forstmann, M. Tittgemeyer, E.-J. Wagenmakers, J. Derfuss, D. Imperati, and S. Brown, "The speed-accuracy tradeoff in the elderly brain: a structural model-based approach," *Journal of Neuroscience*, vol. 31, no. 47, pp. 17242–17249, 2011.
- [2] O. Godefroy, M. Roussel, P. Desprez, V. Quaglino, and M. Boucart, "Age-related slowing: perceptuomotor, decision, or attention decline?" *Experimental Aging Research*, vol. 36, no. 2, pp. 169–189, 2010.
- [3] C. D. Hall, K. V. Echt, S. L. Wolf, and W. A. Rogers, "Cognitive and motor mechanisms underlying older adults' ability to divide attention while walking," *Physical Therapy*, vol. 91, no. 7, pp. 1039–1050, 2011.
- [4] M. Inzitari, M. Baldereschi, A. di Carlo et al., "Impaired attention predicts motor performance decline in older community-dwellers with normal baseline mobility: results from the Italian

- Longitudinal Study on Aging (ILSA)," *Journals of Gerontology A: Biological Sciences and Medical Sciences*, vol. 62, no. 8, pp. 837–843, 2007.
- [5] N. Aksan, S. W. Anderson, J. D. Dawson, A. M. Johnson, E. Y. Uc, and M. Rizzo, "Cognitive functioning predicts driver safety on road tests 1 and 2 years later," *Journal of the American Geriatrics Society*, vol. 60, no. 1, pp. 99–105, 2012.
 - [6] R. Holtzer, R. Friedman, R. B. Lipton, M. Katz, X. Xue, and J. Verghese, "The relationship between specific cognitive functions and falls in aging," *Neuropsychology*, vol. 21, no. 5, pp. 540–548, 2007.
 - [7] W. James, *The Principles of Psychology*, vol. 1, Holt, New York, NY, USA, 1890.
 - [8] J. C. Johnston, R. S. McCann, and R. W. Remington, "Chronometric evidence for two types of attention," *Psychological Science*, vol. 6, no. 6, pp. 365–370, 1995.
 - [9] W. T. Maddox and J. L. Dodd, "Separating perceptual and decisional attention processes in the identification and categorization of integral-dimension stimuli," *Journal of Experimental Psychology: Learning Memory and Cognition*, vol. 29, no. 3, pp. 467–480, 2003.
 - [10] M. E. Goldberg and M. A. Segraves, "Visuospatial and motor attention in the monkey," *Neuropsychologia*, vol. 25, no. 1, pp. 107–118, 1987.
 - [11] H. Pashler, "Shifting visual attention and selecting motor responses: distinct attentional mechanisms," *Journal of Experimental Psychology: Human Perception and Performance*, vol. 17, no. 4, pp. 1023–1040, 1991.
 - [12] M. F. S. Rushworth, P. D. Nixon, S. Renowden, D. T. Wade, and R. E. Passingham, "The left parietal cortex and motor attention," *Neuropsychologia*, vol. 35, no. 9, pp. 1261–1273, 1997.
 - [13] E. Symes, G. Ottoboni, M. Tucker, R. Ellis, and A. Tessari, "When motor attention improves selective attention: the dissociating role of saliency," *Quarterly Journal of Experimental Psychology*, vol. 63, no. 7, pp. 1387–1397, 2010.
 - [14] M. Hahn, N. Wild-Wall, and M. Falkenstein, "Age-related differences in performance and stimulus processing in dual task situation," *Brain Research*, vol. 1414, pp. 66–76, 2011.
 - [15] S. M. Kosslyn, H. D. Brown, and I. E. Dror, "Aging and the scope of visual attention," *Gerontology*, vol. 45, no. 2, pp. 102–109, 1999.
 - [16] M. P. Milham, K. I. Erickson, M. T. Banich et al., "Attentional control in the aging brain: insights from an fMRI study of the stroop task," *Brain and Cognition*, vol. 49, no. 3, pp. 277–296, 2002.
 - [17] T. Curran, A. Hills, M. B. Patterson, and M. E. Strauss, "Effects of aging on visuospatial attention: an ERP study," *Neuropsychologia*, vol. 39, no. 3, pp. 288–301, 2001.
 - [18] N. Wild-Wall, M. Falkenstein, and J. Hohnsbein, "Flanker interference in young and older participants as reflected in event-related potentials," *Brain Research*, vol. 1211, pp. 72–84, 2008.
 - [19] J. A. Sweeney, C. Rosano, R. A. Berman, and B. Luna, "Inhibitory control of attention declines more than working memory during normal aging," *Neurobiology of Aging*, vol. 22, no. 1, pp. 39–47, 2001.
 - [20] T. A. Salthouse, "The processing-speed theory of adult age differences in cognition," *Psychological Review*, vol. 103, no. 3, pp. 403–428, 1996.
 - [21] T. A. Salthouse, "Aging and measures of processing speed," *Biological Psychology*, vol. 54, no. 1–3, pp. 35–54, 2000.
 - [22] J. Cerella, "Information Processing Rates in the Elderly," *Psychological Bulletin*, vol. 98, no. 1, pp. 67–83, 1985.
 - [23] J. W. Spooner, S. M. Sakala, and R. W. Baloh, "Effect of aging on eye tracking," *Archives of Neurology*, vol. 37, no. 9, pp. 575–576, 1980.
 - [24] G. D. Paige, "Senescence of human visual-vestibular interactions: smooth pursuit, optokinetic, and vestibular control of eye movements with aging," *Experimental Brain Research*, vol. 98, no. 2, pp. 355–372, 1994.
 - [25] L. A. Abel and J. Douglas, "Effects of age on latency and error generation in internally mediated saccades," *Neurobiology of Aging*, vol. 28, no. 4, pp. 627–637, 2007.
 - [26] T. S. Braver, D. M. Barch, B. A. Keys et al., "Context processing in older adults: evidence for a theory relating cognitive control to neurobiology in healthy aging," *Journal of Experimental Psychology: General*, vol. 130, no. 4, pp. 746–763, 2001.
 - [27] T. S. Braver, A. B. Satpute, B. K. Rush, C. A. Racine, and D. M. Barch, "Context processing and context maintenance in healthy aging and early stage dementia of the Alzheimer's type," *Psychology and Aging*, vol. 20, no. 1, pp. 33–46, 2005.
 - [28] L. Hasher, E. R. Stoltzfus, R. T. Zacks, and B. Rypma, "Age and inhibition," *Journal of Experimental Psychology: Learning, Memory, and Cognition*, vol. 17, no. 1, pp. 163–169, 1991.
 - [29] L. Hasher and R. T. Zacks, "Working memory, comprehension, and aging: a review and a new view," in *The Psychology of Learning and Motivation*, G. H. Bower, Ed., pp. 193–225, Academic Press, New York, NY, USA, 1988.
 - [30] R. Cabeza, S. M. Daselaar, F. Dolcos, S. E. Prince, M. Budde, and L. Nyberg, "Task-independent and task-specific age effects on brain activity during working memory, visual attention and episodic retrieval," *Cerebral Cortex*, vol. 14, no. 4, pp. 364–375, 2004.
 - [31] C. L. Folk and W. J. Hoyer, "Aging and shifts of visual spatial attention," *Psychology and Aging*, vol. 7, no. 3, pp. 453–465, 1992.
 - [32] D. J. Madden, J. Spaniol, W. L. Whiting et al., "Adult age differences in the functional neuroanatomy of visual attention: a combined fMRI and DTI study," *Neurobiology of Aging*, vol. 28, no. 3, pp. 459–476, 2007.
 - [33] C. Pesce, L. Guidetti, C. Baldari, A. Tessitore, and L. Capranica, "Effects of aging on visual attentional focusing," *Gerontology*, vol. 51, no. 4, pp. 266–276, 2005.
 - [34] D. Bunce, S. W. S. MacDonald, and D. F. Hultsch, "Inconsistency in serial choice decision and motor reaction times dissociate in younger and older adults," *Brain and Cognition*, vol. 56, no. 3, pp. 320–327, 2004.
 - [35] A. Sterr and P. Dean, "Neural correlates of movement preparation in healthy ageing," *European Journal of Neuroscience*, vol. 27, no. 1, pp. 254–260, 2008.
 - [36] J. A. Anguera and A. Gazzaley, "Dissociation of motor and sensory inhibition processes in normal aging," *Clinical Neurophysiology*, vol. 123, no. 4, pp. 730–740, 2012.
 - [37] J. R. Jennings, D. N. Mendelson, M. S. Redfern, and R. D. Nebes, "Detecting age differences in resistance to perceptual and motor interference," *Experimental Aging Research*, vol. 37, no. 2, pp. 179–197, 2011.
 - [38] W. E. Huddleston, M. S. Aleksandrowicz, A. Yufa, C. R. Knurr, J. R. Lytle, and M. M. Puissant, "Attentional resource allocation during a cued saccade task," *Acta Psychologica*, vol. 144, no. 1, pp. 112–120, 2013.
 - [39] B. E. Ernest, W. E. Huddleston, and K. G. Keenan, "Younger and older adults have different visual and motor attention capabilities," in *Proceedings of the Annual Society for Neuroscience*

- Meeting, Neuroscience Meeting Planner, New Orleans, La, USA, 2012.
- [40] M. F. S. Rushworth, A. Ellison, and V. Walsh, "Complementary localization and lateralization of orienting and motor attention," *Nature Neuroscience*, vol. 4, no. 6, pp. 656–661, 2001.
- [41] B. Hommel and W. X. Schneider, "Visual attention and manual response selection: distinct mechanisms operating on the same codes," *Visual Cognition*, vol. 9, no. 4-5, pp. 392–420, 2002.
- [42] W. E. Huddleston, K. G. Keenan, and B. E. Ernest, "Relations among visual strategies, force fluctuations, and attention during a force-matching task," *Perceptual and Motor Skills*, vol. 117, no. 3, pp. 775–800, 2013.
- [43] R. J. van Beers, "The sources of variability in saccadic eye movements," *Journal of Neuroscience*, vol. 27, no. 33, pp. 8757–8770, 2007.
- [44] A. V. Belopolsky and J. Theeuwes, "When are attention and saccade preparation dissociated?" *Psychological Science*, vol. 20, no. 11, pp. 1340–1347, 2009.
- [45] M. Zhao, T. M. Gersch, B. S. Schnitzer, B. A. Doshier, and E. Kowler, "Eye movements and attention: the role of pre-saccadic shifts of attention in perception, memory and the control of saccades," *Vision Research*, vol. 74, pp. 40–60, 2012.
- [46] A. Gazzaley, J. W. Cooney, J. Rissman, and M. D'Esposito, "Top-down suppression deficit underlies working memory impairment in normal aging," *Nature Neuroscience*, vol. 8, no. 10, pp. 1298–1300, 2005.
- [47] M. K. Healey, K. L. Campbell, and L. Hasher, "Chapter 22 Cognitive aging and increased distractibility: costs and potential benefits," *Progress in Brain Research*, vol. 169, pp. 353–363, 2008.
- [48] P. Cisek, "Cortical mechanisms of action selection: the affordance competition hypothesis," *Philosophical Transactions of the Royal Society B: Biological Sciences*, vol. 362, no. 1485, pp. 1585–1599, 2007.
- [49] P. Cisek and J. F. Kalaska, "Simultaneous encoding of multiple potential reach directions in dorsal premotor cortex," *Journal of Neurophysiology*, vol. 87, no. 2, pp. 1149–1154, 2002.
- [50] J. I. Gold and M. N. Shadlen, "Representation of a perceptual decision in developing oculomotor commands," *Nature*, vol. 404, no. 6776, pp. 390–394, 2000.
- [51] C. S. Chapman, J. P. Gallivan, D. K. Wood, J. L. Milne, J. C. Culham, and M. A. Goodale, "Reaching for the unknown: multiple target encoding and real-time decision-making in a rapid reach task," *Cognition*, vol. 116, no. 2, pp. 168–176, 2010.
- [52] A. W. Dromerick, C. E. Lang, R. L. Birkenmeier et al., "Very early constraint-induced movement during stroke rehabilitation (VECTORS): a single-center RCT," *Neurology*, vol. 73, no. 3, pp. 195–201, 2009.
- [53] J.-H. Song and K. Nakayama, "Hidden cognitive states revealed in choice reaching tasks," *Trends in Cognitive Sciences*, vol. 13, no. 8, pp. 360–366, 2009.
- [54] T. A. Salthouse, "Speed of behavior and its implications for cognition, in Handbook of the Psychology of Aging," J. E. Birren and K. W. Schaie, Eds., D. Van Nostrand, New York, NY, USA, 1985.
- [55] G. A. Smith and N. Brewer, "Slowness and age: speed-accuracy mechanisms," *Psychology and Aging*, vol. 10, no. 2, pp. 238–247, 1995.
- [56] C. W. Eriksen and D. W. Schultz, "Information processing in visual search: a continuous flow conception and experimental results," *Perception and Psychophysics*, vol. 25, no. 4, pp. 249–263, 1979.
- [57] J. Cerella, "Age-related decline in extrafoveal letter perception," *Journals of Gerontology*, vol. 40, no. 6, pp. 727–736, 1985.

Research Article

Using Eye Tracking to Assess Reading Performance in Patients with Glaucoma: A Within-Person Study

Nicholas D. Smith, Fiona C. Glen, Vera M. Mönter, and David P. Crabb

Division of Optometry and Visual Science, School of Health Sciences, City University London, London EC1V 0HB, UK

Correspondence should be addressed to David P. Crabb; david.crabb.1@city.ac.uk

Received 18 December 2013; Accepted 12 March 2014; Published 5 May 2014

Academic Editor: Stefanie I. Becker

Copyright © 2014 Nicholas D. Smith et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Reading is often cited as a demanding task for patients with glaucomatous visual field (VF) loss, yet reading speed varies widely between patients and does not appear to be predicted by standard visual function measures. This *within-person* study aimed to investigate reading duration and eye movements when reading short passages of text in a patient's worse eye (most VF damage) when compared to their better eye (least VF damage). Reading duration and saccade rate were significantly different on average in the worse eye when compared to the better eye ($P < 0.001$) in 14 patients with glaucoma that had median (interquartile range) between-eye difference in mean deviation (MD; a standard clinical measure for VF loss) of 9.8 (8.3 to 14.8) dB; differences were not related to the size of the difference in MD between eyes. Patients with a more pronounced effect of longer reading duration on their worse eye made a larger proportion of "regressions" (backward saccades) and "unknown" EMs (not adhering to expected reading patterns) when reading with the worse eye when compared to the better eye. A between-eye study in patients with asymmetric disease, coupled with eye tracking, provides a useful experimental design for exploring reading performance in glaucoma.

1. Introduction

Glaucoma is a leading cause of visual impairment and affects a significant number of the elderly populations [1]. The conventional view of vision loss in glaucoma suggests disruption of peripheral vision and minimal impact on tasks that require good central vision, like reading. However, patients with glaucoma regularly self-report difficulties with reading [2–6]. Furthermore, evidence is emerging from experimental studies showing that some patients with glaucoma have impaired reading performance when compared to their visually healthy peers. These impairments are particularly evident for patients with advanced or bilateral visual field loss [7–9] when reading small size text [10]; when reading text at low contrast [11]; or when reading for sustained periods of time [12]. However, not all patients displayed reduced reading speeds in these studies, with some patients appearing to be much more affected than others. A limiting feature of the studies that have generated these results is that reading speed, as an experimental outcome measure, is subject to much between-person variability: it is very difficult to isolate

the impact of the glaucomatous visual field loss from all the other factors, such as age, visual acuity, and cognitive and reading ability, that might contribute to slower reading. Furthermore, differences in eye movement patterns may also influence reading speed. Eye movements supplement information about how long a person takes to read, by giving insight into *how* they are reading. Previous research has considered eye movements in patients with glaucoma compared to visually healthy controls when carrying out a number of other visual tasks, such as visual search [13], face recognition [14], viewing of photographs [15], and watching of driving videos [16]. In these studies, patients sometimes displayed different eye movement patterns on average to controls, although it was suggested that some patients may "adapt" their eye movements in ways that enable them to function better in the task [13, 14]. However, the case-control design that featured in all these studies again made it difficult to discern the nature of the contribution of visual field loss to changes in eye movement behaviour.

As yet no studies have considered performing a *within-person*, or between-eye, reading study to examine the impact

of glaucomatous visual field loss on reading performance: the idea here would be that a more damaged eye could be compared with a less affected fellow eye. An experimental design such as this might proffer advantages over studies comparing patients to controls, where large numbers of people are needed to demonstrate effects. In addition, experimental studies of reading speed in glaucoma have been constrained to those where reading “out loud” or timed silent reading is simply the main, or only, outcome measure. One recent study incorporated eye tracking when investigating reading performance in glaucoma [17]: the findings of that case-control study, which measured the maximum and minimum sizes of eye movements made during a reading task by patients compared to controls, hinted that glaucoma may lead to some alterations in fixation behaviour. However, to date, no studies have used an eye tracker to measure more task-specific saccades (i.e., rapid eye movements occurring between locations on the text) to tease out the effects that might result from glaucomatous visual field loss whilst reading short passages of text.

In this study, we explore the usefulness of comparing monocular reading performance in patients with asymmetric glaucomatous visual field loss. The study measures reading performance using eye tracking whilst participants silently read very short passages of text. Our main hypothesis is that patients will take longer to read short passages of text in what is considered to be their worse eye (most visual field damage) when compared to their better eye (least visual field damage); we aim to do this in just a small sample of patients in order to demonstrate the effectiveness of the experimental design. We also, as a secondary aim, test the idea of determining different types of reading-specific saccadic eye movements, in an automated fashion, specifically eye movements that occur in a forward direction (forward saccades), saccades that “backtrack” over previously read text (regressions), those that occur between the end of one line and the beginning of the next (line change saccades), and eye movements that do not fit expected patterns (unknown saccades). Next we investigate if any of these measurements from this automated approach are associated with the size of between-eye deficits in standard measures of visual function.

2. Methods

Participants were recruited from a database of patients that had taken part in previous studies conducted at City University London [13, 18]. All patients had a clinical diagnosis of primary open angle glaucoma and had no other ocular diseases. Patients were contacted if they had previously presented with asymmetric visual field loss between eyes as measured using a central 24-2 SITA Standard Test on the Humphrey Visual Field Analyzer (HFA, Carl Zeiss Meditec, CA, USA). This was quantified by considering the HFA mean deviation (MD); this summary measure expresses the average reduction in the visual field relative to a group of visually healthy age-matched observers [19]. Participants were only invited to the study if the MD differed by more than 6 dB between eyes. This value represents a clinically significant

difference as used in staging schemes for visual field severity [20].

The study was approved by the Ethics Committee for the School of Health Sciences, City University London. All participants gave their informed consent and the study conformed to the Declaration of Helsinki.

2.1. Standard Vision Testing. Fourteen patients were recruited and all testing was carried out on one day. Visual acuity (VA) as measured with the Early treatment diabetic retinopathy study (ETDRS) chart and contrast sensitivity as measured with the Pelli-Robson chart (PR Log CS) were assessed monocularly. Astigmatic error was less than ± 2.5 dioptres in all those recruited. Visual field tests (central 24-2 and 10-2 SITA Standard) were conducted in each eye using a HFA. On testing (central 24-2), two of the 14 patients had a between-eye MD difference of less than 6 dB (4.7 and 4.8 dB). We decided that these patients should still be included in the study. From this point we define the patient’s eye with the worse VF damage (worse MD) to be the “worse eye” and the fellow eye to be the “better eye.”

The reading experiment was performed on a 56 cm CRT computer monitor displaying at a resolution of 1600 by 1200 pixels and a refresh rate of 100 Hz (Iiyama Vision Master PRO 514, Iiyama Corporation, Tokyo, Japan). Participants were seated (with a head rest) in front of the computer screen. Each participant was fitted with a set of trial frames with the appropriate refractive correction. One eye was randomly selected and then occluded by inserting a blackout lens into the trial frames. Participants were then presented with 50 different texts (trials) on the screen, one at a time, and were asked to silently read them “as quickly and accurately as possible.” Once the participants had read the 50 texts, they had a short break before repeating the task using their alternate eye with 50 novel texts. Participants read the same 100 texts but in a randomised order. Each text consisted of one sentence, distributed over two lines, using the “Courier New” font at size 38 in which each letter subtended a maximum height of 0.75° visual angle and a constant width of 0.6° . The standardised passages of text had an average Flesch-Kincaid readability score of 4.6 and were the same as those used by Kabanarou and Rubin [21]. The background brightness was 33.4 cd/m^2 and the text was displayed at 0.04 cd/m^2 . Each paragraph subtended 21° width and 3° in height.

Eye movements were recorded simultaneously during the reading task using an EyeLink 1000 (SR Research Ltd., Mississauga, Ontario, Canada) which was set to record the participant’s eye location at 1000 Hz. It is claimed that the EyeLink 1000 measures at an average accuracy of better than 0.5° . The saccade detection thresholds were defined by a velocity greater than $30^\circ/\text{s}$ and acceleration above $8000^\circ/\text{s}^2$. Before the study commenced, a calibration was performed and had to be classified as a “good” standard as set by the instrument. Furthermore, between each trial (each displayed sentence) a drift check was performed and, if a substantial drift had occurred, a recalibration would be carried out.

2.2. Analysis of Eye-Tracking Data. To prepare the eye movement data for analysis, we developed a novel preprocessing technique. These methods adjusted for calibration errors in the eye tracking and ensured that only those saccades relevant to the reading task were included. Secondly, we report a novel method of classifying reading-specific eye movements according to their saccade type, that is, whether they occurred from left to right (forward saccade), right to left (regression), or between lines (line change) or did not conform to expected reading patterns (unknown saccade). We report both of these methods here as they may be relevant to other studies using eye tracking to measure reading performance. Note that the techniques described below do not require information about the specific content of the underlying text, such as details of the words and characters, but only the locations of the start and end of the text.

2.3. Preprocessing. Data from the eye tracker was used to determine reading duration for each trial in addition to identifying the key eye movement patterns made whilst reading the texts. The eye tracker was running before the display of each text in order to ensure that all eye movements were recorded, meaning that it was highly likely that some additional eye movements were made prior to beginning to read each sentence that were irrelevant to the task. Furthermore, the drift correction carried out before each trial meant that the participant always began the trial by fixating in the middle of the screen, therefore introducing bias into subsequent eye movement recordings. It was therefore necessary to pinpoint the exact points at which the person actually began reading the sentence and the point at which they finished reading. Use of an automatic real-time start and end point has the potential to misidentify when the person started or finished reading, as this technique uses fixed points on the screen and therefore assumes perfect calibration of the eye tracker. To address this issue, a novel “preprocessing” method was therefore implemented and is reported in detail here because it may be of use in other eye-tracking experiments. Some examples of preprocessed scanpaths are shown in Figure 1(a), showing additional saccades that occurred before and after the patient read the passage.

The first stage of the preprocessing algorithm attempted to correct any rotational errors in the eye movement data. As the text was displayed centrally, small errors in edge calibration were not of huge concern for this particular task; however inspection of scanpaths revealed that data sometimes appeared to be rotated along the centre. To correct this, it was assumed that all small saccades running $\pm 20^\circ$ along the horizontal (approximation of reading between words) should be corrected to correspond with the angle of the text (average angle of horizontal or 0°). Therefore, the circular median of all these $\pm 20^\circ$ angles of the saccades was calculated per trial, and all saccades were rotated (corrected) by this amount. Visual analysis of scanpaths also confirmed that, on being first presented with a text, participants sometimes made several involuntary eye movements at locations on the screen that were irrelevant to the task itself, before adjusting their gaze position so that they could start reading from

the beginning of the sentence. In order that the analysis would only include those eye movements that were relevant to the task, an automated procedure was developed that determined which eye movements coincided with the text's start and end location, thereby filtering out all other irrelevant eye movements. This process involved a series of steps to identify the start and end point locations signalling the start and end point of reading each text. The standard preset SR Research EyeLink parser (edf2asc) results in sharp downward movements being recorded at the point just before the pupil disappears (i.e., during a blink). Sharp downward saccades do not correspond with reading, so these were identified and excluded specifically any saccade with an amplitude $>6^\circ$ and with an angle of between 250° and 290° . Next, we aimed to detect the starting point of the saccade nearest to the first word of the text and the end point of the saccade closest to the final word of the text. However, this procedure was complicated by the fact that the text was rectangular in shape, with the height being substantially smaller in size than the width, a factor that would bias end point detection. For instance, the end point of a saccade made at the end of the first line of text (i.e., top right of the text) could be incorrectly classified as being nearer to the end of the text than a saccade made on the line below. We therefore normalised the locations of the saccade start and end points in order to make the axes equal. Specifically, the Euclidian distance from (0, 0) (top left) for each saccade start point and the distance from (1, 1) (bottom right) for each saccade end point were calculated, creating two sets of distances. An exponential weighting was applied to these two sets of distances. As such, the more the distance value increases the further the point is from the start location. The start saccade was then selected as the minimum distance from (0, 0) once the weights have been applied. The purpose of this procedure was to “encourage” the algorithm to select the first element in the set as the start of the sentence; however if, for example, the distance of the first saccade's start point is larger than another saccade, the smallest distance from (0, 0) will be selected to be the start point. To select the end point, the same process is applied to the saccade end points, except that the weights are reversed to “encourage” the algorithm to choose the final value. An example of this process can be seen by viewing Figure 1, Participant 1: when viewing the raw scanpath in column (a) and the processed path in column (b), it can be observed that two points are a similar distance from (0, 0). Using the weighting, the algorithm is “encouraged” to choose the earlier point as the cut-off.

The reading duration was then defined as the time between the start of the first saccade and the end of the final saccade (the rotation and the reading extraction stages are shown in Figure 1(b)). Once this was complete, any trial shorter than 500 ms or less than 2 saccades per second was excluded as it is likely the trial was of poor quality.

2.4. An Automated Algorithm for Classifying the Reading Eye Movements. Eye-tracking software typically expresses data with general measures, such as the size (amplitude) or location of each saccade. However, in tasks such as reading,

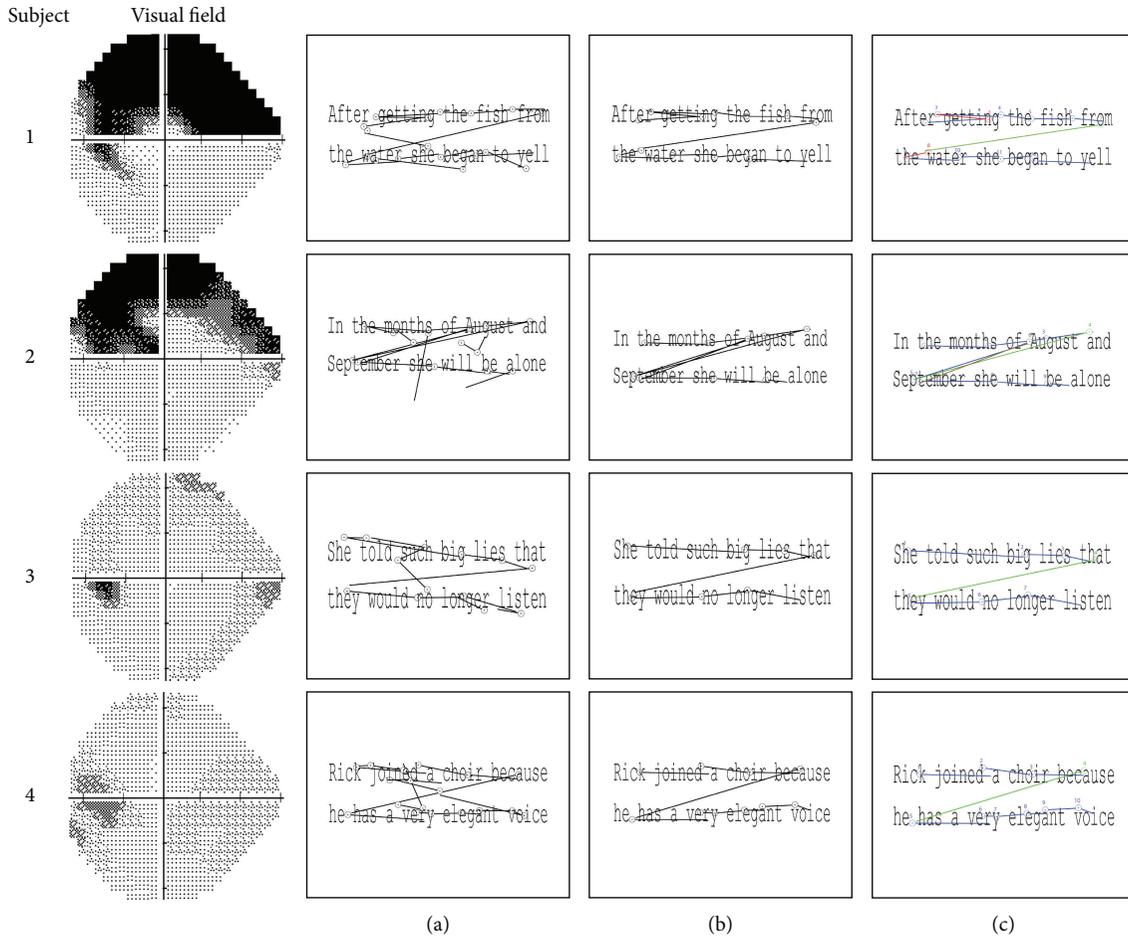


FIGURE 1: Four examples of scanpaths from four different glaucoma patients with their visual fields on the left. The start and end of each saccade are represented by a circle. Column (a) shows the original scanpaths made by the four participants reading the text. Column (b) shows the scanpath after the rotation has been corrected and reading-specific saccades have been extracted using the preprocessing algorithm. Column (c) shows the scanpath results from the clustering and classification algorithm. The number represents the order in which the saccades occurred, and the colours represent the classification that was attributed to them by the automated clustering algorithm (blue: forward saccade, green: between line saccade, red: regression, and brown: unknown).

the properties of each saccade will vary according to the demands of the task. For instance, when reading, a person will make small forward saccades (from left to right). It is also common for people to “backtrack” to reread previous sections (referred to as a “regression”). The properties of a saccade occurring between the end of one line and the beginning of the line below “line change” will again differ. Finally, readers may also make saccadic eye movements that do not conform to expected patterns (unknown). For this experiment we developed an automated data analysis algorithm for classifying the types of saccade made during the task. Again we provide details of this method because it may be of use in other eye-tracking experiments. At the centre of this technique is a Gaussian mixture model that mines for clusters in the data. This approach was only possible due to the type of texts used, where line length was consistent throughout, giving predictable expected saccade angles and similar amplitudes per person. Specifically, the information needed to classify the eye movements is the

amplitude (in degrees) of each saccade and the angle of each saccade, for all 50 sentences (trials) read by the “better eye” in each person. Next, it is necessary to acknowledge that the angle of eye movements occurring in a forward direction (from left to right) will occur at an *average* of 0° ; for example, some forward saccades could occur at 340° and others at 20° . The discrepancy between these values, whilst indicating the same saccade type, will subsequently influence the success of the classification algorithm by yielding two separate clusters that actually give the same information. To avoid having to use circular statistics to compensate for such a scenario, we adjusted all angle values by -90° , meaning that standard statistical methods could be used (Figure 2 shows an example of this procedure in action, whereby the blue forward saccades are now located at approximately 270°). The Netlab pattern analysis toolbox [22] Gaussian Mixture Model was then used to determine four clusters with predefined start points and priors (approximate proportion of points that each cluster contains). Using this method, eye movements made by

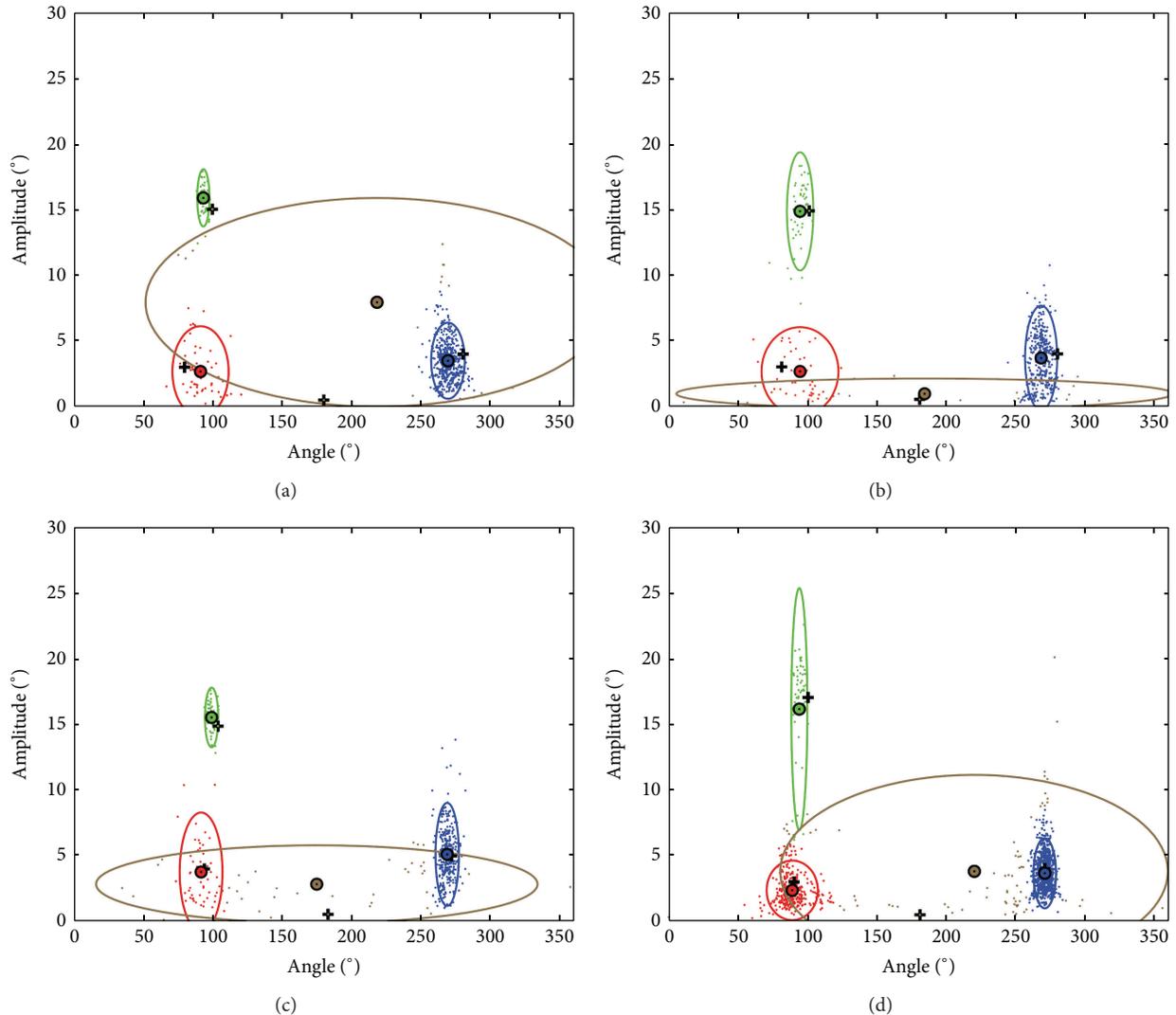


FIGURE 2: Scatterplots showing the amplitude and angle of saccades made across the 50 sentences for four examples of patients reading with the better eye. This data is used by the GMM to detect the four clusters within the data that represent the type of saccades made by the patients. The types of saccade are represented by the colours green (line change saccade), red (regression), blue (forward saccades), and brown (unknown). The black cross represents the start point for the GMM for each of the four clusters. The small circle represents the centre of the cluster and the surrounding larger ellipse represents a distribution of the data (calculated to be 2 standard deviations) captured by that cluster following the GMM process. Examples of outcomes from the GMM clustering are shown in Figure 1(c) for four different patients.

the better eye were grouped into four clusters, representing regressions, lines changes, forward saccades, and unknown saccades (Figure 2). Data yielded when reading with the worse eye was then classified in the same way, so that the proportion of saccades that fell into each of the four clusters could be calculated and compared.

2.5. Data Analysis. A linear mixed effects ANOVA was performed in R [23] using the linear and nonlinear mixed effects models (`nlme`) package to assess differences in the average reading duration and saccade rate between patients' worse and better eyes. A mixed effects model was chosen since different sentences were viewed by the worse and better eye. The random effect was set as the patient. The ANOVA

was performed to test the null hypothesis, for each response, that the means for the patients' worse and better eyes are the same.

For each eye we also calculated the percentage of eye movements that were automatically classed as the four types of saccade by the classification algorithm, namely, "forward saccades," "regressions (backwards saccades)," "between line (line change) saccades," and "unknown" across the 50 trials read by the better and worse eye, respectively. Statistical differences in these proportions between the worse and better eye were then assessed (Wilcoxon's test).

To investigate whether the magnitudes of the change in the key measured variables between eyes for each person were important, we next calculated the difference between

TABLE 1: Descriptive statistics (median and interquartile range [IQR]) for key measured variables in the worse and better eye.

	Better eye	Worse eye	Wilcoxon's <i>P</i> value
24-2 MD (dB, median, and IQR)	-3.4 (-5.4, -1.8)	-14.8 (-19.5, -9.5)	<0.001
10-2 MD (dB, median, and IQR)	-3.0 (-5.0, -2.2)	-13.7 (-17.2, -9.6)	<0.001
CS (Log CS, median, and IQR)	1.85 (1.65, 1.95)	1.65 (1.38, 1.95)	0.02
VA (log units, median, and IQR)	0.11 (-0.06, 0.16)	0.13 (0.06, 0.18)	0.43
Reading duration (seconds, median, and IQR)	2.2 (1.9, 2.5)	2.4 (2.0, 2.7)	
Saccade rate (sac/sec, median, and IQR)	4.6 (4.4, 4.8)	4.3 (3.9, 4.7)	

eyes for reading duration and saccade rate (worse eye minus better eye) to create novel “change” variables for each person. The differences between the worse and better eye were also calculated for all the measured visual function parameters (i.e., change in VF severity, VA, and CS between eyes) and then each of these resulting variables was compared to the changes in reading duration and saccade rate between eyes. Therefore, it could be determined whether larger reductions in visual field defect severity, contrast sensitivity, or visual acuity were related to a greater change in reading duration or eye movement behaviour when reading with the worse eye compared to the better eye.

Finally, differences in the median values for each of the identified eye movement types between the worse and better eye were calculated for each person; these were then compared to the change in reading duration per trial and saccade rate between eyes. Statistically significant associations were tested for using Spearman's rank correlation (ρ) and also using R [23].

3. Results

Fourteen patients with a median age of 69 (interquartile range [IQR] of 64 to 81) years took part in the study. All participants were Caucasian and 50% were men. The patients had a range of visual field defects, visual acuity, and contrast sensitivity measures (shown in Table 1). Participants' worse eyes and better eyes were, as expected, significantly different in 24-2 MD, 10-2 MD, and PR Log CS but not in visual acuity (Wilcoxon's test). For example, median (interquartile range) between-eye difference in 24-2 MD was 9.8 (8.3 to 14.8) dB. In 10 of the 14 patients, the “worse eye” was the right eye.

Table 1 also shows median (IQR) reading durations and saccade rates for the patients' worse and better eyes. A linear mixed effects ANOVA indicated that on average patients took longer to read the sentences with their worse eye than with their better eye and this was statistically significant ($F = 132.3$, $P < 0.001$). Furthermore, patients made fewer saccades per second, on average, when reading with their worse eye compared to their better eye ($F = 84.9$, $P < 0.001$).

When considering statistical associations for the *change* in reading duration and saccade rate between eyes, an average increase in reading duration in the worse eye compared to the better eye was closely related to an average decrease in the saccade rate in the worse eye compared to the better eye ($\rho: -0.83$; $P < 0.001$; Figure 3). In other words, those who took longer to read with their worse eye than the better eye also

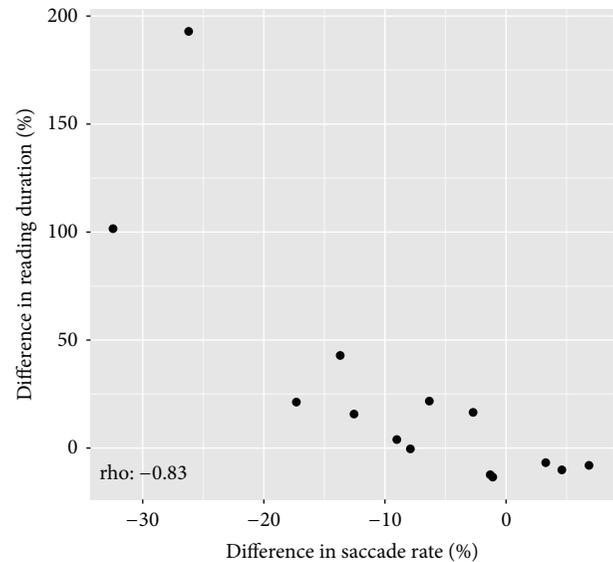


FIGURE 3: Scatterplots depicting the statistically significant relationships between the percentage difference in reading duration between the worse eye and the better eye and the percentage difference in saccade rate between the worse eye and the better eye.

had a greater reduction in saccade rate than those who read at a similar speed in each eye.

Associations for the change in visual function measures between the better and worse eye compared with the changes for reading duration and saccade rate are shown in Table 2. There was noteworthy association between change in saccade rate and the extent of difference in contrast sensitivity between the better and worse eye. So those with a greater reduction in contrast sensitivity in the worse eye were more likely to have a reduced saccade rate in the worse eye (Figure 4(a)). Furthermore, those patients with a greater drop in visual acuity in the worse eye also showed a greater reduction in saccade rate (Figure 4(b)). There were no other statistically significant correlations (Table 2).

Table 3 shows the proportion of saccades classified as each of the four eye movement types for the better and worse eyes, respectively. There were no statistically significant differences in these values between eyes. However, a larger increase in reading duration in the worse eye compared to the better eye was associated with an increase in the percentage of eye movements that were regressions in the worse eye compared to the better eye ($\rho: 0.60$; $P < 0.03$; Figure 5(a)). In

TABLE 2: Spearman's rho correlations comparing the difference in reading duration between the worse eye and the better eye and the difference in saccade rate between the worse eye and the better eye, with key measured variables related to age and vision.

	Difference between eyes					
	24-2 MD	10-2 MD	Mean central VF points	CS	VA	Age
Change in reading duration per trial rho	-0.20	0.13	0.01	-0.41	0.35	0.17
<i>P</i> value	0.48	0.65	0.99	0.14	0.14	0.56
Change in saccade rate rho	0.19	-0.32	0.21	0.65*	-0.56*	-0.09
<i>P</i> value	0.51	0.26	0.47	0.01	0.04	0.76

Statistically significant associations are marked with an asterisk.

TABLE 3: Proportion of saccades that were forward, between lines, regressions, or unknown when reading with the best eye and worse eye, respectively.

	Better eye	Worse eye
Forward saccades (%, median, and IQR)	72.0 (70.1, 73.5)	67.2 (62.4, 75.1)
Line change (%, median, and IQR)	10.6 (9.0, 11.3)	10.2 (9.0, 11.1)
Regressions (%, median, and IQR)	11.4 (9.7, 15.4)	13.8 (10.9, 19.7)
Unknown (%, median, and IQR)	5.6 (3.7, 8.4)	6.5 (4.2, 9.8)

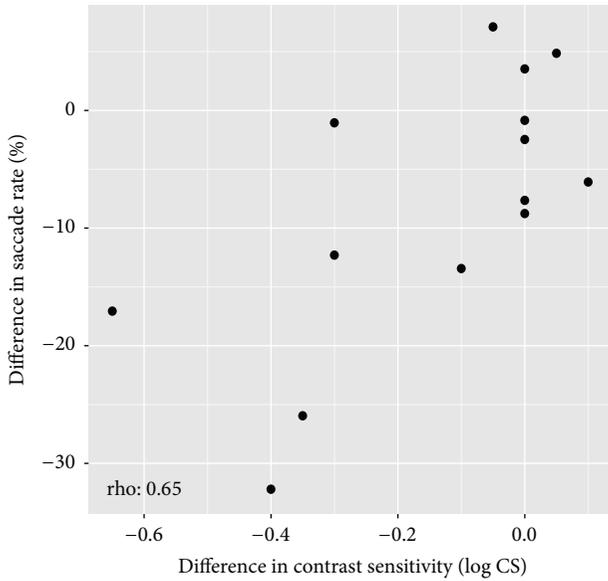
addition, a greater increase in reading duration in the worse eye compared to the better eye was associated with making more unknown eye movements in the worse eye compared to the better eye (rho: 0.59; $P < 0.03$; Figure 5(b)).

4. Discussion

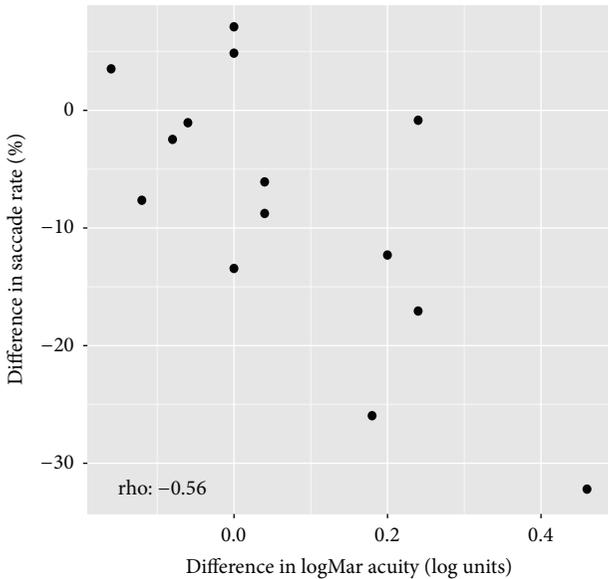
For reading, it is clear that some patients are more affected by vision loss in glaucoma than others. Some patients with glaucoma self-report difficulties with reading [6, 8, 24]. In addition, reading speed experiments indicate that patients with glaucoma have more problems with reading than people with normal vision but only "on average"; some patients with visual field loss performed similarly or better than people with healthy vision [9–12, 25, 26]. Reading speed can vary considerably between people making it difficult to make comparisons between patients and controls; in these studies adjustments are needed for covariates for reading speed such as education, cognitive ability, age, amount of day-to-day reading, and ethnicity. Such studies also require large sample sizes [8]. Our study examined an alternative experimental design: comparing performance between eyes in patients with asymmetrical visual field loss. Principally we demonstrated a statistically significant difference in the time it took patients to read a short passage of text in what is considered to be their worse eye (most visual field damage) when compared to their better eye (least visual field damage). This was done in a small sample of patients that carried out the reading task many times. The effect size was, however, small and the difference in reading duration between eyes was not associated with the magnitude of the difference in visual field

loss between the two tested eyes. In other words, there was no "dose" effect: larger differences in severity of visual field defect between eyes were not associated with worse performance. This was true for the MD from a standard clinical visual field test (24-2 HFA) and a visual field test of more central areas (10-2 HFA). It is therefore unclear if an overall summary measure of visual field defect severity can be predictive of worsening reading performance in glaucoma. There was no significant difference between eyes for visual acuity when considering the average of all patients; this finding likely reflects the fact that many patients with worsening glaucoma maintain relatively good visual acuity while other aspects of visual function decline. However, when considering *within-person* differences in visual acuity in the worse versus the better eye, a larger decline in visual acuity was associated with a greater reduction in reading speed in the worse eye. This finding highlights the benefits of considering performance changes within each individual in addition to considering average effects across all participants. The magnitude of the difference in contrast sensitivity between eyes was also related to difference in reading performance between eyes. The important role of contrast sensitivity in reading performance in glaucoma has been emphasised elsewhere [11].

This experiment was novel in comparison with most other studies investigating reading performance in people with glaucoma because it took advantage of measurements from an eye tracker. Patients had a reduced saccade rate (making fewer saccades per second) on average when reading with their worse eye compared to their better eye. Furthermore, average saccade rate was strongly associated with reading duration. These findings imply that saccade rate, measured by an eye tracker, could be a useful surrogate for reading performance. A reduction in saccade rate in patients with visual field defects has also been observed in other studies involving different visual tasks [13, 15] and other experimental results suggest that saccadic initiation in patients with glaucoma is delayed relative to controls with healthy vision [27]. It may be that visual function loss caused by glaucoma impairs the ability of the visual system to process the surrounding information during each glance, meaning that it takes longer to initiate a saccade towards relevant information. Nevertheless, although reduced reading duration and saccade rate were observed on average for the worse eye compared to the better eye, the degree of change between eyes



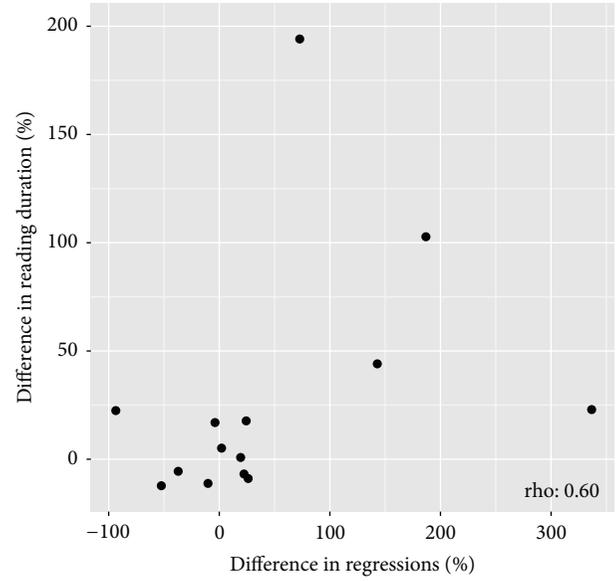
(a)



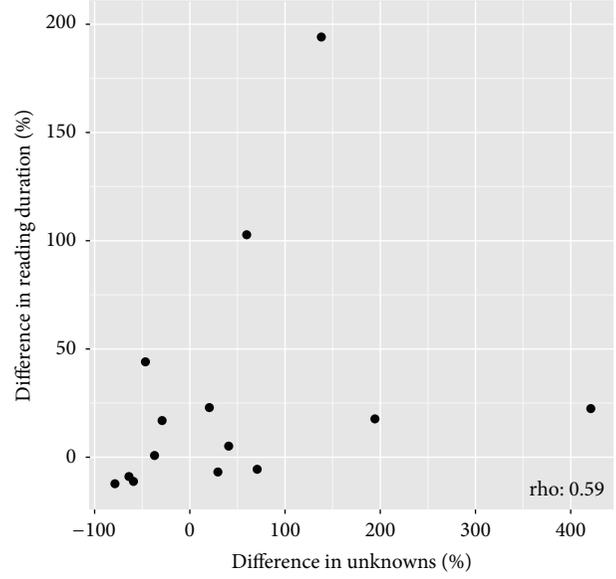
(b)

FIGURE 4: Scatterplots depicting the statistically significant relationships between (a) the difference in contrast sensitivity (log) and percentage difference in saccade rate between eyes and (b) the difference in logMAR visual acuity and the percentage difference in saccade rate between eyes.

varied considerably across patients. For example, Figure 3 shows that certain patients had a much longer reading duration for the worse eye and also tended to show a more reduced saccade rate. However, other patients appeared to be less affected in terms of reading speed when reading with their worse eye and these people also tended to maintain a similar, or increased, saccade rate to the better eye. Typically when reading, there will be a “window” of information that can be absorbed during each fixation, referred to as the “perceptual



(a)



(b)

FIGURE 5: Scatterplots showing statistically significant relationships between the percentage difference in reading duration between the better and worse eye and the difference between the better and worse eye in (a) the proportion of regressions and (b) the proportion of “unknown” eye movement.

span.” Visual degradation caused by visual field defects can be expected to reduce the number of characters that can be read with each fixation [28, 29], suggesting that more saccades must subsequently be made in order to process the same quantity of information. Therefore, some patients may have maintained an adequate reading speed when reading with their worse eye by increasing their saccade rate in order to overcome the impairment that would normally be expected due to visual degradation. This result coincides, in part, with a finding that suggests that glaucomatous visual field loss

restricts saccades during other tasks such as visual search but that increasing saccade rate is associated with maintaining “good” performance [13]. It is unknown whether these eye movements are adaptive behaviour, and so this topic should be the subject of future investigation.

Eye tracking generates copious data that can be easily misidentified or misinterpreted. Eye movement analysis software for reading experiments typically provides scanpath data [21, 30, 31] that has to be manually delineated to extract specific saccades like regressions (a backtracking saccade sometimes observed during reading). So, for this study, we developed some automated techniques for identifying the different types of eye movements made during the reading task. In this experiment, there was no statistically significant difference in the types of eye movements identified by the algorithm made by the eye with more visual field damage compared to the eye with less visual field damage. Still, there was a relationship between increases in the proportion of regressions and worse reading performance. The algorithm also automatically identified unknown or “irregular” eye movements that were associated with poorer reading performance in the worse eye compared to the better eye. Patients who followed more conventional reading patterns (making a smaller proportion of regressions and unknown eye movements compared to forward saccades) in both eyes appeared to read equally quickly in both eyes. These findings illustrate the utility of eye tracking in studies of reading in glaucoma and hint at the design of future studies. For example, recent research suggests that reading performance in patients with glaucoma is particularly affected during sustained reading as opposed to when reading short passages of text [12]; it might be useful to use eye tracking in future experiments of that type.

There are limitations associated with our study. There was no assessment of comprehension of the texts and the nature of the reading experiment—large font size and reading from a computer screen—does not mimic everyday reading. The sample size was not large enough to tease out any statistically significant differences in the types of eye movements that might be used by an eye with worse visual field damage compared to one with less visual field damage. We certainly did not have enough eyes to explore how reading performance is affected by the precise location of a visual field defect or how a similar visual field defect in the right eye as compared to the left eye might influence performance; this awaits further study. Future research may also wish to consider the performance of people with asymmetric visual field loss when reading bilaterally and whether this is comparable to reading monocularly with the better or worse eye. It is also important to point out that our methods for preprocessing the eye movement data and for automatically classifying their properties have not been validated or compared with manual methods. Nevertheless, the study still adds to the literature by showing the potential of eye tracking for understanding how patients with visual field defects function in everyday tasks such as reading.

In summary, this study has shown that patients with glaucoma will take longer to read a short passage of text

in what is considered to be their worse eye (most visual field damage) when compared to their better eye (least visual field damage). However, the effects were small. Unexpectedly, reading performance did not worsen in the eye with most visual field damage as the between-eye differences in visual field defect severity increased (as measured by a single summary measure of the visual field). We have also presented novel analytical eye movement data analysis that might be useful for other reading studies. The results suggest that regressions and unknown saccades result in slower reading speeds. In conclusion, we have demonstrated the utility of a novel experimental design that might help unravel the relationship between glaucomatous vision loss and difficulties with reading. For example, a future study comparing performance between eyes and using eye tracking could help determine the precise location of visual field loss that inhibits reading performance in glaucoma.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgment

This work is funded in part by an unrestricted grant from the Investigator-Initiated Studies Program of Merck Sharp & Dohme, Corp.

References

- [1] H. Quigley and A. T. Broman, “The number of people with glaucoma worldwide in 2010 and 2020,” *British Journal of Ophthalmology*, vol. 90, no. 3, pp. 262–267, 2006.
- [2] P. A. Aspinall, Z. K. Johnson, A. Azuara-Blanco, A. Montarzano, R. Brice, and A. Vickers, “Evaluation of quality of life and priorities of patients with glaucoma,” *Investigative Ophthalmology and Visual Science*, vol. 49, no. 5, pp. 1907–1915, 2008.
- [3] P. Nelson, P. Aspinall, and C. O’Brien, “Patients’ perception of visual impairment in glaucoma: a pilot study,” *British Journal of Ophthalmology*, vol. 83, no. 5, pp. 546–552, 1999.
- [4] A. C. Viswanathan, A. I. McNaught, D. Poinoosawmy et al., “Severity and stability of glaucoma patient perception compared with objective measurement,” *Archives of Ophthalmology*, vol. 117, no. 4, pp. 450–454, 1999.
- [5] E. E. Freeman, B. Muñoz, S. K. West, H. D. Jampel, and D. S. Friedman, “Glaucoma and quality of life: the salisbury eye evaluation,” *Ophthalmology*, vol. 115, no. 2, pp. 233–238, 2008.
- [6] D. P. Crabb, N. D. Smith, F. C. Glen, R. Burton, and D. F. Garway-Heath, “How does glaucoma look? patient perception of visual field loss,” *Ophthalmology*, vol. 120, pp. 1120–1126, 2013.
- [7] K. Fujita, N. Yasuda, K. Oda, and M. Yuzawa, “Reading performance in patients with central visual field disturbance due to glaucoma,” *Nippon Ganka Gakkai zasshi*, vol. 110, no. 11, pp. 914–918, 2006.
- [8] P. Ramulu, “Glaucoma and disability: which tasks are affected, and at what stage of disease?” *Current Opinion in Ophthalmology*, vol. 20, no. 2, pp. 92–98, 2009.

- [9] M. Ishii, M. Seki, R. Harigai, H. Abe, and T. Fukuchi, "Reading performance in patients with glaucoma evaluated using the MNREAD charts," *Japanese Journal of Ophthalmology*, vol. 57, pp. 471–474, 2013.
- [10] U. Altangerel, G. L. Spaeth, and W. C. Steinmann, "Assessment of function related to vision (AFREV)," *Ophthalmic Epidemiology*, vol. 13, no. 1, pp. 67–80, 2006.
- [11] R. Burton, D. P. Crabb, N. D. Smith, F. C. Glen, and D. F. Garway-Heath, "Glaucoma and reading: exploring the effects of contrast lowering of text," *Optometry and Vision Science*, vol. 89, pp. 1282–1287, 2012.
- [12] P. Y. Ramulu, B. K. Swenor, J. L. Jefferys, D. S. Friedman, and G. S. Rubin, "Difficulty with out-loud and silent reading in glaucoma," *Investigative Ophthalmology & Visual Science*, vol. 54, pp. 666–672, 2013.
- [13] N. D. Smith, F. C. Glen, and D. P. Crabb, "Eye movements during visual search in patients with glaucoma," *BMC Ophthalmology*, vol. 12, article 45, 2012.
- [14] F. C. Glen, N. D. Smith, and D. P. Crabb, "Saccadic eye movements and face recognition performance in patients with central glaucomatous visual field defects," *Vision Research*, vol. 82, pp. 42–51, 2013.
- [15] N. D. Smith, D. P. Crabb, F. C. Glen, R. Burton, and D. F. Garway-Heath, "Eye movements in patients with glaucoma when viewing images of everyday scenes," *Seeing and Perceiving*, vol. 25, pp. 471–492, 2012.
- [16] D. P. Crabb, N. D. Smith, F. G. Rauscher et al., "Exploring eye movements in patients with glaucoma when viewing a driving scene," *PloS ONE*, vol. 5, no. 3, p. e9710, 2010.
- [17] A. Cerulli, M. Cesareo, E. Ciuffoletti et al., "Evaluation of eye movements pattern during reading process in patients with glaucoma: a microperimeter study," *European Journal of Ophthalmology*, vol. 24, no. 3, pp. 358–363, 2014.
- [18] F. C. Glen, D. P. Crabb, N. D. Smith, R. Burton, and D. F. Garway-Heath, "Do patients with glaucoma have difficulty recognising faces?" *Investigative Ophthalmology & Visual Science*, vol. 53, no. 7, pp. 3629–3637, 2012.
- [19] P. H. Artes, N. O'Leary, D. M. Hutchison et al., "Properties of the statpac visual field index," *Investigative Ophthalmology & Visual Science*, vol. 52, no. 7, pp. 4030–4038, 2011.
- [20] E. Hodapp, R. I. Parrish, and D. R. Anderson, *Clinical Decisions in Glaucoma*, Mosby, St. Louis, Mo, USA, 1993.
- [21] S. A. Kabanarou and G. S. Rubin, "Reading with central scotomas: is there a binocular gain?" *Optometry and Vision Science*, vol. 83, no. 11, pp. 789–796, 2006.
- [22] I. Nabney, *NETLAB: Algorithms for Pattern Recognition*, Springer, New York, NY, USA, 2002.
- [23] R Development Core Team, *R: A Language and Environment for Statistical Computing*, R Foundation for Statistical Computing, Vienna, Austria, 2010.
- [24] C. M. Mangione, S. Berry, K. Spritzer et al., "Identifying the content area for the 51-item national eye institute visual function questionnaire: results from focus groups with visually impaired persons," *Archives of Ophthalmology*, vol. 116, no. 2, pp. 227–235, 1998.
- [25] K. Fujita, N. Yasuda, K. Nakamoto, and T. Fukuda, "The relationship between difficulty in daily living and binocular visual field in patients with glaucoma," *Nippon Ganka Gakkai Zasshi*, vol. 112, no. 5, pp. 447–450, 2008.
- [26] P. Y. Ramulu, S. K. West, B. Munoz, H. D. Jampel, and D. S. Friedman, "Glaucoma and reading speed: the salisbury eye evaluation project," *Archives of Ophthalmology*, vol. 127, no. 1, pp. 82–87, 2009.
- [27] R. Kanjee, Y. H. Yücel, M. J. Steinbach, E. G. González, and N. Gupta, "Delayed saccadic eye movements in glaucoma," *Eye*, vol. 4, pp. 63–68, 2012.
- [28] G. Loftus, L. Kaufman, T. Nishimoto, and E. Ruthruff, "Effects of visual degradation on eye-fixation duration, perceptual processing, and long-term visual memory," in *Eye Movements and Visual Cognition*, K. Rayner, Ed., Springer, New York, NY, USA, 1992.
- [29] M. A. Bullimore and I. L. Bailey, "Reading and eye movements in age-related maculopathy," *Optometry and Vision Science*, vol. 72, no. 2, pp. 125–138, 1995.
- [30] M. D. Crossland and G. S. Rubin, "Eye movements and reading in macular disease: further support for the shrinking perceptual span hypothesis," *Vision Research*, vol. 46, no. 4, pp. 590–597, 2006.
- [31] G. S. Rubin and M. Feely, "The role of eye movements during reading in patients with age-related macular degeneration (AMD)," *Neuro-Ophthalmology*, vol. 33, no. 3, pp. 120–126, 2009.

Research Article

Salient Distractors Can Induce Saccade Adaptation

Afsheen Khan,¹ Sally A. McFadden,² Mark Harwood,¹ and Josh Wallman¹

¹ Department of Biology, City College of New York, Marshak Science Building, Room 526, New York, NY 10031, USA

² School of Psychology, The University of Newcastle, Callaghan, NSW 2308, Australia

Correspondence should be addressed to Afsheen Khan; akhan4@ccny.cuny.edu

Received 7 December 2013; Revised 5 February 2014; Accepted 11 February 2014; Published 30 April 2014

Academic Editor: Arvid Herwig

Copyright © 2014 Afsheen Khan et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

When saccadic eye movements consistently fail to land on their intended target, saccade accuracy is maintained by gradually adapting the movement size of successive saccades. The proposed error signal for saccade adaptation has been based on the distance between where the eye lands and the visual target (retinal error). We studied whether the error signal could alternatively be based on the distance between the predicted and actual locus of attention after the saccade. Unlike conventional adaptation experiments that surreptitiously displace the target once a saccade is initiated towards it, we instead attempted to draw attention away from the target by briefly presenting salient distractor images on one side of the target after the saccade. To test whether less salient, more predictable distractors would induce less adaptation, we separately used fixed random noise distractors. We found that both visual attention distractors were able to induce a small degree of downward saccade adaptation but significantly more to the more salient distractors. As in conventional adaptation experiments, upward adaptation was less effective and salient distractors did not significantly increase amplitudes. We conclude that the locus of attention after the saccade can act as an error signal for saccade adaptation.

1. Introduction

Saccades are the rapid eye movements that we use to explore the visual world. They typically last a few tens of milliseconds, so the ongoing movement cannot use visual feedback for guidance [1]. This means that the size and direction of the saccade are planned before the eyes move and accuracy is maintained based on error signal(s) related to the consequence(s) of their movement.

An adaptive control mechanism ensures saccade accuracy in the face of changes in motor dynamics due to daily fatigue, aging, or pathology. When extraocular muscle impairment or weakness occurs, the initial large targeting errors diminish over time, meaning that the motor planning is able to adapt and restore saccade accuracy [2–5]. On a much more rapid time scale in the laboratory, surreptitiously displacing a target while the eye is in mid-flight with an intrasaccadic step (when vision is impaired) tricks the oculomotor system into thinking that the saccade had been inaccurate because, when the saccade lands, the target is no longer on the fovea. If this occurs consistently, the oculomotor system gradually

adjusts its saccade amplitude to partially compensate for the imposed error [6]. Despite the observer being unaware of the displacement, their saccades land progressively closer to the displaced position rather than the initial position of the target.

There are several possibilities as to what constitutes the error signal driving such saccade adaptation. Although a simple proposal would be for the oculomotor system to track the relative direction of the primary and the subsequent small corrective saccades needed to foveate the target [7], it appears that adaptation can still take place when there are very few corrective saccades made [8], and saccades can be adapted in the opposite direction to the correctives [9]. Retinal error, which is the distance of the target from the fovea after each saccade, has also been proposed as an alternative error signal. Since saccade amplitude can be induced to decrease when the target is displaced backwards and increase when the intrasaccadic step is forward, the direction and distance of the target from the fovea when the saccade lands could provide a simple possible error signal to guide saccade adaptation ([8, 10, 11], reviewed in [12]). However, a direct test of the potency

of retinal error alone in driving saccade adaptation in the absence of actual intrasaccadic steps showed that it is much weaker than that provided when the predicted target position was changed [13]. Earlier evidence that adaptation is not driven by the size of the retinal error with respect to the target but by the retinal error with respect to the predicted location was provided by Bahcall and Kowler [9]. They demonstrated that there was no saccade adaptation when subjects were instructed to make saccades not to the target but to a location that was 75% of the distance to the target, showing that the retinal error at the end of the saccade to the target alone was not sufficient to cause saccade adaptation. However, with the same saccade goal of 75% of target distance, adaptation was seen when the target did make intrasaccadic steps (saccade amplitudes reduced despite the stepped target remaining beyond the saccade landing position), suggesting that it is the retinal error with respect to the predicted location that is the key. Mathematical models of such “sensory prediction errors” are standard in arm movement adaptation and have also been formulated for saccades ([14]; for reviews see [15, 16]).

We propose that the locus of attention might offer an alternative, or complementary, framework to account for saccade adaptation. At one level, Posner [17] operationally defined attention with respect to expectation (prediction) of cue location being valid. More pertinently, recent evidence shows that attention is predictively allocated before the saccade, to the retinal location in which a secondary target will appear after the saccade is complete [18]. Rolf's and colleagues argued that this predictive remapping of attention facilitates the secondary saccade planning. Attention leaves a “retinotopic trace”: the retinal position of attention before a saccade can be seen in the same retinal location after a saccade [19]. Hence, if Rolf's predictively remapped attention coincides with the retinal location of target after saccade, this might also help explain the perceived stability of the world across saccades to stationary targets [20, 21].

Other work in our lab [22, 23] led to a very similar “placeholder hypothesis” of how attention might keep track of target positions across saccades, in particular, by providing a potential error signal for saccade adaptation. It was partly motivated by another useful feature of attention: selection. How in the real, visually cluttered world might saccade adaptation keep track of “the” error signal? Since attention helps to select the target before the saccade, with presaccadic shifts of attention to the target location [24–27], we hypothesized that attention could act as a placeholder for the target and that mismatches when comparing pre- and postsaccade loci of attention could act as an error signal for adaptation. To account for the Bahcall and Kowler partway paradigm above, our hypothetical comparison has to be between the predicted and actual postsaccadic locus of attention. That is, the predicted postsaccadic attention locus would be dissociated from the fovea when a saccade lands partway and instead be found at the presaccadic locus of attention (the original target location) towards which a secondary saccade is being planned. When the target is not stepped intrasaccadically there is no mismatch between predicted and actual postsaccadic attention locus, and no adaptation occurs. When the target is stepped backwards,

saccades adapt downwards due to the mismatch, despite the target still being more eccentric to the fovea. Although this prediction necessitates some kind of corollary discharge signal and attention can be spatiotopically encoded [28] given the recent evidence [29] and preceding arguments [18, 19], we believe that an attentional comparison in retinotopic coordinates is more tenable.

How is this different from sensory prediction errors? Have we not just substituted predicted and actual “attention locus” for predicted and actual “target location”? Dissociating these was the prime motivation behind the current set of experiments. Abrupt onset distractors can attract attention [30] away from saccade targets [31]. We proposed to use sudden onset salient distractors immediately after saccades to attempt to automatically draw the attention locus away from the extant, unmoved target during the critical window for saccade adaptation (<250 ms after saccade, [32–34]). If predicted and actual target location were critical, no adaptation should occur. If attention locus has a potential role then we conjecture that these distractors would create a mismatch between the pre- and postsaccadic locus of attention, even if the saccade had been accurate, and induce saccade adaptation in the direction of the attentional shift.

A secondary motivation was to dissociate between attention affecting saccade adaptation purely at a selection level and our hypothesis that the locus of attention may be directly involved in the computation of the error signal itself. Ditterich et al. [35] also argued for a comparator model based on attention focus, but attention was primarily invoked to select a snapshot of visual information before the movement (at the locus of the presaccadic attention shift) and then to compare that directly to the reafferent visual information on saccade landing. Briefly, they had two target conditions: a 0.3 deg fixation cross and a 4.8 deg ring, both on backgrounds consisting of random arrays of ellipses. Shifting the background during the saccade induced adaptation when subjects attended to the ring but not when attending to the cross. They argued that the attention focus selected the background in the ring condition, leading to adaptation, but only the unmoved small target in the cross condition, leading to no adaptation.

We argued that, according to the Ditterich scheme, if the visual information after the saccade was not shifted, but simply extra elements were added, there would be no error signal as there would be no mismatch to the information selected prior to the saccade. Consistent with this, we have previously shown that a distractor appearing after a saccade does not invoke saccade adaptation in the direction of the distractor [36]; instead, the adaptation mechanism is able to select only the relevant target information for computation of its error signal. The difference between our current hypothesis and that of Ditterich et al. [35] is that theirs relied on a visual comparison and ours relies on a position of attention comparison. Our previous work [36] does not differentiate between these two. In that study, the small distractor (0.5 deg) had the same size and salience as the target, always appeared at the same location after saccade, and stayed on for the rest of the trial. We suspect that this repetitive stimulus had a very weak attention-attracting effect [37], and therefore the locus

of attention was unmoved by the appearance of the distractor after saccade. In the current set of experiments, we used many different distractors, which changed regularly and were much larger and more visually salient than the target itself. We show here that despite subjects dutifully making saccades to the targets, not to the distractors, saccade gain was influenced by the location and salience of the distractor.

2. Methods

2.1. Subjects. Two experienced and twelve naïve subjects participated in Experiment 1 (7 female, 7 male) including two of the authors. The same two experienced and eight (new) naïve subjects participated in Experiment 2 (4 female, 6 male) including two of the authors. Naïve subjects were recruited from the City College Psychology Department and received course credit for their participation. All subjects had either normal or corrected vision. The Institutional Review Board of the City College of NY approved the experimental protocol, and all subjects signed consent forms before participation.

2.2. Equipment. The stimuli were generated and under the control of an application written in LabView (National Instruments). Stimuli were displayed on a 22 inch Compaq color, CRT monitor with a vertical refresh rate of 160 Hz. Subjects observed the stimuli while seated 57 cm away from the monitor, in an otherwise darkened room.

2.3. Eye Movement Recording and Analysis. Eye movements were recorded using an infrared video eye-tracking system (EyeLink, SR Research Ltd, Mississauga, Ontario, Canada), which sampled pupil position at 1000 Hz. The pixel-to-degrees calibration of the eye tracker was based on having each subject fixate a 0.1 deg target at locations taken from a 9-point rectangular grid. During the experiments, the distractor onset was triggered when a saccade was detected based on a velocity threshold criterion of 30°/sec. During analysis, saccade start- and endpoints were defined by a 10°/sec velocity threshold. Subjects' head position was held steady during the experiment by use of a chin and forehead rest.

2.4. Procedure. Each subject's task was to follow a target spot (0.1° in diameter), while they were tested consecutively in three phases. The first phase (preadaptation) and the last phase (postadaptation) were identical and each consisted of 100 trials to assess normal saccade gain to a target step under open-loop conditions. The intervening 2nd phase (adaptation) consisted of 250 trials in which attentional distractors were present.

In each trial during the preadaptation and postadaptation phases, the target spot randomly stepped left or right, initially from a central fixation position and subsequently from its previous target location on successive trials. During every experiment, the target moved only along the horizontal meridian and never moved further than 13° from the center of the screen. The target step size randomly varied between 7° to 9° and occurred 900–1400 ms after the end of the previous

trial. As soon as a saccade was detected based on the velocity threshold, the target spot disappeared for 500 ms and then reappeared in the same location until the end of the trial. The complete trial length was 1800 ms. In theory, this brief removal of the target once the saccade was underway should prevent any immediate postsaccadic visual error from mitigating any adaptation that had been previously established in the postadaptation phase. The change in saccade gain between the preadaptation and the postadaptation phases was the primary measure used to determine the effect of the adaptation trials on saccade gain.

The adaptation phase consisted of 250 distractor trials in which the target spot stepped the same as in the other two phases, but when the saccade occurred there were two differences: first, the target remained continuously on until the end of the trial (again trials were 1800 ms long); second, additional salient distractors were presented either on the near side of the target (referred to as adapt-down condition) or the far side of the target (referred to as adapt-up condition) during and after the saccade in Experiment 1. In Experiment 2, the distractors were always presented on the near side of the target. The details of distractor type and location varied in both experiments as described below. In addition, there were 25 interleaved trials in which the target disappeared upon saccade detection identical to the pre- and postadaptation trials, and hence, there were no distractors presented in these trials. In both experiments, the different adaptation conditions (distractor location or type) were performed in separate sessions at least one day apart, the order of which was randomly selected.

2.5. Experiment 1: The Effect of Salient Visual Distractors in the Adapt-Down and Adapt-Up Condition. The aim in this experiment was to use salient visual stimuli to attract attention away from the target position during the postsaccadic window so that an attentional error signal might be generated. To do this, during the adaptation phase, when the subject made a saccade to the target (0.1° red spot on a white background which stepped 7–9° randomly to the left or the right), one of 35 different distractor images was randomly selected to appear consistently centered at 3° on the inner side of the target (i.e., at 62.5% of the initial target step, on average) for 300 ms. This timing was selected to allow sufficient time for attentional disengagement with the target and brief reallocation to the visual distractor. It should be noted that, since the spot was left on and the trial lasted for 1.8 sec, there were plenty of attentional resources allocated to the target location with which our early attentional disruption had to compete. The large number of possible distractors was in order for the distractors to remain salient and to prevent habituation to the distractors so that they might continue to draw attention over the 250 adaptation trials. Each image was presented no more than 8 times. Distractors consisted of birds, other animals, anime characters, recognizable objects, and popular cartoon characters. Each image was 2.1° in horizontal width and varied in height between 1.5° and 3.5° (an example is shown in Figure 1). In the adapt-down condition of Experiment 1, we asked whether a strong visual

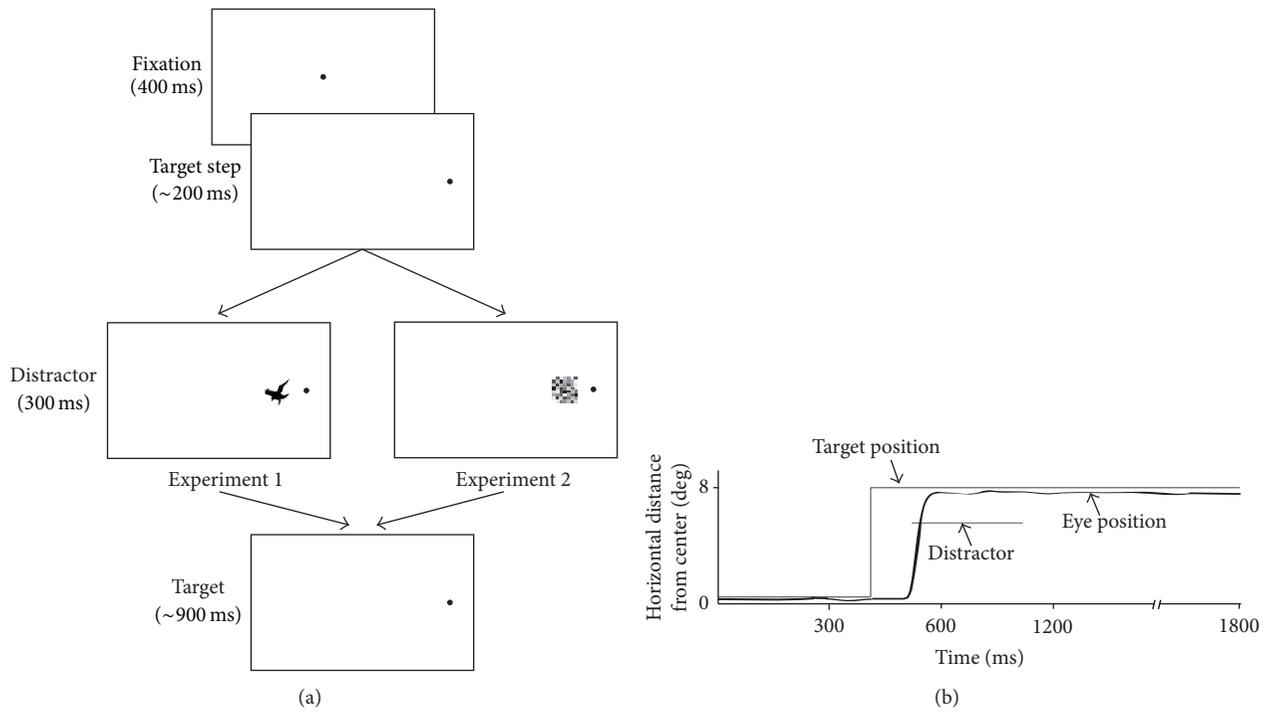


FIGURE 1: (a) Diagram of screen appearance and timing during the downward adaptation trials for the two experiments. Trials in both experiments consisted of a fixation, which stepped to the left or right after a brief variable delay (900–1400 ms, of which only 400 ms was recorded). Diagram shows a rightward step example only. Upon saccade detection, a visual distractor was presented for 300 ms, after which it disappeared leaving only the target on the screen in the stepped location. An example of both types of distractors used in both experiments is shown (drawn approximately to scale). See text for a description of the full set of distractors used in each experiment. (b) A schematic of target, distractor, and eye position during an adaptation trial. After the target step, the eye follows with a saccade, upon which time a distractor is presented a short distance from the target, which remains at the stepped location for the remainder of the trial.

attentional signal located on the near side of the target might also be able to compete with the target to bias saccades to decrease their amplitudes. The adapt-up condition of this experiment was identical to the adapt-down condition, except that the visual distractors were centered 3° on the far side of the target spot. The same subjects were tested in both the adapt-down and adapt-up conditions, to compare the effectiveness of attentional location to cause amplitude decreases versus increases, respectively.

2.6. Experiment 2: The Effect of Nonsalient Distractors on the Near Side of the Target. In Experiment 2, we asked whether a distractor that was less attention grabbing than those used in Experiment 1 would cause an equal or diminished magnitude of adaptation. This experiment was identical to the adapt-down condition of Experiment 1, except that the visual distractor used was a random noise pattern that was similarly 2.1° in horizontal width and also varied in height between 1.5° and 3.5° . This will be referred to as the “nonsalient condition.” The same subjects also performed a task that was identical to the adapt-down condition of Experiment 1 (to be referred to as the “salient condition”) in order to compare the magnitude of adaptation to the salient distractor images with that of the nonsalient, repetitive noise pattern.

2.7. Data Analysis. The data presented here are the changes in the gain of the primary saccade during the pre- and postadaptation phases, which were the open-loop saccade periods before and after the attention distractor trials. All trials were previewed in a custom graphical interface (Matlab, The Mathworks, Natick, MA). Statistical tests for individual experiments were based on paired t -tests. The raw data are shown together with a 20 point moving average calculated separately for each phase of the experiment. Saccade amplitudes elicited when the distractor was on the near or the far side of the target were compared using repeated measures ANOVA within individual subjects.

3. Results

In brief, we found that a salient visual stimulus displayed on the near side of the target after the saccade was underway caused a decrease in saccade gain. The magnitude of adaptation was reduced when a nonsalient, neutral distractor stimulus was used in all of the adapt trials instead of the salient visual images. The salient images in Experiment 1 were used to increase the attraction of attention away from the continuously visible, unchanging target and towards the locus of the distractor. These findings suggest that a discrepancy

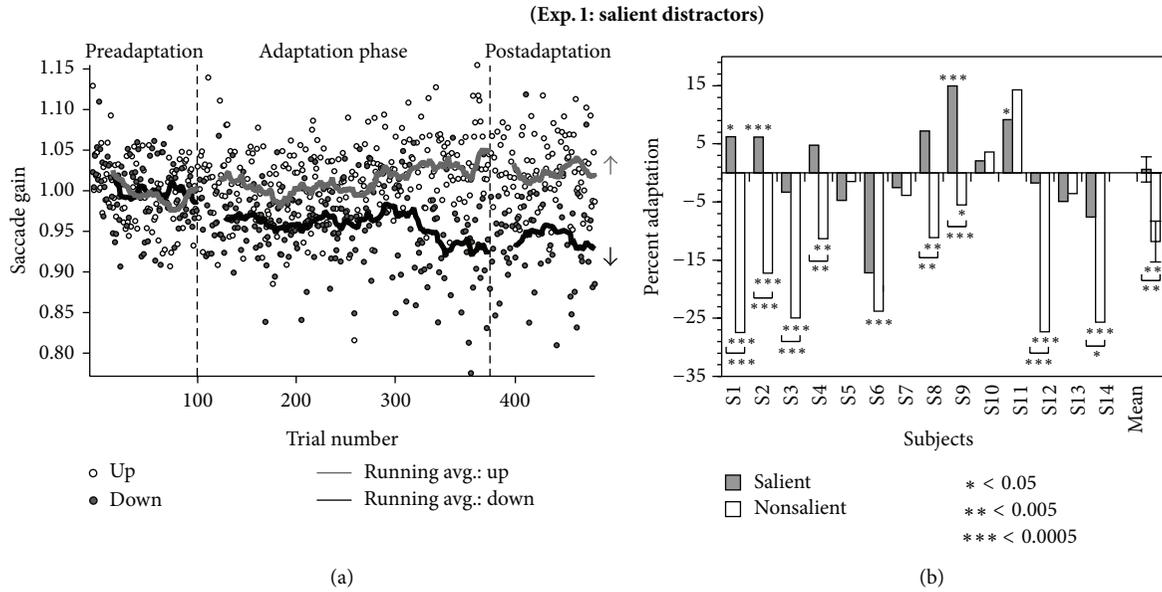


FIGURE 2: (a) Saccade gain data of subject S1 during Experiment 1 in which distractors consisted of salient images. Gain decreased gradually in the adapt-down condition (Experiment 1(a), closed circles, black curves) and displayed a significant decrease in gain of the postadaptation phase from the preadaptation phase. The adapt-up condition did not demonstrate any significant change (Experiment 1(b), open circles, gray curves). (b) Percentage adaptation (calculated as the difference between the pre- and postadaptation phases relative to the percent of distance of the distractor from the target) for each subject. Mean and standard error across all subjects are shown on the right. The asterisks below or above the bars represent significance between the pre- and postadaptation phase in an individual experiment, the asterisks below a square bracket represent the significance between the adaptation in the adapt-down compared to adapt-up condition.

between the locus of attention and the fovea can provide an error signal to drive saccade adaptation. Moreover, when the distractor is not salient, the magnitude of adaptation that the distractor is able to induce is diminished.

3.1. Experiment 1: Salient Images Can Change the Saccade Gain. An example of the raw data from one subject in both the adapt-down and adapt-up conditions of Experiment 1 is shown in Figure 2(a). It is evident that in the adapt-down condition the saccade gain declined throughout the adaptation portion of the experiment. We found that, when the visual distractor was on the near side of the target, the postsaccadic gain decreased significantly in 9 out of 14 subjects ($P < 0.05$ in 2 cases and $P < 0.01$ in 7 cases). We calculated the percentage adaptation, which was the difference in saccade gains between the pre- and postadaptation phases divided by the maximum gain change possible (calculated as the difference between the pre- and postadaptation phases relative to the percent distance of the distractor from the target). The average decrease for all subjects was $11.8 \pm 3.5\%$ after 250 adaptation trials (one-way repeated measures ANOVA, $F = 11.4$, $P = 0.005$, Figure 2(b)).

In the adapt-up condition when the distractor was presented on the far side of the target, the distractors were less effective in increasing the gain than decreasing it (Figure 2). Gain increased significantly in only four subjects (one-tailed t -tests). Across subjects, the average increase in gain between the pre- and postadaptation phases was $0.6 \pm 2.2\%$ which

was not significant (one-way repeated measures ANOVA, $F = 0.0876$, $P = 0.77$; Figure 2(b)). However, the interaction between phase (before versus after) and adaptation direction (down versus up) across all subjects was significantly different (repeated measures ANOVA, $F = 13.6$, $P = 0.003$).

3.2. Experiment 2: Nonsalient Random Noise on the Near Side of the Target Caused Less of a Decrease in Saccade Gain. A nonsalient, random noise distractor alone was able to decrease saccade gain when presented on the near side of the target, as can be seen by the raw data from a sample subject in Figure 3(a). Comparing the saccade gain during the preadaptation and postadaptation phases, we found a significant decrease in eight out of the ten subjects in the nonsalient condition. The average decrease was $8.1 \pm 1.0\%$ (one-way repeated measures ANOVA, $F = 60.9$, $P = 0.00003$, significant). The overall decrease in gain between the pre- and postadaptation phases for the salient condition was $14.4 \pm 2.9\%$ (one-way repeated measures ANOVA, $F = 24.2$, $P = 0.0008$). Only two subjects (S1 and S2) were common to both experiments, and hence there were small differences in the average gain decrease in the salient condition of Experiment 1 (11.8%). Both the random noise and the salient distractors caused a gain decrease. The magnitude of gain decrease between the pre- and postadaptation conditions was significantly different between the two distractor types for 4 of the 10 subjects (Figure 3(b)). The overall effect of distractor type was significant across all subjects as demonstrated by the interaction between the phase (preadaptation and

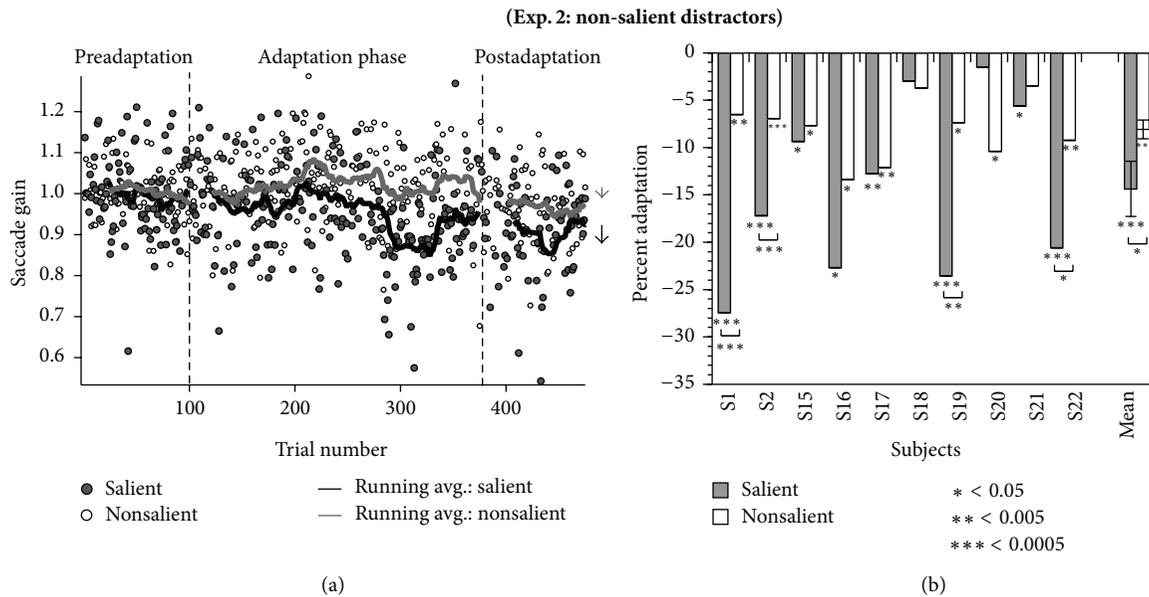


FIGURE 3: (a) Saccade gain data of subject S2 during Experiment 2 in which distractors consisted of a random noise patch (nonsalient) in Experiment 2(a) and salient images in Experiment 2(b). Gain decreased gradually in the presence of the random noise distractor (Experiment 2(a), open circles, grey curves) and displayed a significant decrease in gain of the postadaptation phase from the preadaptation phase. The salient distractors decreased gain even more rapidly and demonstrated a significant change (Experiment 2(b), closed circles, black curves). (b) Percentage adaptation (calculated as the difference between the pre- and postadaptation phases relative to the percent distance of the distractor from the target) for each subject. Mean and standard error across all subjects are shown on the right. The asterisks below each bar represent significance between the pre- and postadaptation phase in an individual experiment. The asterisks below a bracket represent the significance between the adaptation in the salient distractor and nonsalient distractor condition.

postadaptation) and distractor type (salient and nonsalient) (repeated measures two-way ANOVA, $F = 4.99$, $P = 0.05$).

3.3. Corrective Saccades. Corrective saccades to the distractors cannot explain our observed gain changes. Because we are testing the hypothesis that the presumed change in the postsaccadic locus of attention is responsible for the gain changes, we needed to assess whether we had inadvertently provided other cues, in particular, whether subjects made secondary saccades to the attentional distractor and then made a third saccade back to the target when the distractor disappeared. If this occurred during the adaptation phase, the direction of the secondary saccade might function as an error signal, as corrective saccades have been hypothesized to do during normal saccade adaptation. In our experiment, although hypothetical saccades to the distractors would be followed by ones in the opposite direction, this could still function as a motoric error signal, because the saccade toward the distractors would occur earlier within the postsaccadic window that is most responsive to error signals. To evaluate this possibility, we assessed the number of secondary saccades to the distractors made during the adaptation phase of the experiment. In the adapt-down conditions of both experiments, corrective saccades made were considered to have been made to the distractor if they were downwards and resulted in eye gaze landing closer to the distractor than

the target. In the adapt-up condition of Experiment 1, corrective saccades were considered to the distractor if they were forward and resulted in gaze landing closer to the distractor than the target. During the adaptation phase of Experiment 1, when the distractors were presented on the near side of the target (adapt-down condition), saccades were made to the distractor on average in 1.6% of the total number of valid trials (Table 1). Similarly, on average, during the adaptation phase of the adapt-up condition subjects made corrective saccades to the distractor in 7.3% of the total number of valid trials. The correlation between the number of corrective saccades to the distractor and the change in saccade gain for the adapt-down condition was -0.09 ($P = 0.76$) and was 0.24 ($P = 0.40$) for the adapt-up condition. Hence, we found that the number of secondary saccades to the distractor was not correlated with the change in saccade gain, suggesting that the error signal is more likely to be related to the shift of attention than to incidence of corrective saccades. Additionally, no correlation between the change in saccade gain and the number of corrective saccades to the distractor was also found in Experiment 2. The correlation between the adaptation and the number of corrective saccades to the distractor for the adapt-down salient distractor condition was 0.12 ($P = 0.73$), and for the nonsalient distractor condition the correlation was 0.3 ($P = 0.40$) (in which on average 0.9% and 0.8% of the correctives were to the distractor in the adaptation phase, respectively) (Table 2).

TABLE 1: Corrective saccades in Experiment 1. The percentage of adaptation trials with corrective saccades for the adapt-down and adapt-up condition, respectively, and the percentage of those that were in the direction of the distractor and that landed nearer the distractor compared to the saccade target.

Subject	Adapt-down condition			Adapt-up condition		
	Trials with corrective (%)	Trials with backward correctives (%)	Trials with correctives nearer distractor (%)	Trials with corrective (%)	Trials with forward corrective (%)	Trials with correctives nearer distractor (%)
S1	86.0	2.2	0.0	79.4	70.9	0.4
S2	87.2	1.1	0.0	40.6	37.6	2.1
S3	86.2	7.9	0.0	69.5	56.8	0.0
S4	76.8	5.2	2.4	84.1	80.2	4.0
S5	78.3	2.2	0.0	63.9	59.0	0.0
S6	84.3	6.6	5.4	86.6	86.1	12.4
S7	95.0	0.5	0.0	87.3	83.5	0.8
S8	90.1	0.9	0.9	93.5	92.9	11.8
S9	50.0	28.0	11.5	72.6	64.2	56.2
S10	13.5	5.7	0.0	36.6	19.8	0.0
S11	79.6	2.8	0.0	80.1	70.2	3.1
S12	49.3	2.8	0.9	58.4	57.9	5.6
S13	79.1	1.9	0.0	86.6	83.1	1.7
S14	75.8	3.1	0.6	77.4	74.9	4.1
Mean	73.7	5.1	1.6	72.6	66.9	7.3
Median	79.4	2.8	0.0	78.4	70.5	2.6

TABLE 2: Corrective saccades in Experiment 2. The percentage of adaptation trials with corrective saccades for the salient distractor and non salient distractor condition, respectively, and the percentage of those that were in the direction of the distractor and that landed nearer the distractor compared to the saccade target.

Subject	Salient distractor condition			Nonsalient distractor condition		
	Trials with corrective (%)	Trials with backward correctives (%)	Trials with correctives nearer distractor (%)	Trials with corrective (%)	Trials with backward corrective (%)	Trials with corrective nearer distractor (%)
S1	86.0	2.2	0.0	76.3	0.0	0.0
S2	87.2	1.1	0.0	24.4	0.0	0.0
S15	53.6	4.8	0.5	73.8	8.1	0.0
S16	27.6	9.9	1.6	53.0	22.1	1.1
S17	57.7	0.0	0.0	79.9	2.9	0.5
S18	63.1	3.6	1.2	72.7	11.0	0.5
S19	68.9	3.3	1.1	85.3	2.6	5.2
S20	77.7	15.5	1.5	82.2	21.2	0.5
S21	74.3	2.8	0.0	84.7	1.5	0.0
S22	86.1	5.6	2.8	73.2	9.5	0.6
Mean	68.2	4.9	0.9	70.6	7.9	0.8
Median	71.6	3.4	0.8	75.1	5.5	0.5

4. Discussion

We find that salient, unpredictable image distractors appearing after a saccade can lead to saccade adaptation despite the target remaining visible and stationary. In both experiments, when distractors were consistently presented on the near side of the target during the adaptation phase, we found that saccade gain gradually decreased. As we decreased the salience and image unpredictability of the distractor, the magnitude of adaptation decreased (Figure 3). Even though the distance

between the target and visual distractor was within the range of intrasaccadic step sizes shown to be most effective for saccade adaptation [38], the adaptation that we observed was smaller than that typical in conventional saccade adaptation experiments ([6], reviewed in [12], reviewed in [39]). The smaller magnitude of adaptation in our experiment however is not surprising considering that the target spot did not make any intrasaccadic movements and simply remained in its stepped location even after the saccade was made. Since a postsaccadic error must persist for >32 ms to affect adaptation

[32, 34], although we may have attracted attention away from the fovea, it was in competition with multiple veridical cues associated with the target being located on the fovea, and the putative attentional shift was presumably transient, as it had to be shared between the distractor location and the target location at the fovea. The adaptation we found was similar to conventional saccade adaptation, in terms of the asymmetry of larger gain changes for downward adaptation than for upward adaptation.

4.1. Possible Error Signals for Saccade Adaptation. Possible error signals for saccade adaptation must incorporate prediction and selection mechanisms. Previously, either the motor error (i.e., corrective saccades) or the visual error (difference between the target position and the eyes landing position) was thought to drive adaptation [7]. We know now that corrective saccades are not necessary for saccade adaptation, suggesting that the error signal is visual [8]. However, it appears that it is not purely a sensory error, but rather is the difference between the actual retinal image of the target at the end of a saccade and the predicted retinal image after the saccade that primarily drives adaptation [9, 13, 35, 40, 41], and yet visual feedback of the target is not even required for saccade adaptation to occur [42]. In addition to suggesting that prediction was required in saccade adaptation, Ditterich et al. [35] invoked selective attention to explain some of their data. They argued that a large scale of attention coded their background stimulus along with the saccade target (see Section 1), such that the background influenced adaptation, and a small scale did not code the background, which therefore had no influence on adaptation. Similarly, we and others have found that the adaptive mechanism can selectively ignore shifts of the background when a target is present [43, 44] or that static backgrounds have no effect on adaptation [45].

Attention is intimately linked to prediction, selection, and saccades [17, 24–28, 35]. Here, we tested the novel hypothesis that the locus of attention can act as the error signal for adaptation, by attempting to consistently direct attention to an attention grabbing, postsaccadic distractor located a few degrees from the target. As detailed in Section 1, if we assume that the sudden onset distractor draws attention away from the target, it would lead to a mismatch between the predictively remapped locus of postsaccadic attention and the actual locus of distractor captured attention. We conjectured that this would lead to adaptation towards the distractor to reduce the mismatch. In our experiment, the target was still present postsaccadically and in the predicted retinal location. The fact that neither retinal error nor predictive error can explain our findings presents a challenge to current ideas for the error signal guiding saccade adaptation. We must emphasize, of course, that we are conjecturing as to the attention grabbing properties of our sudden onset, salient distractors. In future work we would like to include specific attention tasks to confirm these findings. However, as argued in Section 1, the addition of salient, unpredictable distractors after the saccade is a feasible means to distinguish between the existing evidence for attention acting on adaptation shown by Ditterich et al. [35] and our locus of attention hypothesis.

4.2. Ethology of Saccade Adaptation. Attention is likely to be used to maintain the accuracy of saccades since in the visually complex natural world overt attention generally follows covert attention to objects that attract our attention. Most saccade adaptation experiments however rely on very sparse visual stimuli that rarely require any target selection. This fails to reflect the continuous competition in the natural world for our limited resources. In the natural world we utilize covert attention to select our next focus of gaze [46]; therefore it is likely also involved in maintaining saccade accuracy as well. Although it has been shown that attention shifts and saccades can be dissociated [47, 48], it is unlikely that a saccade would be judged inaccurate if the saccade were made to what was being covertly attended in a crowded visual scene. It has been previously shown that only the attended visual information after a saccade is utilized in saccade adaptation [35]. Therefore, we propose that the locus of attention after a saccade is also integrated to deem whether a saccade is accurate or not.

For the purposes of saccade adaptation the oculomotor system has demonstrated the ability to select the target over other distractors presented on the screen [36]; however we demonstrated here that salient, unpredictable distractors are able to interfere with this target selection. The Madelain et al. [36] experiment was similar to the current study in that a distractor was presented after saccade initiation a short distance from the target (2° or 2.4°) but differed in that it was present for the remainder of the trial. More importantly, unlike the array of possible distractors used in the present experiment, the distractor in the Madelain et al. [36] experiment was not more salient than the target; indeed, the target and distractor were interchangeable between trials (the target was simply the first of the two colored spots to appear). Although explicit attentional tasks were not included in either study, it is likely that the distractors in the Madelain et al. [36] experiment had a weaker attention attracting effect than the visual distractors in Experiment 1 in the current study. Due to the predictable color and location of the distractor in Madelain et al. [36], they may even have prevented capturing attention (e.g., see [49, 50]). Therefore, the mere presence of a visual stimulus on the screen along with the target by itself will not elicit saccade adaptation [36] unless, as implied in our experiments, the distractor is salient and unpredictable enough to consistently attract attention.

To further test this relative salience and unpredictability explanation for the differences between our data and that of Madelain et al. [36], we compared varied and salient natural images to fixed, static noise patch distractors in Experiment 2 and found that the predictable noise patch distractors (but ones larger and more salient than the target) gave some, but weaker, adaptation than the set of salient distractors. Thus, between our two experiments and those of Madelain and colleagues we observe a spectrum of increasing predictability and decreasing salience of distractors leading to decreased levels of adaptation, with predictable distractors of equal salience to the target being effectively ignored by the adaptation machinery [36]. In the absence of an explicit attentional task, we conjecture that the locus of attention after the saccade is more strongly drawn away from the saccade

target by larger or more unpredictable distractors and that this directly caused the differences in adaptation that we have observed.

4.3. Alternative Explanations. One might argue that the gain change occurs because the oculomotor system does not distinguish between the saccade target and the attentional distractors, despite their diversity and dissimilarity to the target. That is, the center of gravity of all the stimuli on the screen might be used for computing an error signal or adaptation occurs due to some averaging of the target and distractor locations such as in the global effect [51], albeit postsaccadically for our situation since the distractor was not present at the time of saccade onset. However, no global averaging of the target and distractor locations was found in a similar experiment where the distractor was similar in appearance to the target [36]. Under these conditions, despite a global stimulus configuration similar to ours, the oculomotor system effectively distinguished between the target and the distractor. Furthermore, if the purely visual signal of having more stimuli on one side of the fovea than on the other might act as an error signal to adjust the saccade gain in the directions shown here, it is surprising that such a small percentage of the secondary saccades (average of 1.6% for adapt-down condition in Experiment 1 and 7.3% for the adapt up condition) were made to the distractors, making it unlikely that they were regarded as the saccade target. Additionally, if the global effect were responsible for the saccade adaptation that we observe, it would be expected that the magnitude of the adaptation might be similar between upward and downward adaptation, and between the unpredictable/salient and the predictable/reduced salient conditions of Experiments 2. Instead it was found that the predictable distractors used in Experiment 2 produced a gain decrease that was about half of that produced in the more salient/less predictable condition.

4.4. Similar Characteristics to Conventional Saccade Adaptation. The gradual adaptation in our distractor paradigm was similar to adaptation elicited in conventional intrasaccadic paradigms. In Experiment 1 there was the same asymmetry as that found in conventional saccade adaptation between the magnitudes of saccade gain change in the adapt-up and adapt-down conditions (Figure 2). The adapt-down condition demonstrated a significant decrease while there was no significant change in the adapt-up condition in Experiment 1. Conventionally, subjects frequently do not increase gain and an asymmetry in the degree of adaptation between the two directions has often been observed (reviewed in [12, 52–54]). Therefore, it is unsurprising that we also did not find an increase in gain in the adapt-up salient distractor condition, possibly because the putative attentional error signal alone was too weak to induce saccade adaptation in a direction which is already difficult to adapt. One might even argue that the matching asymmetry in our data and in normal adaptation supports the relevance of our data to more standard saccade adaptation studies.

4.5. Neural Correlate of Saccade Adaptation. Further support for the interpretation of the current results in terms of attention induced adaptation can be found by considering the possible neural basis of the protocol. The neural correlate of saccade adaptation is thought to be either the superior colliculus (SC) or the cerebellum (reviewed in [12]). More recently, saccade adaptation, very similar in spatial and temporal dynamics to what can be produced by the McLaughlin method [6], was elicited by subthreshold microstimulation of the SC immediately after the saccade [55, 56]. Interestingly, it has also been found that subthreshold stimulation of the SC can cause shifts of attention [57, 58]. Hence, not only is it likely that the SC plays a major role in saccade adaptation, but also the SC has a role in attentional shifts. Therefore, the distractors in our study might have acted as bottom-up visual transients on an SC map, producing adaptation by the same mechanism as these two recent studies. Because the target was always present, competing with these transients, any such attentional error signal originating in the SC would be expected to result in smaller magnitude effects compared to conventional saccade adaptation.

In conclusion, by using salient visual distractors suddenly appearing after a saccade, the current results show that adaptation can be induced even in the presence of an unambiguous target location. This supports the notion that consistent differences between the locus of attention before and after a saccade may act as an error signal for saccade adaptation. Because the locus of attention is strongly influenced by predictive information [17], this novel hypothesis may provide an alternative interpretation for previous findings arguing for retinal or predictive error mechanisms of saccade adaptation.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Authors' Contribution

Afsheen Khan, Sally A. McFadden, and Josh Wallman were responsible for the conception and design of experiment; Afsheen Khan performed experiments; Mark Harwood wrote the saccade analysis application; Afsheen Khan and Sally A. McFadden analyzed data; Afsheen Khan prepared figures; Afsheen Khan, Sally A. McFadden, and Josh Wallman interpreted results of experiments; Afsheen Khan and Sally A. McFadden drafted the paper, Afsheen Khan, Sally A. McFadden, and Mark Harwood revised and approved final version of the paper.

Acknowledgments

The authors thank James Herman for technical assistance in setting up the experiment and for valuable comments during discussions on the design of the experiment. They also thank Annabelle Blangero for invaluable comments and assistance completing this experiment. They would also like

to thank the two reviewers whose comments have been very helpful in improving the paper. This research was funded in part by Grant BCS-0842464 from the National Science Foundation (Afsheen Khan, Mark Harwood, and Josh Wallman) and Grants 1R01EY019508, 5G12RR003060-26, and 8G12MD7603-28 from the National Institute of Health (Mark Harwood and Josh Wallman).

References

- [1] W. Becker, "Metrics," in *The Neurobiology of Saccadic Eye Movements*, Wurtz and Goldberg, Eds., pp. 13–67, Elsevier Science, 1989.
- [2] G. Kommerell, D. Olivier, and H. Theopold, "Adaptive programming of phasic and tonic components in saccadic eye movements. Investigations in patients with abducens palsy," *Investigative Ophthalmology*, vol. 15, no. 8, pp. 657–660, 1976.
- [3] L. A. Abel, D. Schmidt, L. F. Dell'Osso, and R. B. Daroff, "Saccadic system plasticity in humans," *Annals of Neurology*, vol. 4, no. 4, pp. 313–318, 1978.
- [4] L. M. Optican and D. A. Robinson, "Cerebellar-dependent adaptive control of primate saccadic system," *Journal of Neurophysiology*, vol. 44, no. 6, pp. 1058–1076, 1980.
- [5] R. Snow, J. Hore, and T. Vilis, "Adaptation of saccadic and vestibulo-ocular systems after extraocular muscle tenectomy," *Investigative Ophthalmology and Visual Science*, vol. 26, no. 7, pp. 924–931, 1985.
- [6] S. C. McLaughlin, "Parametric adjustment in saccadic eye movements," *Percept Psychophys*, vol. 2, no. 8, pp. 359–362, 1967.
- [7] J. E. Albano and W. M. King, "Rapid adaptation of saccadic amplitude in humans and monkeys," *Investigative Ophthalmology and Visual Science*, vol. 30, no. 8, pp. 1883–1893, 1989.
- [8] J. Wallman and A. F. Fuchs, "Saccadic gain modification: visual error drives motor adaptation," *Journal of Neurophysiology*, vol. 80, no. 5, pp. 2405–2416, 1998.
- [9] D. O. Bahcall and E. Kowler, "The control of saccadic adaptation: implications for the scanning of natural visual scenes," *Vision Research*, vol. 40, no. 20, pp. 2779–2796, 2000.
- [10] C. T. Noto and F. R. Robinson, "Visual error is the stimulus for saccade gain adaptation," *Cognitive Brain Research*, vol. 12, no. 2, pp. 301–305, 2001.
- [11] K. Havermann and M. Lappe, "The influence of the consistency of postsaccadic visual errors on saccadic adaptation," *Journal of Neurophysiology*, vol. 103, no. 6, pp. 3302–3310, 2010.
- [12] J. J. Hopp and A. F. Fuchs, "The characteristics and neuronal substrate of saccadic eye movement plasticity," *Progress in Neurobiology*, vol. 72, no. 1, pp. 27–53, 2004.
- [13] T. Collins and J. Wallman, "The relative importance of retinal error and prediction in saccadic adaptation," *Journal of Neurophysiology*, vol. 107, no. 12, pp. 3342–3348, 2012.
- [14] H. Chen-Harris, W. M. Joiner, V. Ethier, D. S. Zee, and R. Shadmehr, "Adaptive control of saccades via internal feedback," *Journal of Neuroscience*, vol. 28, no. 11, pp. 2804–2813, 2008.
- [15] M. R. Harwood and J. P. Herman, "Optimally straight and optimally curved saccades," *Journal of Neuroscience*, vol. 28, no. 30, pp. 7455–7457, 2008.
- [16] J. P. Herman, A. Blangero, L. Madelain, A. Khan, and M. R. Harwood, "Saccade adaptation as a model of flexible and general motor learning," *Experimental Eye Research*, vol. 114, pp. 6–15, 2013.
- [17] M. I. Posner, "Orienting of attention," *The Quarterly Journal of Experimental Psychology*, vol. 32, no. 1, pp. 3–25, 1980.
- [18] M. Rolfs, D. Jonikaitis, H. Deubel, and P. Cavanagh, "Predictive remapping of attention across eye movements," *Nature Neuroscience*, vol. 14, no. 2, pp. 252–258, 2011.
- [19] J. D. Golomb, M. M. Chun, and J. A. Mazer, "The native coordinate system of spatial attention is retinotopic," *Journal of Neuroscience*, vol. 28, no. 42, pp. 10654–10662, 2008.
- [20] P. Cavanagh, A. R. Hunt, A. Afraz, and M. Rolfs, "Visual stability based on remapping of attention pointers," *Trends in Cognitive Sciences*, vol. 14, no. 4, pp. 147–153, 2010.
- [21] T. Collins, M. Rolfs, H. Deubel, and P. Cavanagh, "Post-saccadic location judgments reveal remapping of saccade targets to non-foveal locations," *Journal of Vision*, vol. 9, no. 5, pp. 1–9, 2009.
- [22] S. A. McFadden and J. Wallman, "Shifts of attention and saccades are very similar. Are they causally linked?" in *Vision and Attention*, M. Jenkin and L. Harris, Eds., pp. 19–39, Springer, New York, NY, USA, 2001.
- [23] S. A. McFadden, A. Khan, and J. Wallman, "Gain adaptation of exogenous shifts of visual attention," *Vision Research*, vol. 42, no. 24, pp. 2709–2726, 2002.
- [24] E. Castet, S. Jeanjean, A. Montagnini, D. Laugier, and G. S. Masson, "Dynamics of attentional deployment during saccadic programming," *Journal of Vision*, vol. 6, no. 3, article 2, pp. 196–212, 2006.
- [25] H. Deubel and W. X. Schneider, "Saccade target selection and object recognition: evidence for a common attentional mechanism," *Vision Research*, vol. 36, no. 12, pp. 1827–1837, 1996.
- [26] J. E. Hoffman and B. Subramaniam, "The role of visual attention in saccadic eye movements," *Perception and Psychophysics*, vol. 57, no. 6, pp. 787–795, 1995.
- [27] E. Kowler, E. Anderson, B. Doshier, and E. Blaser, "The role of attention in the programming of saccades," *Vision Research*, vol. 35, no. 13, pp. 1897–1916, 1995.
- [28] R. Desimone and J. Duncan, "Neural mechanisms of selective visual attention," *Annual Review of Neuroscience*, vol. 18, pp. 193–222, 1995.
- [29] J. D. Golomb, A. C. Marino, M. M. Chun, and J. A. Mazer, "Attention doesn't slide: spatiotopic updating after eye movements instantiates a new, discrete attentional locus," *Attention, Perception, and Psychophysics*, vol. 73, no. 1, pp. 7–14, 2011.
- [30] T. Koelewijn, A. Bronkhorst, and J. Theeuwes, "Auditory and visual capture during focused visual attention," *Journal of Experimental Psychology*, vol. 35, no. 5, pp. 1303–1315, 2009.
- [31] E. McSorley, P. Haggard, and R. Walker, "Time course of oculomotor inhibition revealed by saccade trajectory modulation," *Journal of Neurophysiology*, vol. 96, no. 3, pp. 1420–1424, 2006.
- [32] J. L. Shafer, C. T. Noto, and A. F. Fuchs, "Temporal characteristics of error signals driving saccadic gain adaptation in the macaque monkey," *Journal of Neurophysiology*, vol. 84, no. 1, pp. 88–95, 2000.
- [33] M. Fujita, A. Amagai, F. Minakawa, and M. Aoki, "Selective and delay adaptation of human saccades," *Cognitive Brain Research*, vol. 13, no. 1, pp. 41–52, 2002.
- [34] M. Panouillères, C. Urquizar, R. Salemme, and D. Pélisson, "Sensory processing of motor inaccuracy depends on previously performed movement and on subsequent motor corrections: a study of the saccadic system," *PLoS ONE*, vol. 6, no. 2, Article ID e17329, 2011.
- [35] J. Ditterich, T. Eggert, and A. Straube, "The role of the attention focus in the visual information processing underlying saccadic adaptation," *Vision Research*, vol. 40, no. 9, pp. 1125–1134, 2000.

- [36] L. Madelain, M. R. Harwood, J. P. Herman, and J. Wallman, "Saccade adaptation is unhampered by distractors," *Journal of vision*, vol. 10, no. 12, p. 29, 2010.
- [37] K. Grill-Spector, R. Henson, and A. Martin, "Repetition and the brain: neural models of stimulus-specific effects," *Trends in Cognitive Sciences*, vol. 10, no. 1, pp. 14–23, 2006.
- [38] F. R. Robinson, C. T. Noto, and S. E. Bevans, "Effect of visual error size on saccade adaptation in monkey," *Journal of Neurophysiology*, vol. 90, no. 2, pp. 1235–1244, 2003.
- [39] D. Pélissier, N. Alahyane, M. Panouillères, and C. Tilikete, "Sensorimotor adaptation of saccadic eye movements," *Neuroscience and Biobehavioral Reviews*, vol. 34, no. 8, pp. 1103–1120, 2010.
- [40] A. L. Wong and M. Shelhamer, "Sensorimotor adaptation error signals are derived from realistic predictions of movement outcomes," *Journal of Neurophysiology*, vol. 105, no. 3, pp. 1130–1140, 2011.
- [41] J. P. Herman, C. P. Cloud, and J. Wallman, "End-point variability is not noise in saccade adaptation," *PLoS ONE*, vol. 8, no. 3, Article ID e59731, 2013.
- [42] L. Madelain, C. Paeye, and J. Wallman, "Modification of saccadic gain by reinforcement," *Journal of Neurophysiology*, vol. 106, no. 1, pp. 219–232, 2011.
- [43] L. Madelain, J. P. Herman, and M. R. Harwood, "Saccade adaptation goes for the goal," *Journal of Vision*, vol. 13, no. 4, 2013.
- [44] F. Robinson, C. Noto, and S. Watanabe, "Effect of visual background on saccade adaptation in monkeys," *Vision Research*, vol. 40, no. 17, pp. 2359–2367, 2000.
- [45] H. Deubel, "Is saccadic adaptation context-specific?" in *Eye Movement Research: Mechanisms, Processes and Applications*, J. M. Findlay, R. W. Kentridge, and R. Walker, Eds., Elsevier Science, 1995.
- [46] E. Awh, K. M. Armstrong, and T. Moore, "Visual and oculomotor selection: links, causes and implications for spatial attention," *Trends in Cognitive Sciences*, vol. 10, no. 3, pp. 124–130, 2006.
- [47] C.-H. Juan, S. M. Shorter-Jacobi, and J. D. Schall, "Dissociation of spatial attention and saccade preparation," *Proceedings of the National Academy of Sciences of the United States of America*, vol. 101, no. 43, pp. 15541–15544, 2004.
- [48] A. V. Belopolsky and J. Theeuwes, "When are attention and saccade preparation dissociated?" *Psychological Science*, vol. 20, no. 11, pp. 1340–1347, 2009.
- [49] A. V. Belopolsky and J. Theeuwes, "No capture outside the attentional window," *Vision Research*, vol. 50, no. 23, pp. 2543–2550, 2010.
- [50] H. J. Müller, T. Geyer, M. Zehetleitner, and J. Krummenacher, "Attentional capture by salient color singleton distractors is modulated by top-down dimensional set," *Journal of Experimental Psychology*, vol. 35, no. 1, pp. 1–16, 2009.
- [51] J. M. Findlay and I. D. Gilchrist, "Spatial scale and saccade programming," *Perception*, vol. 26, no. 9, pp. 1159–1167, 1997.
- [52] J. M. Miller, T. Anstis, and W. B. Templeton, "Saccadic plasticity: parametric adaptive control by retinal feedback," *Journal of Experimental Psychology*, vol. 7, no. 2, pp. 356–366, 1981.
- [53] J. L. Semmlow, G. M. Gauthier, and J.-L. Vercher, "Mechanisms of short-term saccadic adaptation," *Journal of Experimental Psychology*, vol. 15, no. 2, pp. 249–258, 1989.
- [54] J. Tian and D. S. Zee, "Context-specific saccadic adaptation in monkeys," *Vision Research*, vol. 50, no. 23, pp. 2403–2410, 2010.
- [55] Y. Kaku, K. Yoshida, and Y. Iwamoto, "Learning signals from the superior colliculus for adaptation of saccadic eye movements in the monkey," *Journal of Neuroscience*, vol. 29, no. 16, pp. 5266–5275, 2009.
- [56] R. Soetedjo, A. F. Fuchs, and Y. Kojima, "Subthreshold activation of the superior colliculus drives saccade motor learning," *Journal of Neuroscience*, vol. 29, no. 48, pp. 15213–15222, 2009.
- [57] J. Cavanaugh and R. H. Wurtz, "Subcortical modulation of attention counters change blindness," *Journal of Neuroscience*, vol. 24, no. 50, pp. 11236–11243, 2004.
- [58] J. R. Müller, M. G. Philiastides, and W. T. Newsome, "Microstimulation of the superior colliculus focuses attention without moving the eyes," *Proceedings of the National Academy of Sciences of the United States of America*, vol. 102, no. 3, pp. 524–529, 2005.

Research Article

Response Time, Visual Search Strategy, and Anticipatory Skills in Volleyball Players

Alessandro Piras,¹ Roberto Lobietti,² and Salvatore Squatrito¹

¹ Department of Biomedical and Neuromotor Sciences, Section of Human and General Physiology, University of Bologna, 40126 Bologna, Italy

² Department of Histology, Embryology and Applied Biology, University of Bologna, 40126 Bologna, Italy

Correspondence should be addressed to Alessandro Piras; alessandro.piras3@unibo.it

Received 20 October 2013; Revised 2 January 2014; Accepted 11 April 2014; Published 30 April 2014

Academic Editor: Stefanie I. Becker

Copyright © 2014 Alessandro Piras et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

This paper aimed at comparing expert and novice volleyball players in a visuomotor task using realistic stimuli. Videos of a volleyball setter performing offensive action were presented to participants, while their eye movements were recorded by a head-mounted video based eye tracker. Participants were asked to foresee the direction (forward or backward) of the setter's toss by pressing one of two keys. Key-press response time, response accuracy, and gaze behaviour were measured from the first frame showing the setter's hand-ball contact to the button pressed by the participants. Experts were faster and more accurate in predicting the direction of the setting than novices, showing accurate predictions when they used a search strategy involving fewer fixations of longer duration, as well as spending less time in fixating all display areas from which they extract critical information for the judgment. These results are consistent with the view that superior performance in experts is due to their ability to efficiently encode domain-specific information that is relevant to the task.

1. Introduction

Sport expertise has been defined as the ability to consistently demonstrate superior athletic performance. It is generally accepted that expert athletes perform better than novices but it is not clear whether superior performance stems from more refined sensory-motor coordination alone. Athletes must be able to identify the most information-rich areas of the visual field, direct their attention appropriately, and extract meaning from these areas efficiently and effectively [1]. In a successful sport performance, knowing where and when to look may be crucial, especially when the scene is wide and information relevant to the task can be presented in different forms and locations.

Athlete's superiority on beginners in elementary visuomotor tasks, such as visual acuity, saccadic eye movements, depth perception, and oculomotor reaction time, has been widely investigated but results cannot be generalized to all sports [2–5]. As such, the differences in visual search strategy, that is, the ability to quickly locate task-relevant

information between expert and novice players, in one sport may be inconsistent with those of others [6]. Anticipation is an important part in sports expertise; it refers to the ability to predict what is likely to happen prior to the event itself. This ability to “read the play” is essential in sport where the speed of the game means that decisions must typically be made in advance of an opponent's action. Key factors behind anticipation in sport include visual abilities and perceptual and cognitive skills. The ability to recall and recognise an evolving pattern of play is the strongest predictor of anticipatory skill in team ball sports. For instance, we cannot compare anticipation of a volleyball serve, where the main goal is to send the ball over the net into the opposing court, with the anticipating of a volleyball setting action, where the purpose is to set the ball in proper position for the attack. The task in the first case may require different information processing strategies with respect to the other, such as the detection of postural cues or the recognition of an evolving pattern of play. Therefore, in certain situations it is conceivable that players may rely exclusively on the ability

to process information from an opponent's postural orientation, whereas in others they have to make an anticipatory judgment based on perceived event probabilities. The ability to extract important information from a sport action, even in the same sport, may be related to the type of action being examined.

In this research we addressed the question whether gaze behaviour can affect performance in volleyball. In this regard, volleyball has been extensively investigated, but we still do not have exhaustive results that let us know about better visual search strategy of expert over novice players. Some authors, using simple laboratory tasks, demonstrated that there are specific visual skills and better results in advanced volleyball players compared with beginners [7–9]; others showed faster simple reaction times (RTs) in expert than novice players [10–12]; still others established some differences in gaze strategy due to the level of expertise [13–15]; and a few studies have reported athletes performing a little faster than novices, in the choice of RT tasks with generic stimuli [11, 16].

In volleyball, experts perform better in tasks concerning perceptual speed, extent of the focus of attention, prediction and estimation of speed, and direction of moving objects [13, 17]. Relevant information would include, among others, the ball distance, its angle, velocity, and acceleration of descent, setter's body movements, as well as the appropriate procedures for using these variables to correctly evaluate the ball trajectory. What processes volleyball player actually can and do use to solve the task? As a result, employing a strategy that accurately and swiftly identifies and interprets the relevant information from the surroundings ensures that athletes are better prepared to perform successfully. As it turns out, human decision makers often use simple rules that neither require all available relevant information nor integrate the information that is used but that however allows them to accomplish their aims quickly and effectively, following a simple heuristic [18]. Shim et al. [19] found that increasing the information shown to the participants had opposite effects on novice and skilled performers. Novice players' anticipation accuracy decreased as more information was presented because they are unable to distinguish between relevant and irrelevant information.

Piras et al. [13] compared gaze strategy of expert and novice volleyball players while observing a filmed action in which the coach tosses the ball to the setter. They found that expert players did a fewer number of fixations of longer duration to the setter's hands and body, likely trying to gain the greatest information from the body motion, to predict the ball trajectory. This simple decision strategy, also called simple heuristic [20], can rely on the concept that less (in terms of fewer number of fixations) can be more (in terms of predictive ability) connected to the idea that athletes use less information or require fewer cognitive steps to achieve the target [21]. From the simple heuristic perspective, visual search strategy is based on the importance of the cues and their relationships as a simple decision strategy for future actions. The ability to extract better quality information per fixation and to acquire information more effectively via peripheral vision contributes to expert's superior anticipation in these contexts. By contrast, novices jump back and forth

between relevant and irrelevant regions, probably because they cannot distinguish task-relevant from task-irrelevant cues, thus producing many fixations of shorter durations. If one cue is more important than the sum of the others, experts can use this knowledge, which they gain from experience, and stop searching after considering one cue. On the other hand, novices consider multiple cues because they have not figured out which one is the most predictive and they have more problems to distinguish which cue is important when the amount to be processed increases (for a review see [20]). In line with the simple heuristics explanation, some authors reported that experts show fewer fixations of longer durations within the task [22]. However, other studies have found an opposite results pattern, with experts showing an increased number of fixations of shorter duration on more cues than novices [23]. These divergent results indicate that the simple heuristics explanation cannot completely account for expert's superior performance.

To explain the shorter fixation durations of experts, a long-term memory hypothesis has been proposed. According to this hypothesis, experts can encode and retrieve information more rapidly than novices and thus have on average shorter fixation durations than novices. Long-term working memory is a memory skill that individuals acquire to meet the particular memory demands of a complex cognitive activity in a particular domain. In order to attain skilled performance, individuals acquire domain-specific knowledge, procedures, and various perceptual motor skills. To meet the particular demands for working memory in a given skilled activity, subjects acquire encoding methods and retrieval structures that allow efficient storage and retrieval from long-term memory (for a review see [24]). According to the long-term memory hypothesis, if expertise in a particular context is based on more efficient encoding and retrieval of information, we can expect fixations of shorter durations. What differs is the point of view of the information reduction hypothesis [25] that focuses on the learned selectivity of information processing. Experts optimize the amount of processed information focusing on task-relevant information and arrive at more accurate predictions. This is accomplished through strategic considerations in order to selectively allocate attentional resources. Therefore, experts should exhibit fewer fixations of shorter duration on task-redundant areas and more fixations of longer duration on task-relevant areas. Previous studies have shown that athletes focus their attention on task-relevant areas and overall show fewer fixations of longer durations than novices, presumably because experts use parafoveal regions to extract information from a large number of visual cues [13, 26, 27]. These results seem inconsistent with the long-term memory hypothesis, which would have predicted shorter fixation durations for experts.

In a previous study [13] we presented a viewing task where experts and novices were instructed to watch video clips very carefully. The task was different with respect to the present study because the video clips showed the complete sequence of setter's action with the ball tossed to either forward (to field position 4) or backward (to field position 2). Our first intention was to discover the differences in visual search strategy analyzing the mean number and duration of each

fixation, identifying where, when, and how athletes fixate their gaze in order to better understand opponent's tactical behaviour. This second purpose was achieved by analyzing the temporal sequence of fixations, that is, a quantitative analysis of the most frequent gaze shifts over the different interest areas. Results favoured an information reduction account, showing that expert volleyball players, compared to novices, used a search strategy involving fewer fixations with longer duration, spending more time fixating first at the initial ball flight and then making a saccade to setter's hand, disregarding the intermediate phase of the ball trajectory. Their gaze was directed mainly to setter's body [13]. A shortcoming of this study was that the key-press response time and the response accuracy were not considered.

In order to study the relationship between gaze strategy and anticipatory processes, in this paper we report results of key-press response time and gaze behaviour recorded from experts and novices, in a task in which the participants were required to predict the target location of setter's toss. According to previous research [13], we wanted to test the hypothesis whether expert volleyball players demonstrate superior anticipation, defined as higher response accuracy and shorter key-press response times, with respect to novices and, if so, whether this superiority can be explained with the use of a more efficient and effective visual search strategy, evaluated as fewer number of fixations of longer durations on relevant interest areas.

Furthermore, given that the majority of researchers interested in visual search behaviour in sports, and particularly in volleyball, have attempted to identify differences in point of gaze as a function of expertise, it is important to examine whether successful performers employ different visual search patterns than unsuccessful performers within a group where the participants are presumed to have a similar level of expertise [28]. Several researchers have highlighted the potential advantage of using a within-task criterion to stratify participants into groups, to reduce variability in performance level in measures of perceptual-cognitive skill [28–30]. Thus, to strengthen the hypothesis of a relationship between gaze strategy and action effectiveness, we wanted to determine whether there are any differences in visual search behaviour within a group of experts on successful versus unsuccessful volleyball settings. This methodology would increase measurement sensitivity and highlight the potential relationship between visual search behaviour and decision making skill in simulated dynamic volleyball setting action.

2. Methods

2.1. Participants. Fifteen expert volleyball players (Italian professionals league B1) and fifteen novices were recruited for the study. Novices had not participated in any sport at a professional level, and although they all knew the rules and the practice of volleyball, they had never participated regularly in volleyball. Mean age of participants was 24.47 ± 1.52 years (experts = 24.87 ± 1.92 ; novices = 24.07 ± 0.88 , $F = 2.14$, $P = 0.15$, Cohen's $d = -0.15$, $r = -0.26$). They all voluntarily underwent the test, which did not include

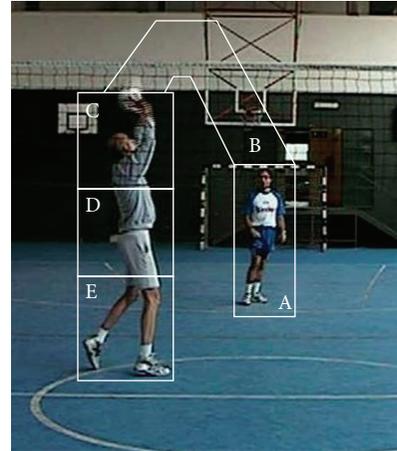


FIGURE 1: Viewpoint of the participant showing the setter's hands-ball contact. White lines delineate the interest areas. A = IA-1, coach; B = IA-2, ball trajectory; C = IA-3, setter's hands; D = IA-4, setter's trunk; and E = IA-5, setter's legs. Areas external to the contours are considered as out.

any invasive or harmful procedures. All participants received a verbal explanation of experimental procedures and gave their written informed consent before participating in the study. None of them reported any uncompensated visual deficit or difficulty with the stimuli used in the present study. The experimental protocol was approved by the Institutional Ethic Committee of the University of Bologna.

2.2. Test Film. The setup was the same used in a previous research [13]. A setter was filmed from the block and defense team's perspective. The film clips were recorded using a digital video camera (Hitachi Dz-Mv270 e) at 30 frames/s, with resolution of 1280×960 pixels, and placed 154 cm from the floor and 550 cm from the net in the middle of the court. The filmed action consisted of the coach (positioned on back zone of the volleyball court) tossing the ball to the setter (positioned on front zone of the volleyball court), who had to set it either forward (to field position 4) or backward (to field position 2). When presented to the experimental participants the film finished when the ball touched setter's hands (see Figure 1). Specifically, we stopped the film sequences at the moment when the setter received the ball to prevent participants from receiving any feedback in relation to the decision that was made during the actual filming session.

The filming perspective we used provided a wide viewing angle and some perspective, which enable us to facilitate the perception of depth. That viewing angle provided the closest correspondence to the field of view that a central defensive player typically observes. We therefore asked the participants to image themselves as a defensive blocker playing in a central position that was just in front of the camera. The setter had to play as if he was in a real game, doing the perfect pass for the hitter. The role of the blocker is to read opponent's setter and determine where the ball will be sent, and once the ball is hit, he/she has to try to block it.

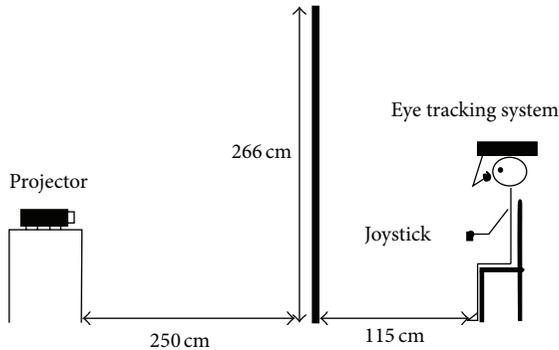


FIGURE 2: A lateral view of the experimental setup.

Twelve 6 sec video clips, containing either a forward or a backward set, were shown to each subject for 10 times in a random order. Thus, each participant viewed a total of 120 trials.

2.3. Apparatus. The participants sat on a chair, in front of a vertical translucent screen (266×269 cm), 115 cm from subject's eyes (see Figure 2). The sequences were back-projected by a digital projector with a resolution of 1024×768 pixels, distant 250 cm from the screen and forming an image 87 cm high and 120 cm wide. Eye movements were recorded binocularly by a video-based eye tracking system (EyeLink II, SR Research Ltd, Mississauga, Canada). The system consists of two miniature cameras mounted on a leather-padded headband. The entire system, weighing ~420 g, has a low center of mass for stability and subjective comfort. Pupil tracking was performed at 500 samples/s, with a gaze resolution $<0.005^\circ$ and noise limited to $<0.01^\circ$. Data were encoded by software (Eyelink Data Viewer) that allows displaying, filtering, and presenting the results. Only data regarding the right eye were analyzed for this work. Gaze behaviour consisted of gaze fixations defined as the time the eye remained stationary (within 1.5° window) for a period greater than 99.99 ms. All events corresponding to eyelid occlusion (blinks), to pupil size very small, or to image missed or severely distorted were discarded. Events that occurred 100 ms before or after a blink were also discarded.

2.4. Procedure. Before each participant was tested, eye tracking calibration was carried out, in order to link participant's eye position to specific positions on the screen. To do this, eye position was recorded while randomly presenting a target on regularly spaced points of a nine-point grid of known size; then, data validation was performed after each block of twelve videos. Finally, drift correction was executed after each trial.

In the video stimulus, each video clip started with a 500 ms acoustic tone to prepare participants for the video onset. The duration of each clip was equal across all trials. The participants were required to follow the action as if they were on volleyball field. The locations of the volleyball sets were completely randomized but kept in the same order for each participant. The filmed action consisted of the coach tossing the ball to the setter, who had to set either forward (to

court position 4) or backward (to court position 2). When the ball reached setter's hands, the participant had to determine as quickly and accurately as possible whether the offensive action in the stimulus would come forward or backward of the setter. The response was given by pressing one of two buttons (right or left) of a game pad. The response cleared the screen (i.e., caused the end of the video clip) for the next video to begin. No feedback was given to the participants as to their performance on each trial. Practice, calibration, validation, rest periods, and data collection took on average 30–40 minutes per participant. Practice (5 similar trials but with different video clip) was necessary in order to avoid incorrect response due to the lack of ability to use the system. Participants were encouraged to take a break of 5 minutes midway through the experiment, after 60 trials.

2.5. Dependent Variables and Analysis

Anticipation Test. The ability to make accurate predictions from advanced sources of information was measured as follows.

(i) **Response Accuracy.** The percentage of trials in which subject's response was correct or incorrect (i.e., forward or backward judgement) was determined.

(ii) **Key-Press Response Time.** The time (ms) from setter's hands-ball contact to the button pressed by the participant was determined. Responses with RTs shorter than 150 msec and longer than 600 msec were discarded (early or delayed responses) [11]. After preprocessing we used 980 videos for athletes (from 1800 or 54%, 820 videos were excluded) and 669 for novices (from 1800 or 37%, 1131 videos were excluded). Response time was also related to the accuracy of the response (correct/incorrect).

Visual Search Data. The following visual search measures were analyzed.

(i) **Search Rate.** This measure included the mean number of visual fixations and the mean fixation duration per trial between groups across correct and incorrect responses.

(ii) **Percentage Viewing Time.** Mean percentage of time participants spent fixating the gaze on each interest area of the display when trying to anticipate ball direction was determined. For this purpose, the screen was divided into five areas (IAs): (i) IA-1, 6° (width) \times 12° (height) of visual angle in size, included the coach that performs the pass to the setter; (ii) IA-2, 10° (w) \times 20° (h), included the ball trajectory from the coach to the setter; and (iii) IA-3 to IA-5 subdivided the setter's body in three: the first part, 12° (w) \times 6° (h), includes the hands and the shoulders, the second part, 12° (w) \times 6° (h), includes the body from the shoulders to the hip, and the third one, 12° (w) \times 8° (h), is from the hip to the tip of the feet. All fixations outside these IAs were referred to as "out" fixations (see Figure 1).

TABLE 1: Dependent measures, choice response time (CRT) and response accuracy (RA), recorded on the anticipation test across groups (mean \pm s). Only trials with response time between 150 and 600 msec are reported.

			Experts	Novices
Choice reaction time (ms)		Total	351.02 \pm 14.47	406.21 \pm 12.19
		Correct response	385.31 \pm 21.23	397.48 \pm 17.72
		Incorrect response	316.73 \pm 17.91	414.94 \pm 16.91
Response accuracy (number of trials)	Total	Incorrect	92.00	154.00
		Correct	888.00	515.00
		Total count	980.00	669.00
	Correct	% of total forward	88.00%	72.00%
		% of total backward	93.00%	81.00%
		% of total	91.00%	77.00%
	Incorrect	% of total forward	12.00%	28.00%
		% of total backward	7.00%	19.00%
		% of total	9.00%	23.00%

We analyzed these data in relation to key-press response time and accuracy of the response (correct, incorrect). To examine whether performance levels changed across consecutive sessions, repeated measures analyses of variance (ANOVA) were carried out for each variable, with trial (10) as the within-subject factor. Mauchly's test was considered for each variable to assess assumptions of sphericity. If assumptions of sphericity were violated, the Greenhouse-Geisser epsilon corrections of degrees of freedom were used [31].

3. Results

No within-session practice effects were observed for any variable; the reason might be related to the lack of feedback in the study.

3.1. Anticipation Test. The anticipation test variables are presented in Table 1.

A repeated measures ANOVA was conducted on the proportion of correct responses in which setting directions (backward, forward) were the within-subjects factors and expertise (experts, novices) the between-subjects factor. ANOVA showed a significant main effect for expertise ($F_{1,28} = 5.50$, $P = .026$, and $\eta p^2 = .16$), suggesting that participants showed more correct responses in comparison to novices (see Table 1).

A 2×2 repeated measures ANOVA was also done to analyse the key-press response time in which setting direction (backward, forward) and response accuracy (correct, incorrect) were the within-subjects factors, expertise (experts, novices) the between-subjects factor. ANOVA showed a significant main effect for expertise ($F_{1,28} = 5.20$, $P = .038$, and $\eta p^2 = .13$) and a response accuracy \times expertise interaction effect ($F_{1,28} = 5.22$, $P = .030$, and $\eta p^2 = .15$). The main effect of expertise was due to the fact that experts showed a shorter key-press response time with respect to novices. The interaction effect was due to the fact that experts took longer to provide correct than incorrect responses, whereas novices

showed the opposite results pattern, of longer response times on incorrect trials (see Table 1).

The results showed a clear effect of expertise, with shorter RT and higher accuracy for experts than novices (91% versus 77%).

3.2. Visual Search Data. All search rate dependent variables (number of fixations and fixation durations) were analysed separately using a 2×2 repeated measures ANOVA, with response accuracy (correct, incorrect) and setting direction (backward, forward) as a within-subjects factor, and expertise (experts, novices) as a between-subjects factor.

Analysis of mean fixation durations showed significant main effects for expertise ($F_{1,28} = 25.29$, $P < .001$, and $\eta p^2 = .47$) and for expertise \times response accuracy interaction ($F_{1,28} = 4.29$, $P = .048$, and $\eta p^2 = .11$).

Analysis of mean number of fixations also showed significant main effects for expertise ($F_{1,28} = 62.66$, $P < .001$, and $\eta p^2 = .69$) and for expertise \times response accuracy interaction ($F_{1,28} = 36.90$, $P < .001$, and $\eta p^2 = .56$).

Experts performance and correct responses were both associated with a lower number of fixations and shorter fixation durations. Athletes made 12.72 and 15.62 number of fixations with 508.50 and 495.27 milliseconds of fixation durations for correct and incorrect responses. Novices made 20.61 and 17.12 number of fixations with 444.22 and 466.75 milliseconds of fixation durations for correct and incorrect responses, respectively.

3.3. Correlation Analysis. To assess whether the pattern of response time correlates with gaze behaviour, we calculated the correlation between gaze parameters and response time in correct and incorrect responses across groups. The partial correlations procedure computes partial correlation coefficients that describe the linear relationship between two variables while controlling for the effects of one or more additional variables ($P < 0.05$). There was a significant correlation between fixation durations and response time

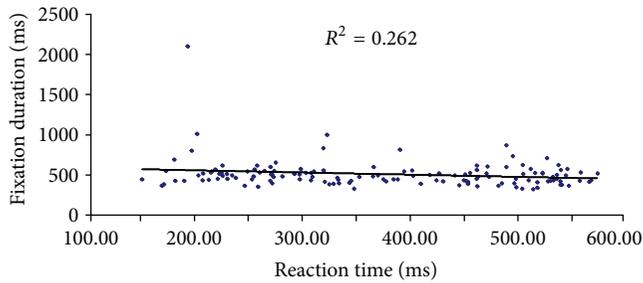


FIGURE 3: Correlation between gaze parameter and response time in experts' correct responses. Dots represent all participants' mean value for each correct trial. The line represents the regression coefficient ($r = -.22$, $P < .001$) for expert groups.

in expert's correct responses when fixation number was a control variable ($r = -.22$, $P < .001$) (see Figure 3). A significant correlation was also found between fixation durations and number of fixations in experts ($r = -.18$, $P = .003$) and novices' correct responses ($r = -.19$, $P = .003$) using response time as a control variable. None of the corresponding correlations were significant for incorrect responses.

3.4. Percentage Viewing Time. Results are presented in Figures 4 and 5. A $2 \times 6 \times 2$ repeated measures ANOVA was used to analyse percentage viewing time in which setting direction (backward, forward), fixation locations (coach, legs, hands, out, ball, and trunk), and response accuracy (correct, incorrect) were the within-subjects factors and expertise (experts, novices) the between-subjects factors. The analysis indicated significant main effects for expertise ($F_{1,28} = 3.84$, $P = .048$, and $\eta p^2 = .06$), setting direction ($F_{1,28} = 10.73$, $P = .003$, and $\eta p^2 = .27$), fixation locations ($F_{5,140} = 17.20$, $P < .001$, and $\eta p^2 = .38$), and accuracy ($F_{1,28} = 27.54$, $P < .001$, and $\eta p^2 = .49$). Analysis also showed expertise \times accuracy ($F_{1,28} = 12.41$, $P < .001$, and $\eta p^2 = .30$) and fixation locations \times accuracy \times expertise ($F_{5,140} = 9.46$, $P < .001$, $\eta p^2 = .25$) interactions. t -tests, with Bonferroni correction, revealed that when the responses were incorrect, experts showed longer fixations on legs [$t(28) = 5.28$; $P < .001$] and on hands [$t(28) = 3.40$; $P < .001$] areas in comparison to novices (see Figure 4(a)).

Paired sample t -tests, with Bonferroni correction, showed that only experts revealed significant differences between areas on correct/incorrect trials, looking longer on legs [$t(14) = 9.13$; $P < .001$], hands [$t(14) = 5.70$; $P < .001$], and trunk [$t(14) = 3.95$; $P < .001$] areas when the responses were incorrect than correct (see Figure 5(a) (right panel)). No significant differences were found for the novice group (see Figure 5).

In correct responses, experts spent less time fixating on all locations with respect to novices and more time fixating on leg and hand areas in incorrect ones. The percentage of time spent by experts increased during backward setting and when they made wrong responses (see Figure 5).

4. Discussion

The aims of this study were (1) to examine the relationships between visual search behaviour and anticipatory responses in order to discover differences between expert and novice volleyball players and (2) to compare gaze strategies and action effectiveness in an expert group.

As predicted, experts had better performance on the anticipation test than their novice counterpart, in that they were more accurate in predicting the direction of the setting and faster in response than novices' group. They showed 91% of correct responses against 77% of novices and a shorter key-press response time. In the gaze behaviour domain, experts, as already shown in a previous study [13], used a search strategy involving less number of fixations of longer duration than their novice counterpart.

As was mentioned in previous reports [4, 32], experts are able to reduce the amount of information to be processed or require fewer fixations to create a coherent perceptual representation of the display. Our results seem to be in contrast with the theory of long-term working memory [33], for which experts when encode and retrieve information more rapidly than novices need shorter instead of longer fixation durations. On the other hand, our results on fixation durations are in agreement with the information reduction hypothesis, in which experts should exhibit longer fixation durations on task-relevant areas [25]. Our experts demonstrated longer fixation durations on task-relevant areas, especially when time on task was limited and response accuracy was a performance predictor. Moreover, we found significant correlations between fixation durations and number of fixations in experts and novices' correct responses and between fixation durations and response time in expert's correct response, when fixation number was a control variable. Results indicate that as the number of fixations decreases, duration of each fixation increases linearly only when the responses are correct. This is in line with the simple heuristics explanation and previous studies that reported that experts show less fixations of longer duration within the task [22]. Experts also showed longer fixations when response time decreased and they gave correct responses, which resulted in superior performance, characterized by faster decision times and greater response accuracy. This is interpreted as a simple heuristic and is in line with the hypothesis that athletes use less information or require fewer cognitive steps to arrive at a correct prediction. From this perspective, search is based on the importance of the cues and their reciprocal relationships. If one cue is more important than the sum of the others, experts can use this knowledge, which they gain from experience, and stop searching after considering this cue. As a matter of fact, the mean percentual viewing time analysis of incorrect responses, in this research, was similar to that of our previous paper, where athletes fixated the gaze particularly on hands, trunk, and legs of the setter [13]. In the present experiment, athletes, instructed to anticipate rather than just observe film clips, fixated longer on legs, hands, and trunk in incorrect than in correct trials. The fixation of setter's body parts (legs, trunk, and hands) by the experts could be explained by the fact that they chose to anchor the fovea close

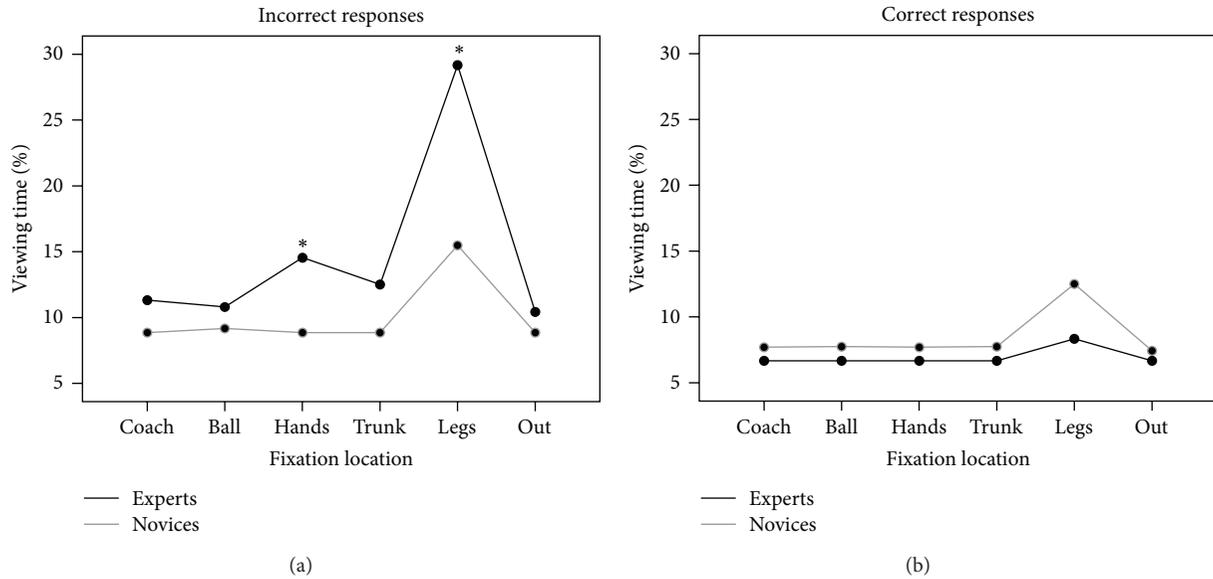


FIGURE 4: Mean percentage of time spent by subjects viewing each fixation location for the correct and incorrect responses across groups. Black lines = experts; gray lines = novices. Asterisks show significant differences ($P < .001$).

to these key locations so that they could use the parafovea and visual periphery to pick up relevant information [27]. The effective use of such “visual pivots,” in which the gaze is centrally located between locations, thus enabling the optimal use of both the foveal and parafoveal vision, suggests that a specific information cue is less important than the relative motions between these areas (i.e., legs, hands, and trunk). A visual pivot is needed when spatial information is complex and where there is a need to shift the gaze quickly between different locations [34]. We would agree and add that, in volleyball, experts use such visual pivot for maximum information extraction under extreme time constraints, and simultaneously, we can assume that if they remain for too long time there, the likelihood to respond incorrectly increases. Moreover, when the comparison was done between groups, experts revealed more fixations on legs and hands areas in incorrect responses. It seems that setter’s hands, legs, and trunk, if fixated for too long time, are not the optimal areas to predict the future setting direction.

The results did not support all predictions of the information reduction hypothesis, as errors, or poorer performance, could not be related to longer inspection of task-irrelevant areas. Although both recognition (our first study) and anticipation (present results) tasks stimulate complex retrieval structures, the processes involved in activating these structures do differ to some degree. While recognition may be involved in anticipation, the latter expertise appears more complex, invoking different and more refined retrieval structures [35, 36]. Present results suggest that, for experts, more time spent in fixating on legs, hands, and trunk ended up with more incorrect than correct responses. In fact, experts’ group spent more time than novices on all interest areas when they gave incorrect responses and less time when the responses were correct. Considering just experts’ group, they spent

longer period of time fixating on legs, hands, and trunk when they gave wrong responses during backward setting. It seems that athletes, trying to foresee setter’s intention, watch longer all interest areas. This could be because setter’s actions are more difficult in a subset of videos and the increased difficulty level brings about the divergent eye movement patterns as well as the wrong responses. This might be related to the difficulty to “catch visual cues” from the setter when time is short. Volleyball players often have to quickly shift from a diffuse attention, coarsely attending to opponent’s scene, to a more focused attention, aiming at opponent’s body or at the ball. Results of visual scanning studies and kinematics analysis of volleyball settings show that expert players direct their gaze not only towards specific relevant information in the visual field, but also towards intermediate positions between several visual cues [34]. Thus, it can be assumed that volleyball players perform zooming operations, adapting the span of the attentional focus to encompass only few or many elements depending on the game context.

In conclusion, the present study discerned two strategies among expert players in their attempts to block two different types of volleyball attack. With respect to setting directions, experts appear to use a different strategy in backward than forward settings. In fact, in the first case, they watched for too long all interest areas, especially legs, hands, and trunk, while, in forward setting, they watched equally, for short times, coach, ball, hands, and trunk areas and, more, although not significant, setter’s legs. With respect to response accuracy, experts employ a distinct anticipation strategy in correct responses, where they watched equally, for short times, all areas, while in incorrect responses they watched more the setter’s legs, hands, and trunk. The critical difference for success seems not to fix for long time any of the interest areas to decide the ball destination but to use a visual

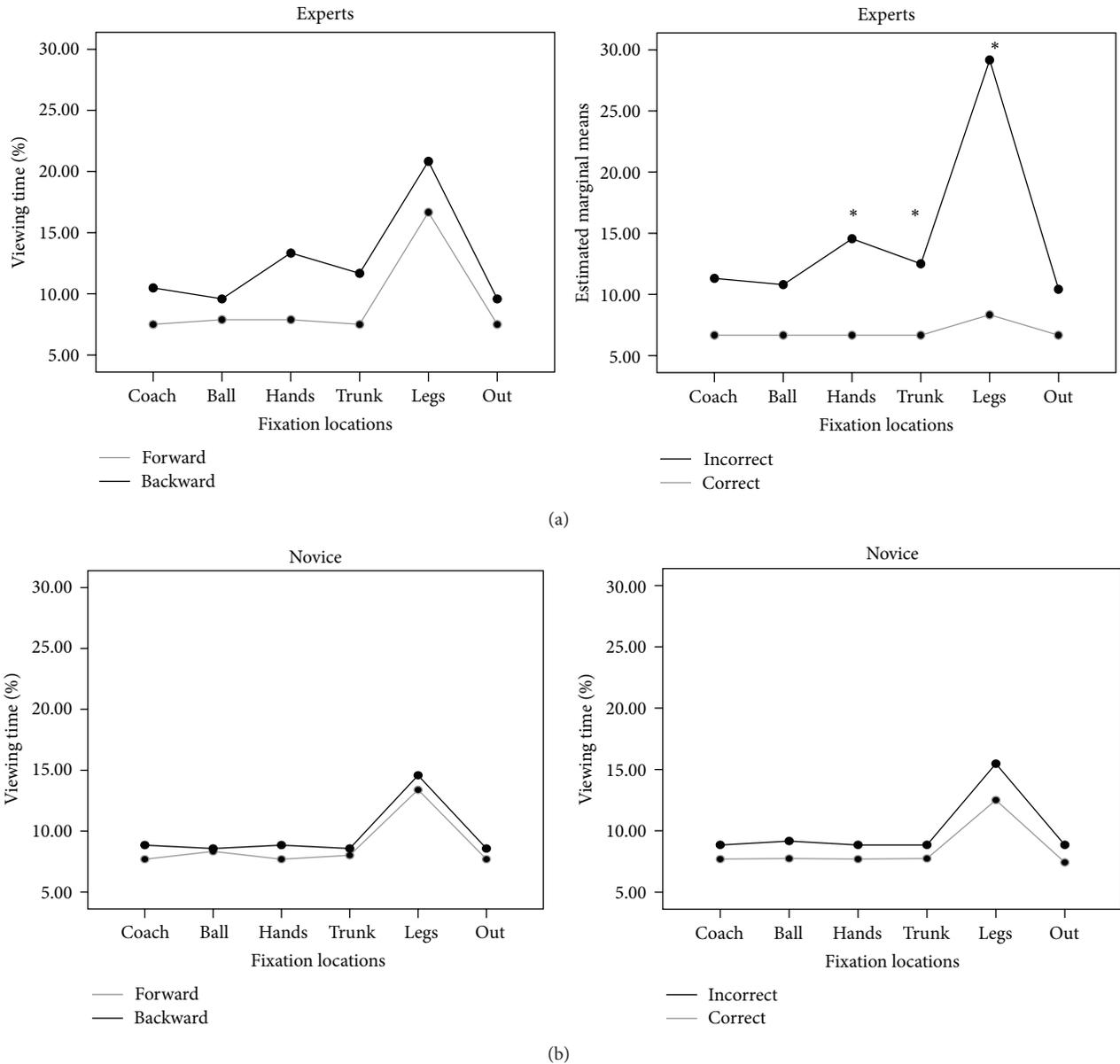


FIGURE 5: Mean percentage of time spent by experts (a) and novices (b) viewing each location for the backward (black lines) and forward (gray lines) settings on the left chart and incorrect (black lines) and correct (gray lines) responses to the right chart. Asterisks show significant differences ($P < .001$).

search strategy aimed at the most efficient extraction of information per fixation. The best parameters for successful performance, on expert group, were few number of fixations, of 500 ms each, during the phase before hands-ball contact, an anticipatory response time between 346 and 367 ms after the hands-ball contact, and a low number of interest areas fixated per trial.

Our study confirmed the superior speed of information processing achieved by experts and their greater accuracy in task performance than novice players. Moreover, these findings imply that experts are able to extract relevant

information from different body areas simultaneously when attempting to anticipate their opponents' intentions [35]. Expert athletes optimize the amount of processed information focusing on task-relevant information and selectively allocating attentional resources.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgment

This paper is dedicated to the memory of Roberto Lobietti, a volleyball coach, our colleague, friend, and coauthor of this work, who recently passed away.

References

- [1] A. M. Williams and D. Elliott, "Anxiety, expertise, and visual search strategy in karate," *Journal of Sport and Exercise Psychology*, vol. 21, no. 4, pp. 362–375, 1999.
- [2] R. J. Babu, L. Lillakas, and E. L. Irving, "Dynamics of saccadic adaptation: differences between athletes and nonathletes," *Optometry and Vision Science*, vol. 82, no. 12, pp. 1060–1065, 2005.
- [3] B. Abernethy, "Training the visual-perceptual skills of athletes: insights from the study of motor expertise," *The American Journal of Sports Medicine*, vol. 24, pp. S89–S92, 1996.
- [4] B. Abernethy, "Visual search strategies and decision-making in sport," *International Journal of Sport Psychology*, vol. 22, pp. 189–201, 1991.
- [5] B. Abernethy and J. M. Wood, "Do generalized visual training programmes for sport really work? An experimental investigation," *Journal of Sports Sciences*, vol. 19, no. 3, pp. 203–222, 2001.
- [6] D. Y. Mann, A. M. Williams, P. Ward, and C. M. Janelle, "Perceptual-cognitive expertise in sport: a meta-analysis," *Journal of Sport and Exercise Psychology*, vol. 29, no. 4, pp. 457–478, 2007.
- [7] E. Jafarzadehpur, N. Aazami, and B. Bolouri, "Comparison of saccadic eye movements and facility of ocular accommodation in female volleyball players and non-players," *Scandinavian Journal of Medicine and Science in Sports*, vol. 17, no. 2, pp. 186–190, 2007.
- [8] J. McAuliffe, "Differences in attentional set between athletes and nonathletes," *Journal of General Psychology*, vol. 131, no. 4, pp. 426–437, 2004.
- [9] P. Borgeaud and B. Abernethy, "Skilled perception in volleyball defense," *Journal of Sport Psychology*, vol. 9, pp. 400–406, 1987.
- [10] E. Kioumourtzoglou, T. Kourtessis, M. Michalopoulou, and V. Derri, "Differences in several perceptual abilities between experts and novices in basketball, volleyball and water-polo," *Perceptual and Motor Skills*, vol. 86, no. 3, pp. 899–912, 1998.
- [11] T. Zwierko, W. Osiński, W. Lubiński, D. Czepita, and B. Florkiewicz, "Speed of visual sensorimotor processes and conductivity of visual pathway in volleyball players," *Journal of Human Kinetics*, vol. 23, no. 1, pp. 21–27, 2010.
- [12] C. P. Anzeder and R. Bösel, "Modulation of the Spatial Extent of the Attentional Focus in High-level Volleyball Players," *European Journal of Cognitive Psychology*, vol. 10, no. 3, pp. 247–267, 1998.
- [13] A. Piras, R. Lobietti, and S. Squatrito, "A study of saccadic eye movement dynamics in volleyball: comparison between athletes and non-athletes," *Journal of Sports Medicine and Physical Fitness*, vol. 50, no. 1, pp. 99–108, 2010.
- [14] J. L. Starkes, P. Edwards, P. Dissanayake, and T. Dunn, "A new technology and field test of advance cue usage in volleyball," *Research Quarterly for Exercise and Sport*, vol. 66, no. 2, pp. 162–167, 1995.
- [15] D. L. Wright, M. Gomez-Meza, and F. Pleasants, "Use of advanced visual cue sources in volleyball," *Journal of Sport & Exercise Psychology*, vol. 12, pp. 406–414, 1990.
- [16] M. Kokubu, S. Ando, N. Kida, and S. Oda, "Interference effects between saccadic and key-press reaction times of volleyball players and nonathletes," *Perceptual and Motor Skills*, vol. 103, no. 3, pp. 709–716, 2006.
- [17] B. A. Sibley and J. L. Etnier, "Time course of attention and decision making during a volleyball set," *Research Quarterly for Exercise and Sport*, vol. 75, no. 1, pp. 102–106, 2004.
- [18] G. Gigerenzer, *Fast and Frugal Heuristics: the Tools of Bounded Rationality*, Blackwell Handbook of Judgment and Decision Making, 2004.
- [19] J. Shim, L. G. Carlton, J. W. Chow, and W.-S. Chae, "The use of anticipatory visual cues by highly skilled tennis players," *Journal of Motor Behavior*, vol. 37, no. 2, pp. 164–175, 2005.
- [20] M. Raab, "Simple heuristics in sports," *International Review of Sport and Exercise Psychology*, vol. 5, no. 2, pp. 104–120, 2012.
- [21] W. M. Bennis and T. Pachur, "Fast and frugal heuristics in sports," *Psychology of Sport and Exercise*, vol. 7, no. 6, pp. 611–629, 2006.
- [22] C. Bertrand and F. Thullier, "Effects of player position task complexity in visual exploration behavior in soccer," *International Journal of Sport Psychology*, vol. 40, no. 2, pp. 306–323, 2009.
- [23] P. Konstantopoulos, *Investigating drivers' visual search strategies: towards an efficient training intervention [Ph.D. Dissertation]*, University of Nottingham, 2009.
- [24] K. A. Ericsson and W. Kintsch, "Long-term working memory," *Psychological Review*, vol. 102, no. 2, pp. 211–245, 1995.
- [25] H. Haider and P. A. Frensch, "Eye movement during skill acquisition: more evidence for the information-reduction hypothesis," *Journal of Experimental Psychology: Learning Memory and Cognition*, vol. 25, no. 1, pp. 172–190, 1999.
- [26] A. Piras, E. Pierantozzi, and S. Squatrito, "Visual search strategy in judo fighters during the execution of the first grip," *International Journal of Sports Science and Coaching*, vol. 9, no. 1, pp. 185–198, 2014.
- [27] A. Piras and J. N. Vickers, "The effect of fixation transitions on quiet eye duration and performance in the soccer penalty kick: instep versus inside kicks," *Cognitive Processing*, vol. 12, no. 3, pp. 245–255, 2011.
- [28] G. J. P. Savelsbergh, J. Van der Kamp, A. M. Williams, and P. Ward, "Anticipation and visual search behaviour in expert soccer goalkeepers," *Ergonomics*, vol. 48, no. 11–14, pp. 1686–1697, 2005.
- [29] R. Vaeyens, M. Lenoir, A. M. Williams, and R. M. Philippaerts, "Mechanisms underpinning successful decision making in skilled youth soccer players: an analysis of visual search behaviors," *Journal of Motor Behavior*, vol. 39, no. 5, pp. 395–408, 2007.
- [30] A. M. Williams and K. A. Ericsson, "Perceptual-cognitive expertise in sport: some considerations when applying the expert performance approach," *Human Movement Science*, vol. 24, no. 3, pp. 283–307, 2005.
- [31] J. R. Jennings, M. J. Cohen, D. S. Ruchkin, and A. J. Fridlund, "Methodology. Editorial policy on analyses of variance with repeated measures," *Psychophysiology*, vol. 24, no. 4, pp. 474–478, 1987.
- [32] G. J. P. Savelsbergh, A. M. Williams, J. Van Der Kamp, and P. Ward, "Visual search, anticipation and expertise in soccer goalkeepers," *Journal of Sports Sciences*, vol. 20, no. 3, pp. 279–287, 2002.
- [33] N. Cowan, "The focus of attention as observed in visual working memory tasks: making sense of competing claims," *Neuropsychologia*, vol. 49, no. 6, pp. 1401–1406, 2011.

- [34] H. Ripoll, "Analysis of visual scanning patterns of volley ball players in a problem solving task," *International Journal of Sports Psychology*, vol. 19, pp. 9–25, 1988.
- [35] A. M. Williams, "Perceiving the intentions of others: how do skilled performers make anticipation judgments?" *Progress in Brain Research*, vol. 174, pp. 73–83, 2009.
- [36] J. S. North, A. M. Williams, N. Hodges, P. Ward, and K. A. Ericsson, "Perceiving patterns in dynamic action sequences: investigating the processes underpinning stimulus recognition and anticipation skill," *Applied Cognitive Psychology*, vol. 23, no. 6, pp. 878–894, 2009.

Clinical Study

Suppression of Face Perception during Saccadic Eye Movements

Mehrdad Seirafi,^{1,2} Peter De Weerd,^{2,3} and Beatrice de Gelder^{1,2}

¹ *Cognitive and Affective Neuroscience Laboratory, Tilburg University, 5037 AB Tilburg, The Netherlands*

² *Department of Cognitive Neuroscience, Faculty of Psychology and Neuroscience, Maastricht University, 6229 EV Maastricht, The Netherlands*

³ *Donders Institute for Brain, Cognition and Behaviour, Radboud University, 6500 GL Nijmegen, The Netherlands*

Correspondence should be addressed to Beatrice de Gelder; b.degelder@maastrichtuniversity.nl

Received 14 December 2013; Accepted 29 March 2014; Published 24 April 2014

Academic Editor: Stefanie I. Becker

Copyright © 2014 Mehrdad Seirafi et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Lack of awareness of a stimulus briefly presented during saccadic eye movement is known as saccadic omission. Studying the reduced visibility of visual stimuli around the time of saccade—known as saccadic suppression—is a key step to investigate saccadic omission. To date, almost all studies have been focused on the reduced visibility of simple stimuli such as flashes and bars. The extension of the results from simple stimuli to more complex objects has been neglected. In two experimental tasks, we measured the subjective and objective awareness of a briefly presented face stimuli during saccadic eye movement. In the first task, we measured the subjective awareness of the visual stimuli and showed that in most of the trials there is no conscious awareness of the faces. In the second task, we measured objective sensitivity in a two-alternative forced choice (2AFC) face detection task, which demonstrated chance-level performance. Here, we provide the first evidence of complete suppression of complex visual stimuli during the saccadic eye movement.

1. Introduction

We typically make hundreds of saccadic eye movements every minute [1, 2], resulting in a continuous shift of the visual world on the retina. Answering the question of how stable vision is achieved during saccade has been one of the major problems in unifying models for vision.

One of the key approaches in addressing this question is to study the dynamics of visual sensitivity in a time window around the saccadic eye movement. Several lines of research have revealed a dramatic deterioration of visual sensitivity at the time of saccade, known as saccadic suppression [3–6]. However, there is no general consensus about the domain and the underlying mechanisms of such sensitivity loss.

The source of sensitivity loss during saccade has been attributed to two different streams: top-down and bottom-up. In the top-down account, an active extraretinal suppression process is proposed [7] which targets only the magnocellular pathway [8] and does not affect the equiluminant visual stimuli [9]. On the other hand, the bottom-up account postulates a simple passive process of retinal motion smear

as a source of suppression during saccade [10, 11]. In this account, the presence of high contrast spatial structure before and after the saccade introduces the masking of the blurred perisaccadic retinal image [12, 13].

One of the questions regarding saccadic suppression is its possible effect in processing more complex and more biologically significant visual objects. The majority of saccadic eye movement studies in the past century have generally employed simple stimuli such as bars, dots, and gratings with different spatial frequencies and small window sizes that affected luminance instead of pattern detection. Some recent studies employing modern gaze-contingent paradigms have been focused on vision around the time of freely made eye movements in natural dynamic scenes [14]. However, such paradigms are not able to dissociate the sensitivity change during saccade from the forward and backward masking effects introduced by the pre- and postsaccadic retinal images. Furthermore, none of these experiments has been focused on measuring the sensitivity loss during saccade for object detection or object recognition tasks.

One of the challenges of dealing with more realistic objects is how to measure the visual sensitivity in the object detection/categorization tasks. There is an ongoing debate about whether the objective or the subjective measure is appropriate for this purpose. Subjective measures are based on a subject's report about the task-relevant attribute (e.g., object category) of the stimulus. Objective measures rely on the participant's performance in a certain task regardless of the participant's conscious awareness of the task-relevant attribute. Consequently, to fill in this theoretical gap, a new approach has emerged in recent years which takes into account both subjective and objective measures [15–17].

In the present study, we investigated the levels of saccadic suppression for the category of complex visual objects. The goal was to see whether a salient visual stimulus could still be rendered fully invisible if presented during saccadic eye movement. This was done by measuring the sensitivity loss during saccade for face stimuli using two separate tasks. In the first task, we recorded the subjective rating of the stimuli that were presented during saccade. In the second task, we measured the participants' objective face detection performance.

2. Methods and Materials

2.1. Participants. We recruited 14 participants (11 females, M_{age} : 24, age range: 18–32) from Maastricht University through local advertisements for this study. The study was conducted in accordance with university ethics committee requirements. The subjects gave informed consent to participate and were rewarded with 7.5 Euro vouchers. All participants were right-handed, with normal or corrected-to-normal vision and naive as to the purpose of the experiment. Two participants were excluded from the analysis due to the fact that they always pressed the same button to all stimuli in all conditions during the face detection task (see below).

2.2. Stimuli and Procedure

2.2.1. Physical Setup. Movements of the right eye were measured using an EyeLink 1000 Desktop Mount (SR Research, Osgoode, ON, Canada) with an average spatial resolution of 0.25- to 0.5-, sampling at 1 kHz. Manual responses were recorded via a standard keyboard. The real-time connection between the eye tracker and the stimulus presentation control as well as the response collection was implemented in E-Prime 2.0 Professional software (Psychological Software Tools, Inc., Pittsburgh, PA).

2.2.2. Image Preprocessing. Original face images were color images of two males and two females, each displaying the emotional conditions of happy, fearful, and neutral. These were selected from a subset of the Karolinska Directed Emotional Faces (KDEF) [18], previously validated to be correctly (>90%) categorized as happy, fearful, and neutral in a pilot study.

The stimuli were preprocessed as follows: first, all the original images were cropped and resized to fit into a

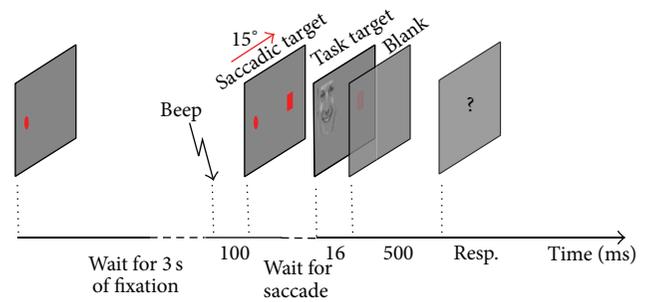


FIGURE 1: Schematic view of one trial: after 3 seconds, an auditory cue initiates the saccade followed by visual saccadic target. As soon as the saccade is detected, one visual stimulus (face or scramble) is presented, followed by a blank screen. Next, the task-relevant question is displayed on the screen.

rectangle matching eye position by Adobe Photoshop CS6 (Adobe; <http://adobe.com>). Then, average pixel values for each image were shifted to 128 in Matlab 2012a (Mathworks; <http://www.mathworks.com>). Scrambled faces (*scrambles*) were generated by randomizing the phases of Fourier transform of the preprocessed face stimuli while keeping the Fourier power constant. The phase shuffling is quantified by a phase coherence index, in which 0 means that all phase information has been randomized, preserving the overall distribution, and in which 100 means that all phase information is intact [19–21]. The main advantage of this technique is keeping the significant components for low-level vision (such as average luminance and Fourier power distribution) constant. The scrambles used in this experiment were generated at zero phase coherence.

2.2.3. Procedure and Stimuli. Before the beginning of the first block, participants were familiarized with the experimental procedure using a short run of the subjective rating task (see below) consisting of 4–8 trials. After the practice phase, we showed them two target stimulus examples of the two experimental conditions in order to acquaint them with the stimuli of the scramble condition. Therefore, they were completely aware of possible face and scramble conditions.

A trial proceeded as follows. A red circle was displayed on horizontal median, 1/4 of the screen to the left horizontally on a gray background (Figure 1). After 3 seconds of fixation on the circle (diameter = 0.5°) as measured by the eye tracker, a beep cued the participants to make a saccade. The auditory cue was accompanied with a *saccadic target* indicating where the end-location of the saccade should be. The saccadic target was a small rectangle, 15° to the right of the fixation on the horizontal meridian. As soon as the participant initiated the saccade, a *task target* (width = 8.5°) was displayed on top of the initial fixation point (*saccadic origin*) for 16.7 ms. Next, a blank grey screen was shown for 500 ms, followed by the response screen including task-relevant question (see below).

2.2.4. Design and Tasks. The participants performed two tasks in four separate experimental blocks: the first and

the last blocks were the subjective rating tasks; the second and the third blocks were the face detection task.

Task 1: Subjective Rating. In the subjective rating task, the participants reported what they saw during the saccade. They were instructed to choose “nothing,” “something,” or “everything” by pressing the corresponding arrow keys on the keyboard: (a) *left arrow key* for “nothing,” when they did not perceive any target stimulus or its background flashing on the screen during the saccade; (b) *down arrow key* for “something,” when they saw a bright rectangle flashing on the screen but did not see anything inside it; (c) *right arrow key* for “everything,” if they saw the target stimulus which could have been a face or a noisy grey texture. In addition, the participants were always asked if they had perceived something other than the three alternatives, to be sure that our options were inclusive of all the possible choices. Each experimental block in the subjective rating task consisted of 24 trials. The scramble and each of the three emotional face conditions (neutral, happy, and fearful) had the same proportion.

Task 2: Face Detection. In the face detection task, the procedure was similar to the subjective rating task except that the participants were asked to report whether they perceived the stimuli as a *face* or as a *scramble*. *Left* and *right* button presses corresponded, respectively, to face and scramble responses. Each experimental block in the face detection task consisted of 32 trials. In half of the trials, face stimuli were presented (with the same proportion of all three emotional conditions), and in the other half, scramble stimuli were presented.

2.3. Data Analysis

2.3.1. Signal Detection Theory. The sensitivity to the signal was estimated by calculating the *d*-prime (d'). The d' is a measure of the distance between the signal and the noise distribution means in standard deviation units [22]. A d' of 0 means that the participants are not able to discriminate the faces from scrambles in face detection task. The d' was calculated as

$$d' = \Phi^{-1}(H) - \Phi^{-1}(FA), \quad (1)$$

where H is the hit rate (proportion of correctly responded trials with face stimuli) and FA is the false alarm rate (proportion of correctly responded trials with scramble stimuli). The function Φ^{-1} converts the rates into z -scores.

2.3.2. Gaze Analysis and Saccade Detection. The saccades were detected based on the commonly used saccadic threshold for the velocity of eye movement based on weighted sum of four samples as follows:

$$V^2 + V'^2 > \nu (\text{thrs})^2, \quad (2)$$

where V and V' are components of pupil velocity on horizontal and vertical axes, respectively, and ν (thrs) is set to 40

degrees/second. Velocity for each sample was calculated by a weighted sum of four samples as follows:

$$V_{s[n]} = \frac{(1000 (x_{[n+2]} + x_{[n+1]} - x_{[n-1]} - x_{[n-2]}))}{(6\text{PPD}_{[n]})}, \quad (3)$$

in which the units are in true degree per second and PPD is the corresponding resolution for each sample. In order to ensure that only the correct horizontal saccades are detected, an additional constraint was set to exclude the saccades diverging more than 5 degrees from the horizontal axis.

3. Results

We first preprocessed the data by removing the trials without response and the trials where no saccade was detected within a time window of 10 seconds (≈ 5 percent of the whole trials). Then, we checked for any significant difference between different emotional conditions (happy, fearful, and neutral) in any of the two tasks by pooling the data from all participants. For the subjective rating task, we tested if there were any significant differences between the proportions of responses to the three emotional conditions. The Pearson Chi-square nonparametric test showed no significant difference between the proportions of responses to the three emotional conditions ($\chi^2(4, N = 401) = 2.77, P = 0.60$). Afterwards, we tested if the proportion of correct responses to the three different emotional conditions differed in the face detection task. For this, we applied analysis of variance (ANOVA) with the proportion of correct response as the dependent variable and emotion as the independent variable. The average proportion of correct responses for the three emotions ($M_{\text{Fear}} = 0.43; M_{\text{Happy}} = 0.48; M_{\text{Neutral}} = 0.42$) did not show a significant difference ($F(2, 365) = 0.64; P = 0.52$).

3.1. Subjective Rating Task. Figure 2 shows the proportion of responses to each of the three options in the subjective rating task. The results showed that none of the participants had conscious awareness of the stimulus category in most of the trials (“nothing” and “something” conditions).

Next, we analyzed the subjective measure of conscious perception of the stimuli in the subjective rating task averaged across the participants to see the extent of stimulus visibility during the saccade.

As depicted in Figure 3, the results showed that in only a small portion of all trials ($\approx 11\%$) the participants could consciously perceive the presented stimuli during a saccade, and in about one-third of the trials, the participants could only perceive a flashing square (the size of the face frame). In the remaining trials ($\approx 56\%$), the participants perceived absolutely nothing during the saccade. It is noteworthy that, because of the dependence of the variables (proportion responses), analysis of variance (ANOVA) was not suitable; this might also have caused inflated significance of the correlation analysis. Thus, we compared the proportions of responses to the three response options with a non-parametric test. The Friedman test revealed a significant difference between the three options ($\chi^2(2, N = 12) =$

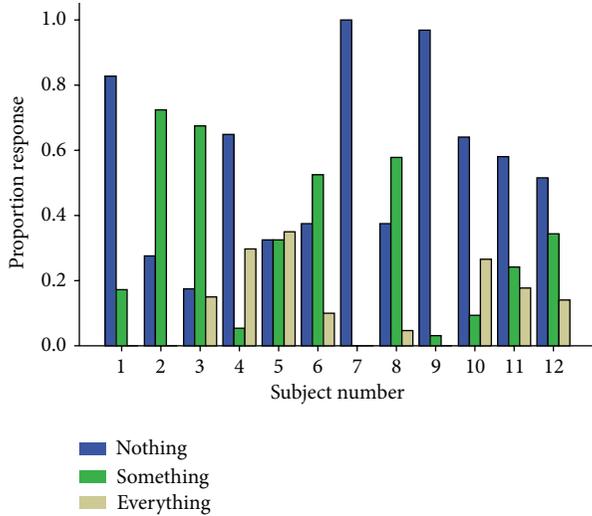


FIGURE 2: Proportion response in subjective rating task for every individual participant.

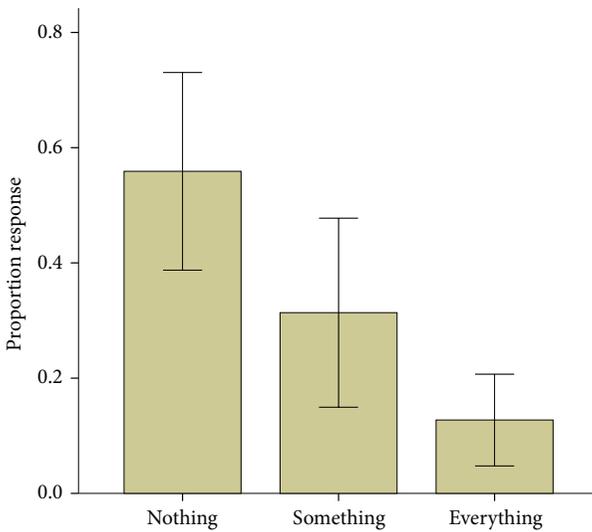


FIGURE 3: Proportion response to each of the three alternatives averaged across participants. The error bars represent 95% confidence interval.

8.65, $P = 0.013$). Then, we compared all the pairs using a nonparametric test of Wilcoxon signed ranks. The results showed a nonsignificant difference between the “something” and “nothing” conditions ($P > 0.1$). The difference between “everything” and “something” was marginally significant ($Z = -1.87$; $P = 0.062$), and the difference between “everything” and “nothing” was significant ($Z = -2.94$; $P = 0.003$).

3.2. Face Detection Task. First, we calculated d' as a measure of sensitivity for each participant (see Section 2). Four participants exhibited below-chance behavior (negative d') in the face detection task (Figure 4). A negative d' at subject level can generally be related to either mislabeling the response

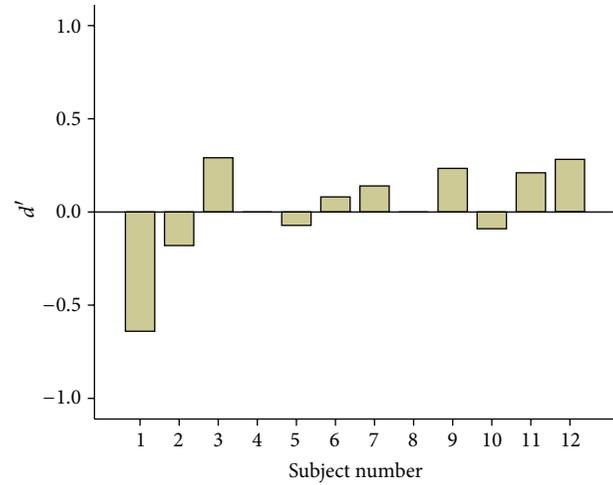


FIGURE 4: Sensitivity of individual participants in the face detection task.

options by the subject or a case of sampling error similar to the most subliminal studies [16, 23]. The former is quite unlikely in our experimental setup due to presentation of response options on the screen after every single trial; hence, the latter is most likely the case in this experiment. In group analysis, resetting negative d' s to zero value or simply omitting them from the analysis might lead to an inflated estimate of group d' [24, 25]; thus, we kept them for the main analysis. Nevertheless, a post hoc analysis excluding only the highest negative d' (subject 1) exhibited no difference in the significance of the statistical results (below).

Then, we compared the d' with the baseline ($d' = 0$) using Student’s t -test across all of the participants. The average d' for face detection was 0.02 ± 0.075 . The results show that face detection is not significantly different from the baseline ($t(11) = 0.285$; $P = 0.78$). We further analyzed the data using bootstrap for a one-sample t -test with 1000 iterations. The results were consistent with the previous test showing the mean difference of 0.02 (bias: 0.002; standard error: 0.07; $P = 0.82$).

3.3. Comparison of the Two Tasks. We further compared the results from the two tasks to examine the possible relationship of the proportion of responses of subjective rating from the first task and face detection sensitivity in the second task. For this, we calculated the Pearson correlation of each of the three response options in the subjective rating task with the d' calculated from the second task across the participants. The correlation of face detection sensitivity to “everything,” “something,” and “nothing” responses was 0.132, 0.056, and -0.11 , respectively. None of the correlations reached the significance level ($P > 0.35$).

4. Discussion

During saccadic eye movements, stable vision is maintained by the reduction of visual sensitivity. Here, we tested the

extent of this reduction for complex stimuli that were briefly presented only during the saccadic eye movements. First, we showed that when a complex visual object is displayed during a saccade, the participants could not self-report its presence in 90% of trials (subjective rating task). Then, we used sensitivity analysis as an objective measure in a 2AFC face detection task. The results indicated near-zero discrimination sensitivity for faces versus scrambles. Finally, we examined the relationship between subjective rates from the first task and the face detection sensitivities from the second task across the participants. The results showed that none of the three rating conditions was significantly connected to the face detection performance. This suggests at least some degree of independence between the subjective and objective measures.

The results from the face detection task show that there is no awareness of the face even with objective measures during saccadic eye movement. It has been repeatedly demonstrated that the mere subjective indication of “not seeing” the visual stimuli does not exclude the fact that certain aspects of the stimulus cannot still be processed and revealed by a 2AFC task (for a review see [17]). Thus, the combination of the two tasks is necessary. However, the validity of the “seen” trials was not directly confirmed since the two tasks were run in different experimental blocks. It is important to validate these results with simultaneous responses to both objective and subjective tasks in every trial.

In the current theoretical framework of object detection, there is no consensus on how the conscious awareness is defined precisely. The main debate is whether the subjective or the objective measure is suitable to measure conscious awareness. However, a third approach has emerged in the past decade arguing that both accounts are important and each one is actually representing one distinct network [15–17]. By introducing the two levels of “unseen” conditions in this experiment, we aimed to examine the connection of those two subjective levels to subliminal face detection performance. However, due to the chance-level performance in the face detection task and lack of simultaneous measure of the two tasks, we were unlikely to find a strong correlation that is only based on correlation across the participants. The absence of such strong correlation suggests that the two subjective and objective measures are independent to some extent. This is consistent with the previous research demonstrating the divergence of the two measures in certain conditions and reiterates the necessity of running both tasks in similar research [16].

This experiment is relevant to the context of unconscious and subliminal perception from the methodological point of view. We showed that saccadic suppression is a powerful tool to mask complex visual stimuli completely. Masking has been a very important tool for studying the basic stages of visual processing. The results of this experiment show that saccadic eye movement can strongly disrupt the perception of the complex visual stimuli even if they are as salient as faces. This is interesting as rendering face stimuli invisible with traditional masking techniques is a difficult task particularly when they are presented at normal contrast, binocularly, and with large sizes [26, 27]. Furthermore, in forward and backward masking paradigms, both mask and target need to

be displayed. To avoid the assumptions made about the interaction between the target and mask, saccadic suppression could be a useful alternative. Moreover, saccadic suppression does not need to include assumptions about the interaction of the different stimuli presented to each eye as in binocular rivalry where different stimuli are presented to different eyes and the percept of one eye suppresses the percept of the other eye. Hence, we believe that saccadic suppression can be employed as a complementary technique in a broad range of face/object detection and discrimination of experimental designs where the visibility of the target stimulus needs to be reduced.

The current study can also be relevant to the recent research revealing that certain properties of the “unseen” perisaccadic stimuli can still be processed unconsciously and influence the perception of the following stimuli. Recently, Watson and Krekelberg showed that the unconscious processing of an oriented bar that is presented during saccade can alter the perception of the upcoming stimulus at the end of saccade [28]. Moreover, there is an increasing body of evidence that the suppressed face stimuli can still be processed unconsciously. Other studies have demonstrated that unperceived objects can still activate cortical [29] and subcortical structures [30] under certain conditions. The results from the current study show that face detection is completely suppressed during saccade. Hence, it would be interesting to investigate if any subliminal perception can take place under these conditions. Future behavioral and imaging studies can address the possibility of such subliminal effects in the context of complex object perception. A remaining question is which underlying factors are involved in different ratings within and across the participants. For example, the timing of the stimulus presentation within the perisaccadic interval and the speed of saccade at the time of stimulus presentation can be two relevant factors for both subjective rating and face detection tasks.

The present work is also related methodologically to the studies using “change blindness” during saccadic eye movement [31]. Change blindness is the inability to detect the changes to an object or scene under certain conditions. The most relevant example, which also used complex objects, is research aiming to examine the rigidity of position-invariant object recognition [32]. In that study, the authors engineered a situation where the participants were instructed to saccade to the complex objects that were displayed peripherally. During the saccade, the identities of the peripheral objects were altered. In line with the present study, the authors first demonstrated that the participants were unaware of the identity change happening to the complex artificial target objects during saccade. Implementing this technique allowed them to construe a virtual environment, with different visual statistics, where the associations of the peripheral and the foveal representations of certain object identities were broken. They showed that the participants who were trained in such a “position-variant” environment would lose the position-invariant object recognition drastically for the trained objects. However, that study did not disentangle the masking effect of the presaccadic stimulus on the post-saccadic test stimulus, since they both were presented at

the same position of saccadic landing. The other methodological difference was that they used artificial objects unlike the current study.

Examining the visual system under naturalistic conditions has been one of the main goals of this work. In the past decade, the extension of the findings from simple stimuli to the real-life vision has been debated in the basic vision research [33]. The main criticism of the opponents using simple stimuli is that the visual system has evolved and developed to optimally analyze the visual world. However, the neurons in the early visual areas rarely receive such simple patterns as those that have been extensively used in vision research. In addition, most of these neurons mainly exhibit nonlinear behavior in the presence of more complex inputs. As a result, studying vision under naturalistic conditions is revealed to be an essential step to confirm the models obtained from the studies with simple stimuli. Specifically in the domain of eye movement research, there has been over a century of tradition in studying saccadic eye movements using simple visual stimuli such as light flashes, lines, and Gabor patches [34, 35]. Nevertheless, the extension of such findings to the more realistic visual stimuli is questionable. Moreover, recent technological improvements enable the modification of visual stimuli in real-time, depending on the viewers' gaze direction, which is known as the gaze-contingency paradigm. Using this paradigm, it is now possible to study naturally generated saccades with real-life stimuli. For example, in a recent study providing evidence against the extraretinal source of saccadic suppression, a gaze-contingent high-definition display was developed to modify videos in retinal coordinates in real-time [14]. The present work is one of the few examples of extending the validity of saccadic suppression to natural complex objects.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

References

- [1] E. Hering, "1942 Spatial Sense and Movements of the Eye English translation by C A Radde (Baltimore, MD: American Academy of Optometry, 1942) of "Der Raumsinn und die Bewegung des Auges"" in *Handbuch der Physiologie*, L. Hermann, Ed., vol. 3, Vogel, Leipzig, Germany, 1879.
- [2] G. T. Buswell, *How People Look at Pictures*, University of Chicago Press Chicago, 1935.
- [3] E. Martin, A. B. Clymer, and L. Martin, "Metacontrast and saccadic suppression," *Science*, vol. 178, no. 4057, pp. 179–182, 1972.
- [4] F. C. Volkman, L. A. Riggs, R. K. Moore, and K. D. White, "Central and peripheral determinants of saccadic suppression," in *Eye Movements and the Higher Psychological Functions*, pp. 35–53, Lawrence Erlbaum, Hillsdale, NJ, USA, 1978.
- [5] D. C. Burr and M. C. Morrone, "Spatiotopic coding and remapping in humans," *Philosophical Transactions of the Royal Society B: Biological Sciences*, vol. 366, no. 1564, pp. 504–515, 2011.
- [6] B. L. Zuber and L. Stark, "Saccadic suppression: elevation of visual threshold associated with saccadic eye movements," *Experimental Neurology*, vol. 16, no. 1, pp. 65–79, 1966.
- [7] B. Bridgeman, D. Hendry, and L. Stark, "Failure to detect displacement of the visual world during saccadic eye movements," *Vision Research*, vol. 15, no. 6, pp. 719–722, 1975.
- [8] D. C. Burr and J. Ross, "Contrast sensitivity at high velocities," *Vision Research*, vol. 22, no. 4, pp. 479–484, 1982.
- [9] D. C. Burr, M. C. Morrone, and J. Ross, "Selective suppression of the magnocellular visual pathway during saccadic eye movements," *Nature*, vol. 371, no. 6497, pp. 511–513, 1994.
- [10] M. A. García-Pérez and E. Peli, "Visual contrast processing is largely unaltered during saccades," *Frontiers in Psychology*, vol. 2, p. 247, 2011.
- [11] E. Castet, "Perception of intra-saccadic motion," in *Dynamics of Visual Motion Processing*, pp. 213–238, Springer, New York, NY, USA, 2010.
- [12] E. Castet, S. Jeanjean, and G. S. Masson, "Motion perception of saccade-induced retinal translation," *Proceedings of the National Academy of Sciences of the United States of America*, vol. 99, no. 23, pp. 15159–15163, 2002.
- [13] F. W. Campbell and R. H. Wurtz, "Saccadic omission: why we do not see a grey-out during a saccadic eye movement," *Vision Research*, vol. 18, no. 10, pp. 1297–1303, 1978.
- [14] M. Dorr and P. J. Bex, "Peri-saccadic natural vision," *The Journal of Neuroscience*, vol. 33, no. 3, pp. 1211–1217, 2013.
- [15] S. Dehaene and J.-P. Changeux, "Experimental and theoretical approaches to conscious processing," *Neuron*, vol. 70, no. 2, pp. 200–227, 2011.
- [16] R. Szczepanowski and L. Pessoa, "Fear perception: can objective and subjective awareness measures be dissociated?" *Journal of Vision*, vol. 7, no. 4, article 10, 2007.
- [17] S. Kouider and S. Dehaene, "Levels of processing during non-conscious perception: a critical review of visual masking," *Philosophical Transactions of the Royal Society B: Biological Sciences*, vol. 362, no. 1481, pp. 857–875, 2007.
- [18] D. Lundqvist, A. Flykt, and A. Öhman, *The Karolinska Directed Emotional Faces-KDEF*, Department of Clinical Neuroscience, Psychology section, Karolinska Institutet, Stockholm, Sweden, 1998.
- [19] M. L. Mack, I. Gauthier, J. Sadr, and T. J. Palmeri, "Object detection and basic-level categorization: sometimes you know it is there before you know what it is," *Psychonomic Bulletin and Review*, vol. 15, no. 1, pp. 28–35, 2008.
- [20] J. Sadr and P. Sinha, "Object recognition and random image structure evolution," *Cognitive Science*, vol. 28, no. 2, pp. 259–287, 2004.
- [21] V. Goffaux, J. Peters, J. Haubrechts, C. Schiltz, B. Jansma, and R. Goebel, "From coarse to fine? spatial and temporal dynamics of cortical face processing," *Cerebral Cortex*, vol. 21, no. 2, pp. 467–476, 2011.
- [22] D. M. Green and J. A. Swets, *Signal Detection Theory and Psychophysics*, Wiley, New York, NY, USA, 1966.
- [23] L. J. Norman, C. A. Heywood, and R. W. Kentridge, "Object-based attention without awareness," *Psychological Science*, vol. 24, no. 6, pp. 836–843, 2013.
- [24] N. A. Macmillan and C. D. Creelman, *Detection Theory: A User's Guide*, Psychology Press, 2004.
- [25] D. Los Angeles Thomas, *Elementary Signal Detection Theory*, Oxford University Press, 2001.

- [26] G. Loffler, G. E. Gordon, F. Wilkinson, D. Goren, and H. R. Wilson, "Configural masking of faces: evidence for high-level interactions in face perception," *Vision Research*, vol. 45, no. 17, pp. 2287–2297, 2005.
- [27] N. P. Costen, J. W. Shepherd, H. D. Ellis, and I. Craw, "Masking of faces by facial and non-facial stimuli," *Visual Cognition*, vol. 1, no. 2-3, pp. 227–251, 1994.
- [28] T. L. Watson and B. Krekelberg, "The relationship between saccadic suppression and perceptual stability," *Current Biology*, vol. 19, no. 12, pp. 1040–1043, 2009.
- [29] F. Fang and S. He, "Cortical responses to invisible objects in the human dorsal and ventral pathways," *Nature Neuroscience*, vol. 8, no. 10, pp. 1380–1385, 2005.
- [30] Y. Jiang and S. He, "Cortical responses to invisible faces: dissociating subsystems for facial-information processing," *Current Biology*, vol. 16, no. 20, pp. 2023–2029, 2006.
- [31] D. J. Simons and D. T. Levin, "Change blindness," *Trends in Cognitive Sciences*, vol. 1, no. 7, pp. 261–267, 1997.
- [32] D. D. Cox, P. Meier, N. Oertelt, and J. J. DiCarlo, "'Breaking' position-invariant object recognition," *Nature Neuroscience*, vol. 8, no. 9, pp. 1145–1147, 2005.
- [33] J. M. Henderson, "Human gaze control during real-world scene perception," *Trends in Cognitive Sciences*, vol. 7, no. 11, pp. 498–504, 2003.
- [34] J. Ross, M. C. Morrone, M. E. Goldberg, and D. C. Burr, "Changes in visual perception at the time of saccades," *Trends in Neurosciences*, vol. 24, no. 2, pp. 113–121, 2001.
- [35] M. Tamietto and B. de Gelder, "Neural bases of the non-conscious perception of emotional signals," *Nature Reviews Neuroscience*, vol. 11, no. 10, pp. 697–709, 2010.

Research Article

Attentional Capture and Inhibition of Saccades after Irrelevant and Relevant Cues

Heinz-Werner Priess,¹ Nils Heise,¹ Florian Fischmeister,^{2,3} Sabine Born,⁴
Herbert Bauer,¹ and Ulrich Ansorge^{1,5}

¹ Faculty of Psychology, University of Vienna, Liebiggasse 5, 1010 Wien, Austria

² MR Centre of Excellence, Medical University of Vienna, 1090 Wien, Austria

³ Study Group Clinical fMRI, Department of Neurology, Medical University of Vienna, 1090 Wien, Austria

⁴ Laboratoire Psychologie de la Perception, Université Paris Descartes, 75006 Paris, France

⁵ Institute of Cognitive Science, University of Osnabrück, 49069 Osnabrück, Germany

Correspondence should be addressed to Ulrich Ansorge; ulrich.ansorge@univie.ac.at

Received 17 January 2014; Accepted 20 February 2014; Published 22 April 2014

Academic Editor: Gernot Horstmann

Copyright © 2014 Heinz-Werner Priess et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Attentional capture is usually stronger for task-relevant than irrelevant stimuli, whereas irrelevant stimuli can trigger equal or even stronger amounts of inhibition than relevant stimuli. Capture and inhibition, however, are typically assessed in separate trials, leaving it open whether or not inhibition of irrelevant stimuli is a consequence of preceding attentional capture by the same stimuli or whether inhibition is the only response to these stimuli. Here, we tested the relationship between capture and inhibition in a setup allowing for estimates of the capture and inhibition based on the very same trials. We recorded saccadic inhibition after relevant and irrelevant stimuli. At the same time, we recorded the N2pc, an event-related potential, reflecting initial capture of attention. We found attentional capture not only for relevant but importantly also for irrelevant stimuli, although the N2pc was stronger for relevant than irrelevant stimuli. In addition, inhibition of saccades was the same for relevant and irrelevant stimuli. We conclude with a discussion of the mechanisms that are responsible for these effects.

1. Introduction

Visual attention is the selection of visual information for purposes such as in-depth processing, perception, or action control. Because we have to select information at all times, understanding attention is a key to an understanding of almost any form of cognition. To date, however, the mechanisms by which attention operates are not fully understood.

One persistent debate in this area concerns the role of inhibition of irrelevant stimuli as one form of top-down control over attention. Whereas some researchers believe that inhibition of attention is a response to initial capture of attention and, thus, follows preceding attentional capture by an irrelevant stimulus [1], other researchers believe that active inhibition of attentional capture by an irrelevant stimulus is possible right from the start of such a stimulus [2].

To start with the first proposition, many researchers argued that salient objects capture attention in a bottom-up way (cf. [3, 4]). According to the salience model of attention, any visual stimulus that stands out among its surroundings by a strong feature contrast in color, orientation, or luminance may capture attention in an exogenous stimulus-driven way, regardless of the current goal of the observer (cf. [5, 6]). In line with this prediction, an irrelevant color singleton distractor—that is a stimulus with a color different from its surrounding stimuli, such as one green circle among several red circles, interferes with finding a shape-defined target stimulus (i.e., the one rectangle among several circles) (cf. [4]). This is the case although attending to the specific color of the singleton is neither necessary nor helpful for finding the target. Such findings have been attributed to the bottom-up capture of attention by an irrelevant singleton. As a consequence,

attention is thought to first be distracted away from the relevant target and only later be redirected towards the target. This is possible after a deliberate inhibition of the irrelevant stimulus, allowing attention to disengage from the distractor [1].

Findings by Kim and Cave [7] are in general agreement with this late-inhibition or disengagement hypothesis. These authors used a probe stimulus as a second target in a combined search and probe reaction task. Critically, the probe was shown after the search display with the probe either at the position of the search display's shape-defined target or at the position of the search display's color-singleton distractor. With an interval of 60 ms between search display and probe, Kim and Cave observed (nonsignificantly) faster responses to probes at color-distractor positions than to probes at shape-target positions. However, with a cue-target onset asynchrony (CTOA) of 150 ms between the color-singleton distractor (cue) and the probe (target), responses to probes at the position of the color-singleton distractor were significantly *delayed* relative to responses to probes presented at the location of the shape target. This delay evidently reflected active inhibition of the color distractor that developed over time. Like Theeuwes et al. [1], Kim and Cave [7] took their results as an indication of bottom-up capture by the color-singleton distractor with a short CTOA, giving way to disengagement and even active inhibition with a long CTOA. The core notion of the disengagement hypothesis, that is, the idea of active inhibition following initial allocation of attention towards a stimulus, is also at the heart of another well-known phenomenon called inhibition of return (IOR). IOR denotes the finding that attracting visual attention toward one position in space by a cue delays a second attention shift to the same position at a later point in time [8–10]. IOR is observed with long CTOAs and corresponds to longer reaction times where cue and target are presented at the same position (SP) compared to cue and target at different positions (DP). Thus, the idea of stimuli initially triggering attentional capture and later inhibition is a very dominant notion found throughout the attention literature.

However, recent findings by McDonald et al. [2] and by Ansorge et al. [11] are potentially in disagreement with this late-inhibition or disengagement hypothesis for irrelevant stimuli. Ansorge et al. asked their participants to saccade to one out of four positions, varying randomly from trial to trial (see Figure 1 for an illustration of a similar stimulus and task sequence). Prior to the saccades, participants were presented with a relevant or an irrelevant color singleton cue. Participants only had to attend to the relevant cue because this cue indicated the position of a discrimination target later in the trial. In contrast, the participants were asked to ignore the irrelevant cue: when an irrelevant cue was presented, no target discrimination was required so that it was safe to ignore this cue. In addition, ignorance of the irrelevant cue was encouraged: because cue and saccade target positions were uncorrelated (cf. [12]) and because saccades require a prior attention shift to the target position [13, 14], the participants could fully concentrate on the saccade task and ignore the irrelevant cues completely. In contrast, the participants were

forced to shift their attention to the relevant cue for the encoding of its position for the discrimination task and at the potential cost of a suboptimal preparation of their saccades. All of these cues were nonpredictive of the saccade target position, and relevant and irrelevant cues had different fixed colors, so that the participants knew exactly which color they had to attend to (e.g., red) and which color they could ignore (e.g., green). Under these conditions, Ansorge et al. [11] studied the time course of selective attentional capture and/or inhibition by looking at the development of the saccadic latencies across the latency distribution, from quick to slow saccades. With a long CTOA, and with relevant cues, IOR followed initial capture: initial capture among the fast responses was reflected in quicker saccades to a saccade target at the same position (SP) as the cue compared to slower saccades to a saccade target at a different position (DP) than the cue. With relevant cues, this pattern reversed into IOR among the slower responses. In contrast, with a long CTOA and irrelevant cues, inhibition in the form of slower saccades to SP than DP targets was found right from the beginning and without preceding capture effects. These findings point to a form of proactive inhibition of irrelevant cues, completely preventing attentional capture by the irrelevant cues, rather than late disengagement. In fact, the only reliable capture effect for irrelevant cues showed up in a condition with a different procedure and no subsequent inhibition (experiment 4). Thus, no conclusion could be drawn about transitions from capture to disengagement.

A recent study by McDonald et al. [2] equally found evidence for proactive inhibition of irrelevant stimuli without a trace of preceding attention capture. To discern between capture and inhibition, McDonald and colleagues used two lateralized components of the event-related potential (ERP): the N2pc (cf. [15, 16]) or posterior contralateral negativity (PCN) [17] and the Pd [18, 19]. The N2pc has been widely used to investigate both stimulus-driven capture [20] and top-down contingent capture [21–25]. It is a larger negative deflection contra- than ipsilateral to an attended stimulus. It occurs approximately 200–280 ms after stimulus onset over posterior areas [26]. In contrast, the Pd reflects the active inhibition of potentially distracting stimuli [19]. It is a component of similar latency and scalp distribution as the N2pc. However, it is of opposite polarity as compared to the N2pc. Importantly, when McDonald et al. [2] tested for initial capture of attention by irrelevant stimuli, all they found was a Pd, that is, evidence for proactive inhibition of the irrelevant stimuli. This was found after splitting the ERPs into fast and slow responses: the quickest target responses of the participants indicated proactive inhibition of attentional capture by an irrelevant distractor.

Even so, it is not entirely clear whether the findings reflected only early inhibition or whether some capture of the irrelevant singletons occurred before it was suppressed. Regarding the findings of Ansorge et al. [11], these authors used saccadic latencies after relatively long CTOAs (>200 ms). This method is relatively insensitive to the early attentional effects, so that preceding attention capture even by irrelevant cues might have gone unnoticed (see their condition with a CTOA of 200 ms). Regarding the findings

of McDonald et al. [2], it is possible that their observations reflected a mixture of weaker capture effects of the irrelevant distractors in some of the trials and of stronger inhibition of distraction in other trials. As a result, a net inhibitory Pd effect could have masked evidence for early capture in the form of an N2pc in the study of McDonald et al. At least in the slower responses, there was also clear evidence for this possibility: “On slow response trials (...) there was neither an early distractor (...) nor a late target N2pc (...). The absence of either N2pc suggests that the target and distractor N2pc wave cancelled each other out (...).” (p. 856, McDonald et al.). Thus, to test once more whether capture by irrelevant cues could precede subsequent inhibition, we combined the methods of Ansorge et al. and of McDonald et al., using two different measures for early and late effects based on the very same trials. We used ERPs to assess early effects of capture or proactive inhibition. Late inhibition was assessed through the presence of IOR in saccadic reaction times after a sufficiently long CTOA of 1 s. This procedure allows for the registration of an early capture effect by all singletons, without masking by a concomitant N2pc by the targets [27]. In this situation, initial capture by the irrelevant singleton cue should show up as an N2pc. In addition, we conducted a median-split of the ERPs on the basis of whether a fast or a slow saccade was given that allowed us to test whether the fastest responses were associated with a Pd component, similar to McDonald et al. [2].

2. Experiment

The aim of the current experiment was to investigate the connection between attention capture by relevant and irrelevant stimuli and (subsequent) inhibition. We examined within the same trials (1) the amount of initial capture of attention by an irrelevant cue and a relevant cue—in the form of the N2pc—and (2) the amount of inhibition—in the form of an early Pd and late saccadic inhibition of return.

In detail, in the first display of each trial, we used one of two color-singleton cues: the first cue was relevant in half of the trials and it was irrelevant in the other half of the trials. A relevant first cue had a fixed color (e.g., it was green), known to the participant. The participant had to look for the relevant first cue and importantly, also *covertly*, attend to its *location* because it indicated the position of a subsequent discrimination target. We call this cue “relevant” to make clear that its color serves the same purpose as a searched-for feature of a target in a standard color-search task. The relevant cue indicated with 100% certainty the position of the discrimination target.

In contrast, the irrelevant first cue had a different color (e.g., it was blue if the relevant cue was green), also known to the participants. No target discrimination was required after an irrelevant first cue. Therefore, the participants could have ignored this cue completely and were not required to shift spatial attention to its location. We call this cue “irrelevant” because its color served the same purpose as the color of an irrelevant distractor in a visual search display. That is, the

color of the irrelevant first cue indicated with 100% certainty that this stimulus could be safely ignored.

To test IOR we introduced a later secondary saccade task. After the first cue, our participants had to encode the position of a second singleton cue in a second display for a saccade in a subsequent third display (see Figure 1). This second or saccade cue was always red. Importantly, positions of the first cue and of the second saccade cue were uncorrelated. Because the participants have to allocate their attention to the position of the saccade target (cf. [13, 14, 28, 29]), they had to disengage their attention away from any first cue and to redirect it towards the position of the second cue in anticipation of the saccade target. Also, the CTOA was 1 s long allowing for both inhibition (or disengagement) of attention and saccadic inhibition (of return). We therefore expected saccadic inhibition with respect to the position of the first or covert cue ([11, 30, 31]; see also [32]). The question is whether with irrelevant first cues a capture effect in the form of an N2pc precedes this inhibition effect or whether inhibition is observed from the start, in the form of a Pd. Also, in the relevant condition, an N2pc to the first cue was to be expected because an attention shift to this first cue was required to encode its position.

2.1. Materials and Method

2.1.1. Participants. Twelve volunteers participated but one was excluded because her saccade latencies were more than three standard deviations slower than that of the other participants. The remaining participants (with a mean age of 25 years and a male/female ratio of 6:5) reported normal or corrected-to-normal vision. Written and informed consent was obtained from each participant before the experiment.

2.1.2. Stimuli and Procedure. Visual stimuli were presented on a 19-inch CRT color monitor (Sony Multiscan G400), with a screen resolution of 1,024 × 768 pixels and a refresh rate of 100 Hz. The participants sat at a distance of 57 cm from the screen in a quiet, dimly lit room, with their head resting on a chin rest to ensure a constant viewing distance and a straight-ahead gaze direction.

Three successive displays were shown on each trial (see Figure 1). The first and second displays were presented for 50 ms and the last display for 1 s. All displays were separated by an interstimulus interval of 450 ms, such that the onset asynchrony between two displays was 500 ms. A gray central fixation cross was presented on a black background (<1 cd/m²), visible throughout each trial. All objects on the screen were equiluminant (~30 cd/m²).

The first display consisted of six equidistant placeholders, each in the shape of the digital letter 8 (with a size of 1.7° × 1° and with stroke strength of .3°). A placeholder was located per each of the positions at 0°, 60°, 120°, 180°, 240°, and 300° from the vertical meridian—that is, the shape-8s were presented equally spaced on the circumference of a virtual circle centered on the screen, with an eccentricity of 7°. Five placeholders were presented in gray (CIELAB color coordinates: 6.9, 16.8), and one was presented in a different

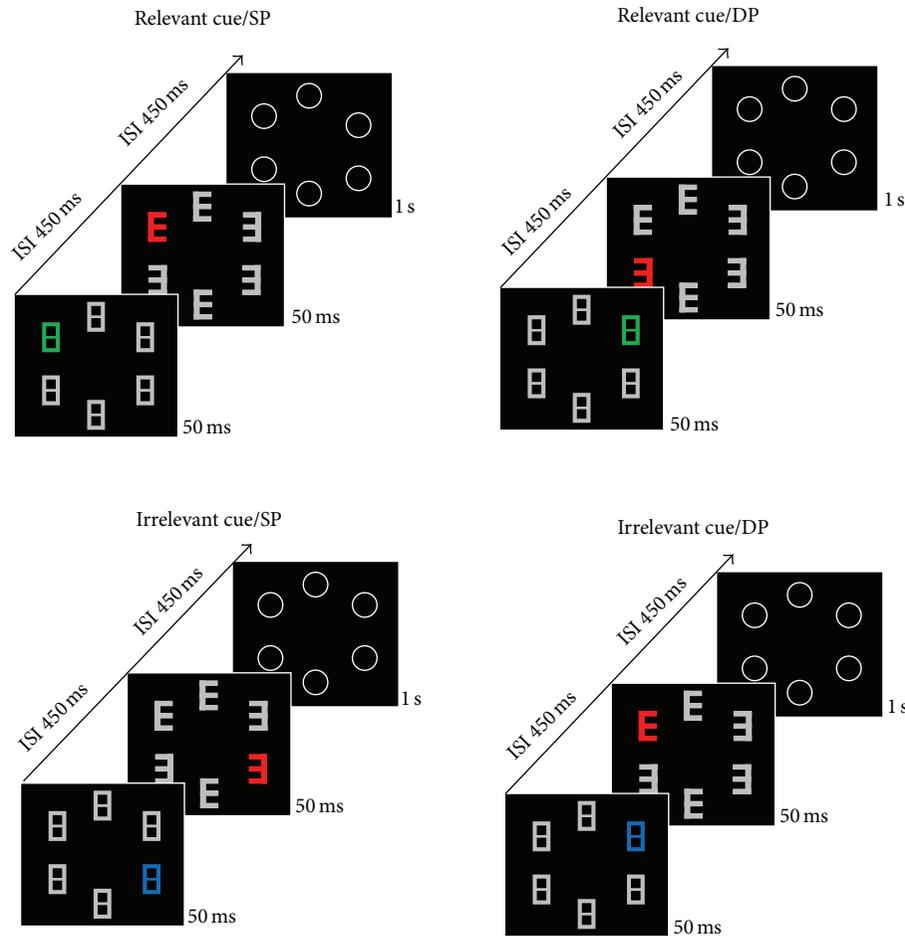


FIGURE 1: Depicted are examples of a different-position (DP) trial with a relevant cue (in the upper right), a same-position (SP) trial with a relevant cue (in the upper left), a different-position (DP) trial with an irrelevant cue (in the lower right), and a same-position (SP) trial with an irrelevant cue (in the lower left). In each of the four depicted conditions, the first (lower) display was the cue display, in which a color singleton cue (illustrated as a green or blue shape-8) was presented. The second (middle) display was the discrimination display where participants had to memorize the identity (i.e., shape-*E* or shape-3) at the position of a relevant cue (here: green) but not after an irrelevant cue (here: blue) in the first display. Alongside the discrimination target, we presented a red color singleton as a saccade cue. The third (upper) display was the saccade display; participants had to saccade to the target ring at the position cued by the red singleton. The arrow illustrates the temporal sequence. Stimuli are not drawn to scale. ISI = interstimulus interval.

color, either in green (CIELAB: -30.2, 24.9) or blue (CIELAB: 46.9, -89). This green or blue stimulus was the first color-singleton cue. It was always shown at one of the four lateral positions but never presented above or below the fixation.

Following the first display, the discrimination display was presented for 50 ms. The shape-8s were replaced by three letters “*E*” and three digits “3”, in digital notation. Five of these shapes were presented in gray and one was presented in red (CIELAB: 47.6, 41.1). This red stimulus was the second or saccade cue and it could also only appear at one of the four lateral positions. The red singleton was called a saccade cue because this second cue served as the cue for the saccade target in the subsequent display. Also, in this display, one figure served as a discrimination target if it had been cued by a relevant first cue (blue or green cue) in the preceding display, with relevant first cue color fixed across trials and balanced across participants. Positions of the discrimination

target and second (or red) cue were uncorrelated across trials. Consequently, in 25% of the trials the discrimination target and second or saccade cue were at the same position (SP condition), and in 75% of the trials they were at different positions (DP condition).

Following another interval of 450 ms the saccade display was presented. This display consisted solely of six empty circles surrounding the stimulus positions as used in the preceding displays. The saccade display was presented for 1 s.

The color of the first singleton cue in the first screen indicated whether the discrimination task in the second screen had to be performed on a given trial. For instance, a first green singleton was linked to the discrimination task while a first blue singleton could be ignored, or vice versa. In the discrimination task, participants had to encode and remember the shape of the digit presented in the second screen at the position of the relevant first singleton cue.

This was necessary for the report of this figure at the end of the trials. The second or red singleton cue indicated the position of the subsequent saccade target. As soon as the third display, the saccade display, appeared the saccade had to be executed. After the saccade was executed, in a relevant-cue trial, participants typed the identity of the discrimination target letter (i.e., whether the letter *E* or the digit 3 was presented) by pressing the marked buttons #*F* and #*J* labeled “left” and “right” on a standard keyboard directly in front of the participants. If no discrimination was necessary (i.e., after irrelevant cues), this part of the trial was skipped. Participants started the next trial in a self-pace manner, by pressing the space bar. After this, 500 ms elapsed before the presentation of the cue display.

Participants were informed that the color singleton cues could only appear at the four lateral positions on the screen and that the position of the second or saccade singleton cue was independent of the position of the first singleton cue. Blocks consisted of 64 trials and feedback was given about whether the target discrimination was correct and about whether the saccade was registered during the third screen. Altogether ten blocks of trials were conducted, of which the first was training and not analyzed. Each factor combination of the variables discrimination target (*E* or 3), first cue position (above/left, above/right, below/left, and below/right), first cue color (blue, green), and second cue’s position (above/left, above/right, below/left, and below/right) was equally likely and presented in a pseudorandom order within each block.

2.1.3. Eye-Tracking and Saccade Analysis. Saccades were recorded with an EyeLink 1000 Desktop Mount system (SR Research, Mississauga, ON, Canada) with a 35 mm lens and EyeLink Software version 4.52, sampling at 1,000 Hz. Eye-tracking was monocular from the dominant eye. A 9-point calibration was used to adjust the eye-tracker before the experiment and in advance of every single block. Saccadic reaction time (saccadic RT) was calculated as the time between (1) the onset of the third display (with the saccade-target stimulus circle) and (2) the time of a local velocity minimum that immediately preceded the point in time at which eye velocity exceeded 80°/s. Only trials with correct saccades were analyzed. A saccade counted as correct if it landed in an area of 1.5° around the center of the saccade target. Saccade landing position was calculated as the *x-y* coordinates of the eye-tracker signal at the time at which eye velocity returned to a presaccadic baseline level. Also, if the eyes started to move earlier than 100 ms after the saccade target, a trial was discarded.

2.1.4. EEG Recording and Analysis. DC-EEG was recorded from 23 scalp electrodes mounted in an elastic cap at standard positions of the extended 10/20 system at sites Fpz, F7, F3, Fz, F4, F8, Fc5, Fc6, T7, C3, Cz, C4, T8, Cp5, Cp6, P7, P3, Pz, P4, P8, O1, O2, and Oz. The continuous EEG was sampled at a rate of 1,000 Hz with a digital low-pass filter of 50 Hz. Impedance was kept below 2 kΩ. No further filters were applied after EEG acquisition. All scalp electrodes

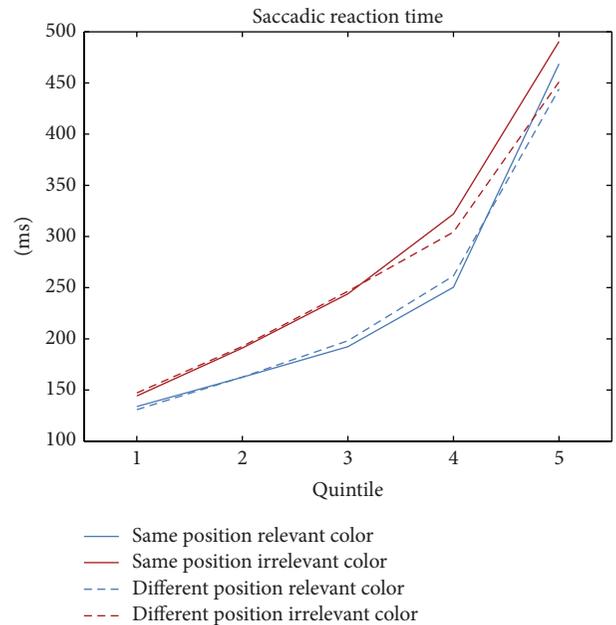


FIGURE 2: Saccadic reaction time (SRT) in milliseconds as a function of the first cue’s relevance (relevant cue = blue lines, irrelevant cue = red lines), cue position (at the same position as the target = solid lines, at a different position than the target = dashed lines), and the quintile of the SRT distribution (1 to 5, from fastest to slowest).

were online referenced to a noncephalic sternovertebral site, above the seventh vertebra and the right manilum sternum [33]. The vertical EOG (electrodes below and above the left eye) and the horizontal EOG (electrodes at the outer canthi) were recorded bipolarly, so as to delete trials with eye movements during the critical EEG recording interval. Trials with saccades earlier than 100 ms after the saccade target (detected with the eye-tracker) or muscular artifacts (exceeding $\pm 80 \mu\text{V}$ at any electrode), as well as trials in which the target was not correctly discriminated, were excluded from analysis. ERPs were calculated for 400 ms after the first cue’s onset relative to a 50 msec precue baseline. N2pc amplitudes in response to the first color cue were calculated separately for left and right and relevant and irrelevant cue, collapsed across all saccade target positions as mean ERP amplitudes at locations P3/4 in the 160–270 ms interval after cue onset.

2.1.5. Synchronization of Eye-Tracking and EEG. A switch box was implemented behind the parallel port of the master to send one unique synchronization trigger every 500 ms (one for the onset of the first display, one for the second display, and one for the third display in each trial) in parallel, separately to the two slaves, eye-tracker and EEG recorder.

2.2. Results. In total, 17.5% of all trials were excluded. Trials with saccades faster than 100 ms and slower than 1 s after the saccade target accounted for 8.1%, trials with saccades towards the wrong target or with muscular artifacts for

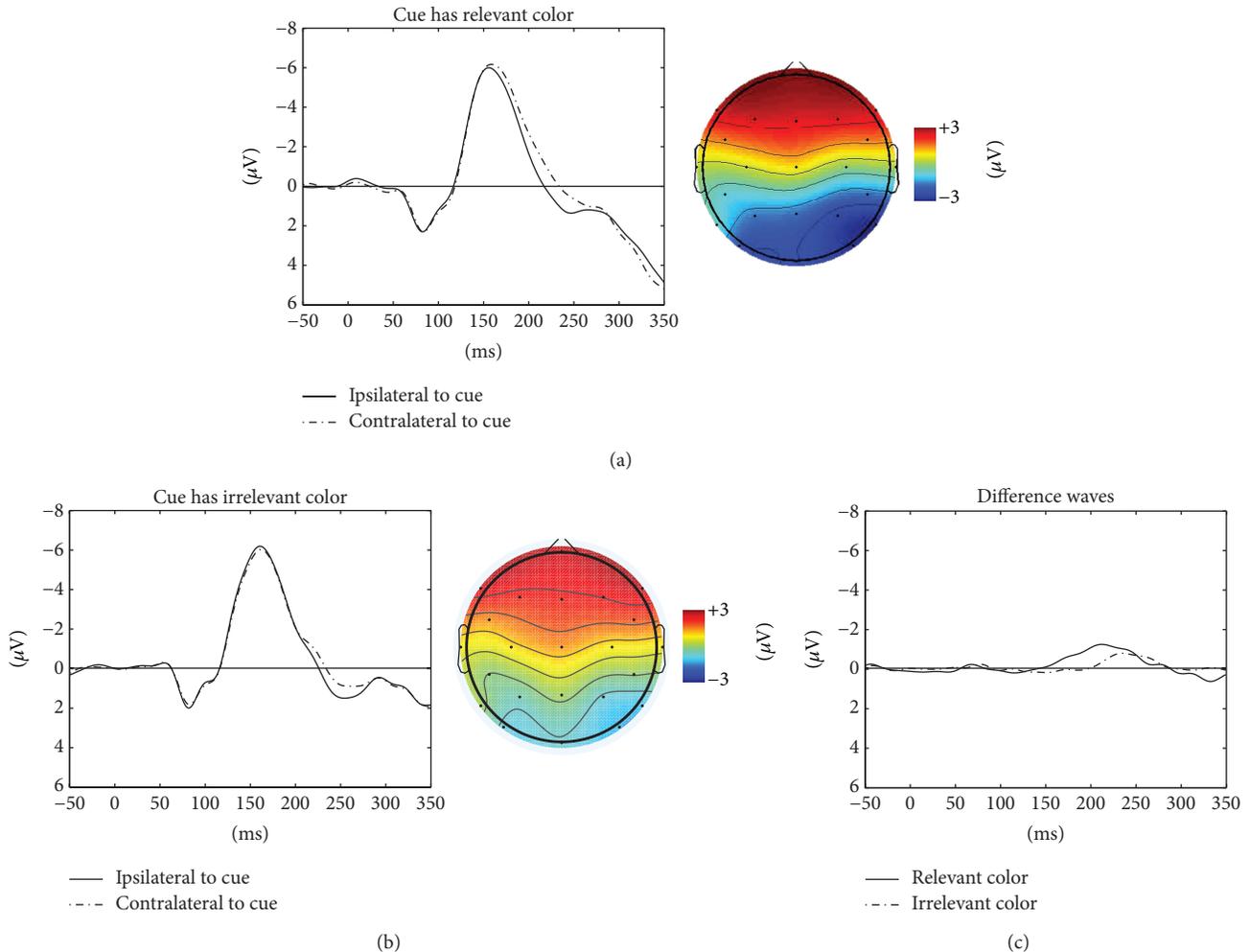


FIGURE 3: (a) ERPs (in μVolts on the y -axis) ipsilateral to the relevant cue (solid line), contralateral to the relevant cue (dashed line) as a function of the time since cue onset (at zero) on the x -axis, and scalp distribution plots of mean ERP activity in response to the cues in a time window of 160 to 270 ms after the cue, with contralateral activity to the right and ipsilateral activity to the left and with negative values in blue and positive values in red. (b) The same as (a) for irrelevant cues. (c) Difference waves of contralateral minus ipsilateral activity, separately for relevant cues (solid line) and for irrelevant cues (dashed line).

another 6.4%, and trials with a false identification of the discrimination target for 3%.

2.2.1. Saccade Task. To take the dynamics of the saccadic response into account, saccadic RTs were sorted and grouped into five percentiles from fast to slow (cf. [31]). This was done to test our hypotheses about IOR with differently fast responses because the amount of capture and of IOR does vary over time and an effect that is absent in the average of all responses can well be present when looking at only the faster or only the slower responses (e.g., [11, 34]).

As can be seen in Figure 2, from fast responses on the left to slow responses on the right, there was a gradual build-up of IOR. This was reflected in faster saccadic RTs under DP conditions (broken lines) as compared to SP conditions (solid lines), more so with the irrelevant cues (red lines) than with the relevant cues (blue lines).

A repeated-measures ANOVA with the variables position (same versus different position of first or covert cue and saccade cue/target), cue type (relevant first cue or irrelevant first cue), and percentile (1st to 5th) revealed inhibition at the location of the first or covert cue only among the slowest responses in the form of slower saccadic latencies in SP than DP conditions. This was reflected in a significant interaction of position and percentile, $F(4, 40) = 2.79$, $p < .05$. From the 1st to the 5th quintile, saccadic inhibition (saccadic RT in SP conditions minus saccadic RT in DP conditions) was 0 ms, -1 ms, -4 ms, 3 ms, and 32 ms (1st to 4th quintile, all $t_s < 1$; 5th quintile, $t(9) = 2.29$, $p < .05$). In addition, we found faster saccadic RTs in trials with a relevant than an irrelevant cue in the first display (241 ms versus 273 ms), resulting in a marginally significant main effect for cue type, $(1, 10) = 4.72$, $p = .055$. There was also a trivial main effect of percentile (increasing saccadic RTs with percentile), $(4, 10) = 94.56$, $p < .01$.

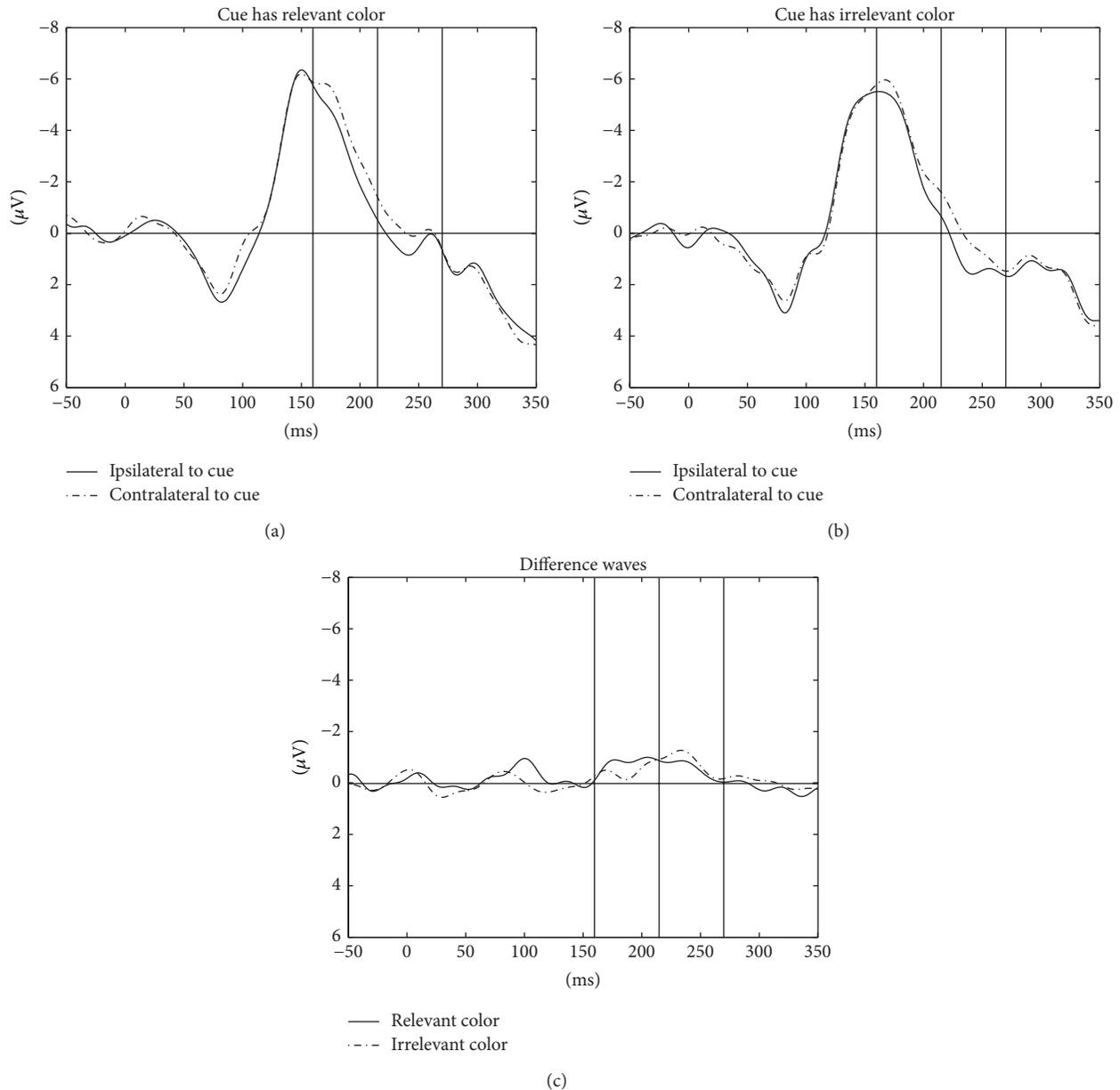


FIGURE 4: Data from the 50% fastest responses. (a) ERPs (in μ Volts on the y -axis) ipsilateral to the relevant cue (solid lines) and contralateral to the relevant cue (dashed lines), as a function of the time since cue onset (at zero) on the x -axis. (b) Same as (a) but for irrelevant cues. (c) Difference waves of contralateral minus ipsilateral activity, separately for relevant cues (solid line) and for irrelevant cues (dashed line).

Further, there was a numerically stronger inhibitory effect on saccades after the irrelevant cue (10 ms) than after the relevant cue (2 ms), as would be expected based on an active inhibition explanation. However, the two-way interaction of relevance and position was not significant, $(1, 10) = .55$, $p = .48$, as was the three-way interaction, $F < 1$. In sum, saccadic inhibition was selectively present in the slowest saccades and it was largely independent of the type of cue that was used in the first display.

2.2.2. N2pc to the First Cue. Figure 3 shows ERPs time-locked to the first cue's onset at lateral posterior electrodes P3

and P4 contra- and ipsilateral to the first cue, separately for cues with a relevant color (panel a), cues with an irrelevant color (panel b), and difference waves (i.e., contra- minus ipsilateral activity for relevant and irrelevant cues, panel c). The differences are depicted together with topographical ERP-difference maps for the time window of the N2pc (160 ms to 270 ms). All ERPs are relative to a baseline from -50 ms before the first cue to the onset of the first cue. As can be seen, there was an N2pc in the relevant and in the irrelevant cueing conditions. Also, by looking at Figure 3, it seems as if the N2pc started later and was weaker in the irrelevant than in the relevant cueing condition.

These observations were confirmed in a repeated-measures ANOVA with the variables cue type (relevant or irrelevant cue), laterality (electrode ipsi- or contralateral to the first cue), and hemisphere (right or left hemisphere). The analysis revealed a significant main effect for laterality, $(1, 10) = 7.3$, $p < .05$, and a significant interaction of laterality and cue type, $F(1, 10) = 10.14$, $p < .01$. Cues elicited an N2pc, regardless of whether the cue was relevant or irrelevant. However, if the cue was relevant, the N2pc was stronger (contra- minus ipsilateral activity: $0.76 \mu\text{V}$) and started earlier than if the cue was irrelevant ($.30 \mu\text{V}$), as was shown in Section 2.2.3.

We were concerned that the choice of the electrode locations of the N2pc might have been unfortunate. Therefore, we repeated our major analysis of the N2pc in a repeated-measures ANOVA with the additional variable site (P3/P4, P7/P8, and O1/O2) and the variables cue type (relevant or irrelevant cue) and laterality (electrode ipsi- or contralateral to the first cue) as before. Besides replicating the main effect of laterality, $F(1, 10) = 6.86$, $p < .05$, and an interaction of laterality and cue type, $F(1, 10) = 5.56$, $p < .01$, there were no significant main effects, all $F_s < 1.40$ and all $p_s > .28$, and no significant interactions including the three-way interaction of site, cue type, and laterality, all $F_s < 2.10$ all $p_s > .15$. In addition, the ANOVA was also repeated with the ERPs pooled across P3, P7, and O1 (for the left side) and across P4, P8, and O2 (for the right side). This ANOVA also confirmed a laterality effect, $(1, 10) = 6.86$, $p < .05$, and an interaction of laterality and cue type, $F(1, 10) = 5.56$, $p < .01$, and no main effect of cue type, $F < 1$.

2.2.3. N2pc to the First Cue: Early Phase. To demonstrate the earlier onset of the N2pc with relevant cues than with irrelevant cues, we split the N2pc window into an early phase (160 ms to 215 ms after the cue onset) and into a late phase (215 ms to 270 ms after the cue onset; cf. [35]). In the early window, an ANOVA revealed a significant two-way interaction of laterality and cue type, $(1, 10) = 30.17$, $p < .01$. Post-hoc t -tests revealed that the contra-to-ipsilateral negativity difference ($-.78 \mu\text{V}$) was only significant in the relevant condition, $(10) = 4.33$, $p < .01$, but not in the irrelevant condition ($.02 \mu\text{V}$), $t(10) = .08$, $p = .93$.

2.2.4. N2pc to the First Cue: Late Phase. A similar ANOVA of the late time window only led to a main effect of laterality, $(1, 10) = 8.10$, $p < .05$. The contra-to-ipsilateral negativity difference was about similar in relevant ($.77 \mu\text{V}$) and irrelevant ($.66 \mu\text{V}$) cueing conditions. There was neither a main effect of cue type, nor of hemisphere, nor any interaction between the variables, all other $F_s < 2.10$ all $p_s > .18$.

2.2.5. N2pc to the First Cue: Fast Responses. Recently, McDonald and colleagues [2] showed that irrelevant distractors elicited a Pd among the fastest responses. We therefore also repeated our ANOVA of the activity at P3 and P4, with only the fastest 50% of the saccades and the two within-participant variables cue type (relevant or irrelevant cue), and laterality (electrode ipsi- or contralateral to the first cue).

Again, activity was more negative at contra- than ipsilateral electrodes, $(1, 10) = 11.16$, $p < .05$. This time, however, the interaction was far from significant, $F < 1$. In contrast to the findings of McDonald et al. [2], a more prominent N2pc rather than a Pd was observed with the irrelevant singleton cues during the fastest responses. This can also be seen by looking at Figure 4.

3. Discussion

In the present study, we tested whether irrelevant cues were proactively inhibited or whether they captured attention before being inhibited. In line with the latter possibility, relevant, and importantly also irrelevant, cues elicited an N2pc and both stimuli led to inhibition of saccades 1 s after the cues. This was reflected in slower saccadic RTs to targets in SP than DP conditions. In other words, we found the typical IOR effect, an observation in line with the late inhibition or disengagement hypothesis of Theeuwes et al. [1]. This finding is also in agreement with prior findings of Ansoorge et al. [11] with relevant cues. In their study, these authors found a capture effect of the relevant cues when a CTOA of 200 ms was used. This capture effect preceded a subsequent IOR effect. Irrelevant cues only produced reliable IOR effects. Ansoorge et al. also observed that IOR started earlier with an irrelevant cue than with a relevant cue. This particular finding could not be observed in the present study. In the present study, among the slowest responses, IOR with irrelevant cues was only numerically but not significantly stronger than IOR with relevant cues. This latter finding is thus also not so well in line with Theeuwes et al.'s disengagement theory, according to which one would have expected stronger disengagement or IOR after irrelevant than after relevant cues. According to disengagement theory, only the stronger disengagement of attention that follows irrelevant cues accounts for seemingly stronger capture effects by relevant than irrelevant cues. Clearly, this prediction of the disengagement theory was not confirmed. In contrast, our results suggested a mixture of early capture differences—with more capture by relevant than irrelevant cues—and a later disengagement effect that was numerically stronger with irrelevant than relevant cues, as two sources contributing to stronger capture effects by relevant than irrelevant cues.

Concerning stronger capture by relevant than irrelevant cues, this was reflected in the N2pc. When we looked at the N2pc as an index of the initial capture of attention, we found a larger overall N2pc. This reflected on average an earlier start of the N2pc elicited by the relevant cue. These findings are in line with prior findings showing an earlier or temporally less variable capture effect and often even a selective capture effect for top-down matching than nonmatching cues [12, 21, 23, 35, 36]. This difference in capture for top-down matching as compared to nonmatching cues is typically assumed to reflect either of two processes: selective top-down tuning to sets of features so that initial capture is restricted to the cues matching the set [12, 37] or less inhibition of attention captured by the top-down matching cue [1, 38]. With the current procedure, we cannot decide

which of these interpretations holds true, that is, whether the temporally more variable or trailing onset of the N2pc by the irrelevant cues reflected less initial capture by these cues or a combination of initial capture by the irrelevant cues and proactive inhibition of the irrelevant cues. With respect to the latter, however, we did not find any evidence for strong early proactive inhibition of the irrelevant cues in the form of a Pd. The trailing of the N2pc for irrelevant cues might be a tentative hint for some proactive inhibition. Without any proactive influence, one would expect similar onset times of the N2pc for relevant and irrelevant stimuli (although the initially smaller N2pc for irrelevant stimuli may camouflage its early onset).

In particular, prior studies found proactive inhibition in the form of a Pd when only looking at the fastest responses [2]. In contrast to this finding, early or proactive inhibition was not associated with the fastest responses in the present study. This was evident when we sorted the ERPs as to whether they were recorded in a trial with a quick or slow saccade: among the fast saccades, the N2pcs of irrelevant and relevant cues became even more similar. This means that in the present study, more proactive inhibition would have counteracted the irrelevant cue's N2pc onset in the trials with the slower saccades.

Which factors might account for the differences between the present study and the previous study by McDonald et al. [2]? To reconcile the different findings, results from Kiss and colleagues [27] might be of interest. These authors presented target and distractor simultaneously (similar to [2]) and found proactive inhibition of the irrelevant distractor in the form of a Pd when the display was shown for 200 ms but an N2pc plus subsequent inhibition (again in the form of a Pd but occurring at a later point in time) when the display was presented until a response was given. This might indicate that the irrelevant distractor elicits an N2pc and captures attention when the participants have time for their attention to shift to the target so that the distractor-elicited capture is not masked by a concomitant target-elicited N2pc.

This might also explain why we found an N2pc of the irrelevant cues whereas most contingent-capture studies did not find any evidence for capture by irrelevant singleton distractors (e.g., [21, 39]). With respect to the finding of an N2pc to the irrelevant cue in the present study and its absence in prior studies, a few other procedural differences might also play a role. First of all, the relevant cue was 100% valid (100% SP); that is, it predicted the discrimination target position with certainty. Although there was no discrimination target in the irrelevant target position it is possible that a bit of the general informative value of the relevant cues spilled over to the irrelevant cues. In other words, participants might have inadvertently attended to the irrelevant cue on at least some trials, for example, because they were not paying close enough attention to the color of the first cue. In support of this possibility, it would have been possible to find the relevant cues by the so-called *singleton search strategy* [40, 41]. In fact, the use of two different relevant colors—one (e.g., blue) for the first display's relevant cue and another one (red) for the saccade cue in the second display—might have encouraged our participants to use a singleton search strategy rather than

a feature search strategy. A few findings seem to indicate that the use of a top-down set containing two relevant colors leads to the "erroneous" capture of attention by an irrelevant color-singleton distractor in at least some trials (cf. [42–45], but see [46, 47]). In addition, participants might have actively searched for even the irrelevant cues because these cues informed the participants that they would not have to discriminate between the different target orientations and keep the cue's position in mind. The relatively long CTOA might have encouraged this strategy further because it would have allowed sufficient time to first willingly attend to each cue—relevant and irrelevant—and then to return attention to a neutral position after the irrelevant cue and before the onset of the target. Even though this particularity of our procedure might explain why we did find an N2pc for both relevant and irrelevant cues, it is important to note that we were still able to ascertain two things: first, recording EEG we were able to demonstrate capture where behavioral measures only indicated inhibition [11]. Second, we found differences in initial capture for relevant and irrelevant cues. Thus, although one might argue that the difference in the way participants processed relevant and irrelevant cues in our study was only small, our EEG measure was definitely sensitive to it. In sum, we might not have ended the debate over early proactive inhibition for complete prevention of capture once and for all with our study. However, we provide one more piece in the puzzle and another demonstration of the usefulness of combining EEG with behavioral measures to obtain a more complete picture of the processes engaged through a given paradigm.

A further point that needs discussion is the relation between capture and IOR. Originally, IOR was regarded as the reflection of preceding capture [9]. Under this perspective, it would be strange if different degrees of initial capture by relevant versus irrelevant cues ultimately lead to relatively similar degrees of IOR by these stimuli. However, researchers had argued from very early on that capture and certain forms of inhibition could be partly independent processes [48]. Today, it is clear that nonattentional factors like motor inhibition and sensory habituation can also contribute to inhibition [8, 49, 50]. Therefore, it is in principle possible to find similar degrees of late inhibition after different degrees of capture [51–53] or even more inhibition following less capture by an irrelevant stimulus [11]. Along similar lines, Prinzmetal et al. [54] reported that attention capture and IOR are differentially modulated by, on the one hand, the number of potential target locations and, on the other, the presence of distractor stimuli in the target display. Dissociations of attention capture and IOR are also in line with neurophysiological observations suggesting that the two effects arise at different stages of processing and may therefore be modulated differentially (e.g., [55]). In more functional terms, Prinzmetal et al. [54] recently suggested that attention capture may best be described by a serial search mechanism, reminiscent of the attentional spotlight that (at least for top-down matching cues) is first allocated to the cued location and has to be redirected on invalid (DP) trials. IOR, however, may better be accounted for by a decision process in a competitive accumulator model in which the decision to respond to a particular location

previously visited by attention is systematically delayed (see also [56]). In conclusion, the two mechanisms proposed for attention capture and IOR are very distinct, supporting the possibility for dissociations.

The present results also show that IOR can be induced by color singletons. Previous studies such as Gibson and Amelio [57] failed to find any evidence for IOR with color singletons, a result that was ascribed to the special role of abrupt onsets for the occurrence of IOR. Here, we show that relevant and even irrelevant color singletons lead to IOR when an eye movement instead of a manual response is used and when the saccadic RT distribution is taken into account. In line with this interpretation, Godijn and Theeuwes [58] and more recently Priess et al. [30] and Ansorge et al. [11] also demonstrated saccadic IOR after color singletons in a saccade task.

4. Conclusion

In conclusion, in line with the late inhibition or disengagement theory, we have shown that the irrelevant and the relevant distractor first both captured attention (reflected in their N2pc) before they were actively inhibited (reflected in saccadic IOR). This lack of proactive inhibition was also found if only the fastest responses were analyzed. However, we found little indication that IOR was stronger after irrelevant than relevant cues. Therefore, it is not likely that disengagement was the only responsible process. Early inhibition (among the slower responses) or contingent capture must have also contributed to the N2pc differences between relevant and irrelevant cues.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

Research was supported by project number CS11-009 of the WWTF (Wiener Wissenschafts- und Technologiefonds) to Ulrich Ansorge, Otmar Scherzer, and Shelley Buchinger. The authors thank Susanne Neissl for help with the data collection and Will Young for proofreading.

References

- [1] J. Theeuwes, P. Atchley, and A. F. Kramer, "On the time course of top-down and bottom-up control of visual attention," in *Attention and Performance XVIII*, S. Monsell and J. Driver, Eds., pp. 105–125, MIT Press, Cambridge, Mass, USA, 2000.
- [2] J. J. McDonald, J. J. Green, A. Jannati, and V. di Lollo, "On the electrophysiological evidence for the capture of visual attention," *Journal of Experimental Psychology: Human Perception and Performance*, vol. 39, no. 3, pp. 849–860, 2013.
- [3] H. J. Müller and P. M. A. Rabbitt, "Reflexive and voluntary orienting of visual attention: time course of activation and resistance to interruption," *Journal of Experimental Psychology: Human Perception and Performance*, vol. 15, no. 2, pp. 315–330, 1989.
- [4] J. Theeuwes, "Perceptual selectivity for color and form," *Perception & Psychophysics*, vol. 51, no. 6, pp. 599–606, 1992.
- [5] L. Itti, C. Koch, and E. Niebur, "A model of saliency-based visual attention for rapid scene analysis," *IEEE Transactions on Pattern Analysis and Machine Intelligence*, vol. 20, no. 11, pp. 1254–1259, 1998.
- [6] D. Parkhurst, K. Law, and E. Niebur, "Modeling the role of saliency in the allocation of overt visual attention," *Vision Research*, vol. 42, no. 1, pp. 107–123, 2002.
- [7] M.-S. Kim and K. R. Cave, "Top-down and bottom-up attentional control: on the nature of interference from a salient distractor," *Perception & Psychophysics*, vol. 61, no. 6, pp. 1009–1023, 1999.
- [8] R. M. Klein, "Inhibition of return," *Trends in Cognitive Sciences*, vol. 4, no. 4, pp. 138–147, 2000.
- [9] M. I. Posner and Y. Cohen, "Components of visual orienting," in *Attention and Performance*, H. Bouma and D. G. Bouwhuis, Eds., vol. 10, pp. 531–556, Erlbaum, Hillsdale, NJ, USA, 1984.
- [10] T. L. Taylor and R. M. Klein, "On the causes and effects of inhibition of return," *Psychonomic Bulletin & Review*, vol. 5, no. 4, pp. 625–643, 1998.
- [11] U. Ansorge, H. W. Priess, and D. Kerzel, "Effects of relevant and irrelevant color singletons on inhibition of return and attentional capture," *Attention, Perception, & Psychophysics*, vol. 75, no. 8, pp. 1687–1702, 2013.
- [12] C. L. Folk, R. W. Remington, and J. C. Johnston, "Involuntary covert orienting is contingent on attentional control settings," *Journal of Experimental Psychology: Human Perception and Performance*, vol. 18, no. 4, pp. 1030–1044, 1992.
- [13] H. Deubel and W. X. Schneider, "Saccade target selection and object recognition: evidence for a common attentional mechanism," *Vision Research*, vol. 36, no. 12, pp. 1827–1837, 1996.
- [14] E. Kowler, E. Anderson, B. Doshier, and E. Blaser, "The role of attention in the programming of saccades," *Vision Research*, vol. 35, no. 13, pp. 1897–1916, 1995.
- [15] M. Eimer, "The N2pc component as an indicator of attentional selectivity," *Electroencephalography and Clinical Neurophysiology*, vol. 99, no. 3, pp. 225–234, 1996.
- [16] S. J. Luck and S. A. Hillyard, "Spatial filtering during visual search: evidence from human electrophysiology," *Journal of Experimental Psychology: Human Perception and Performance*, vol. 20, no. 5, pp. 1000–1014, 1994.
- [17] P. Jaśkowski, R. H. J. van der Lubbe, E. Schlotterbeck, and R. Verleger, "Traces left on visual selective attention by stimuli that are not consciously identified," *Psychological Science*, vol. 13, no. 1, pp. 48–54, 2002.
- [18] C. Hickey, V. di Lollo, and J. J. McDonald, "Electrophysiological indices of target and distractor processing in visual search," *Journal of Cognitive Neuroscience*, vol. 21, no. 4, pp. 760–775, 2009.
- [19] R. Sawaki and S. J. Luck, "Capture versus suppression of attention by salient singletons: electrophysiological evidence for an automatic attend-to-me signal," *Attention, Perception, & Psychophysics*, vol. 72, no. 6, pp. 1455–1470, 2010.
- [20] C. Hickey, J. J. McDonald, and J. Theeuwes, "Electrophysiological evidence of the capture of visual attention," *Journal of Cognitive Neuroscience*, vol. 18, no. 4, pp. 604–613, 2006.
- [21] M. Eimer and M. Kiss, "Involuntary attentional capture is determined by task set: evidence from event-related brain

- potentials," *Journal of Cognitive Neuroscience*, vol. 20, no. 8, pp. 1423–1433, 2008.
- [22] M. Eimer and M. Kiss, "Top-down search strategies determine attentional capture in visual search: behavioral and electrophysiological evidence," *Attention, Perception, & Psychophysics*, vol. 72, no. 4, pp. 951–962, 2010.
- [23] M. Kiss and M. Eimer, "Attentional capture by size singletons is determined by top-down search goals," *Psychophysiology*, vol. 48, no. 6, pp. 784–787, 2011.
- [24] M.-C. Lien, E. Ruthruff, and L. Cornett, "Attentional capture by singletons is contingent on top-down control settings: evidence from electrophysiological measures," *Visual Cognition*, vol. 18, no. 5, pp. 682–727, 2010.
- [25] M.-C. Lien, E. Ruthruff, Z. Goodin, and R. W. Remington, "Contingent attentional capture by top-down control settings: converging evidence from event-related potentials," *Journal of Experimental Psychology: Human Perception and Performance*, vol. 34, no. 3, pp. 509–530, 2008.
- [26] G. F. Woodman, M.-S. Kang, A. F. Rossi, and J. D. Schall, "Nonhuman primate event-related potentials indexing covert shifts of attention," *Proceedings of the National Academy of Sciences of the United States of America*, vol. 104, no. 38, pp. 15111–15116, 2007.
- [27] M. Kiss, A. Grubert, A. Petersen, and M. Eimer, "Attentional capture by salient distractors during visual search is determined by temporal task demands," *Journal of Cognitive Neuroscience*, vol. 24, no. 3, pp. 749–759, 2012.
- [28] H. Deubel, "The time course of presaccadic attention shifts," *Psychological Research*, vol. 72, no. 6, pp. 630–640, 2008.
- [29] J. E. Hoffman and B. Subramaniam, "The role of visual attention in saccadic eye movements," *Perception & Psychophysics*, vol. 57, no. 6, pp. 787–795, 1995.
- [30] H.-W. Priess, S. Born, and U. Ansorge, "Inhibition of return after color singletons," *Journal of Eye Movement Research*, vol. 5, no. 5, pp. 1–12, 2012.
- [31] J. Theeuwes and R. Godijn, "Inhibition-of-return and oculomotor interference," *Vision Research*, vol. 44, no. 12, pp. 1485–1492, 2004.
- [32] J. Theeuwes and C. Y. D. Chen, "Attentional capture and inhibition (of return): the effect on perceptual sensitivity," *Perception & Psychophysics*, vol. 67, no. 8, pp. 1305–1312, 2005.
- [33] W. A. Stephenson and F. A. Gibbs, "A balanced non-cephalic reference electrode," *Electroencephalography and Clinical Neurophysiology*, vol. 3, no. 2, pp. 237–240, 1951.
- [34] W. van Zoest, M. Donk, and J. Theeuwes, "The role of stimulus-driven and goal-driven control in saccadic visual selection," *Journal of Experimental Psychology: Human Perception and Performance*, vol. 30, no. 4, pp. 746–759, 2004.
- [35] U. Ansorge, M. Kiss, F. Worschech, and M. Eimer, "The initial stage of visual selection is controlled by top-down task set: new ERP evidence," *Attention, Perception, & Psychophysics*, vol. 73, no. 1, pp. 113–122, 2011.
- [36] C. J. H. Ludwig and I. D. Gilchrist, "Stimulus-driven and goal-driven control over visual selection," *Journal of Experimental Psychology: Human Perception and Performance*, vol. 28, no. 4, pp. 902–912, 2002.
- [37] C. L. Folk and R. Remington, "Selectivity in distraction by irrelevant featural singletons: evidence for two forms of attentional capture," *Journal of Experimental Psychology: Human Perception and Performance*, vol. 24, no. 3, pp. 847–858, 1998.
- [38] J. Theeuwes, "Top-down and bottom-up control of visual selection," *Acta Psychologica*, vol. 135, no. 2, pp. 77–99, 2010.
- [39] U. Ansorge, M. Kiss, and M. Eimer, "Goal-driven attentional capture by invisible colors: evidence from event-related potentials," *Psychonomic Bulletin & Review*, vol. 16, no. 4, pp. 648–653, 2009.
- [40] W. F. Bacon and H. E. Egeth, "Overriding stimulus-driven attentional capture," *Perception & Psychophysics*, vol. 55, no. 5, pp. 485–496, 1994.
- [41] A. B. Leber and H. E. Egeth, "It's under control: top-down search strategies can override attentional capture," *Psychonomic Bulletin & Review*, vol. 13, no. 1, pp. 132–138, 2006.
- [42] U. Ansorge and G. Horstmann, "Preemptive control of attentional capture by colour: evidence from trial-by-trial analyses and orderings of onsets of capture effects in reaction time distributions," *The Quarterly Journal of Experimental Psychology*, vol. 60, no. 7, pp. 952–975, 2007.
- [43] U. Ansorge and S. I. Becker, "Contingent capture in cueing: the role of color search templates and cue-target color relations," *Psychological Research*, vol. 78, no. 2, pp. 209–221, 2014.
- [44] C. L. Folk and B. A. Anderson, "Target-uncertainty effects in attentional capture: color-singleton set or multiple attentional control settings?" *Psychonomic Bulletin & Review*, vol. 17, no. 3, pp. 421–426, 2010.
- [45] A. Grubert and M. Eimer, "Qualitative differences in the guidance of attention during single-colour and multiple-colour visual search: behavioural and electrophysiological evidence," *Journal of Experimental Psychology: Human Perception and Performance*, vol. 39, no. 5, pp. 1433–1442, 2013.
- [46] J. L. Irons, C. L. Folk, and R. W. Remington, "All set! Evidence of simultaneous attentional control settings for multiple target colors," *Journal of Experimental Psychology: Human Perception and Performance*, vol. 38, no. 3, pp. 758–775, 2012.
- [47] F. Worschech and U. Ansorge, "Top-down search for color prevents voluntary directing of attention to informative singleton cues," *Experimental Psychology*, vol. 59, no. 3, pp. 153–162, 2012.
- [48] G. Tassinari and G. Berlucchi, "Sensory and attentional components of slowing of manual reaction time to non-fixated visual targets by ipsilateral primes," *Vision Research*, vol. 33, no. 11, pp. 1525–1534, 1993.
- [49] J. Lupiáñez, "Inhibition of return," in *Attention and Time*, A. C. Nobre and J. T. Coull, Eds., pp. 17–34, Oxford University Press, Oxford, UK, 2010.
- [50] Z. Wang and R. M. Klein, "Searching for inhibition of return in visual search: a review," *Vision Research*, vol. 50, no. 2, pp. 220–228, 2010.
- [51] S. Born, D. Kerzel, and J. Theeuwes, "Evidence for a dissociation between the control of oculomotor capture and disengagement," *Experimental Brain Research*, vol. 208, no. 4, pp. 621–631, 2011.
- [52] J. Pratt and J. McAuliffe, "Determining whether attentional control settings are inclusive or exclusive," *Perception & Psychophysics*, vol. 64, no. 8, pp. 1361–1370, 2002.
- [53] J. Pratt, A. B. Sekuler, and J. McAuliffe, "The role of attentional set on attentional cueing and inhibition of return," *Visual Cognition*, vol. 8, no. 1, pp. 33–46, 2001.
- [54] W. Prinzmetal, J. A. Taylor, L. B. Myers, and J. Nguyen-Espino, "Contingent capture and inhibition of return: a comparison of mechanisms," *Experimental Brain Research*, vol. 214, no. 1, pp. 47–60, 2011.
- [55] J. H. Fecteau and D. P. Munoz, "Correlates of capture of attention and inhibition of return across stages of visual processing,"

Journal of Cognitive Neuroscience, vol. 17, no. 11, pp. 1714–1727, 2005.

- [56] C. J. Ludwig, S. Farrell, L. A. Ellis, and I. D. Gilchrist, “The mechanism underlying inhibition of saccadic return,” *Cognitive Psychology*, vol. 59, no. 2, pp. 180–202, 2009.
- [57] B. S. Gibson and J. Amelio, “Inhibition of return and attentional control settings,” *Perception & Psychophysics*, vol. 62, no. 3, pp. 496–504, 2000.
- [58] R. Godijn and J. Theeuwes, “The relationship between inhibition of return and saccade trajectory deviations,” *Journal of Experimental Psychology: Human Perception and Performance*, vol. 30, no. 3, pp. 538–554, 2004.

Research Article

Human Gaze Following Response Is Affected by Visual Acuity

**Marcella Spoor,¹ Behdokht Hosseini,¹ Bart van Alphen,¹
Maarten A. Frens,^{1,2} and Jos N. van der Geest¹**

¹ *Department of Neuroscience, Erasmus MC, P.O. Box 2040, 3000 CA Rotterdam, The Netherlands*

² *Erasmus University College, Rotterdam, The Netherlands*

Correspondence should be addressed to Jos N. van der Geest; j.vandergeest@erasmusmc.nl

Received 20 September 2013; Revised 9 January 2014; Accepted 8 March 2014; Published 6 April 2014

Academic Editor: Stefanie I. Becker

Copyright © 2014 Marcella Spoor et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

The present study investigated how gaze following eye movements are affected by stimulus contrast and spatial frequency and by aberrations in central visual acuity due to refractive errors. We measured 30 healthy subjects with a range of visual acuities but without any refractive correction. Visual acuity was tested using a Landolt-C chart. Subjects were divided into three groups with low, intermediate, or good visual acuity. Gaze following responses (GFR) to moving Gabor patches were recorded by video-oculography. In each trial, the subjects were presented with a single Gabor patch with a specific spatial frequency and luminance contrast that moved sinusoidally in the horizontal plane. We observed that GFR gain decreased with increasing spatial frequency and decreasing contrast and was correlated with visual acuity. GFR gain was lower and decreased more for subjects with lower visual acuity; this was especially so for lower stimulus contrasts that are not tested in standard acuity tests. The largest differences between the groups were observed at spatial frequencies around 4 cpd and at contrasts up to 10%. Aberrations in central visual acuity due to refractive errors affect the GFR response depending on the contrast and spatial frequency of the moving stimulus. Measuring this effect may contribute to a better estimate of changes in visual function as a result of aging, disease, or treatments meant to improve vision.

1. Introduction

Vision is the ability to observe the world by interpreting light that is reflected from the surroundings and reaches the retina. Loss of visual function can severely affect daily human activities and may effectively decrease the quality of life [1, 2]. Loss of vision can be caused by various ocular diseases, such as retinitis pigmentosa, macular degeneration [3], or glaucoma. Loss of vision can also occur as a symptom of other disorders like multiple sclerosis [4] or diabetic retinopathy.

Visual acuity is one of the important aspects of visual function. Currently, visual acuity is mainly assessed by measuring central visual acuity using, for instance, a letter chart on which a subject has to read increasingly smaller letters while standing at a particular distance (Snellen acuity). Other acuity measures use the E-chart or the Landolt-C chart, in which subjects are asked to report the orientation of a capital E or C, respectively. A person with normal acuity (20/20 vision) can identify the standardized symbols on the chart at a distance of about 6 meters (20 feet). A person with

20/30 vision can identify symbols on the chart from 20 feet that a person with normal acuity could see from 30 feet. This method to assess acuity measures the highest resolution that the visual system can perceive and is useful to determine refractive errors of the eye.

However, several issues arise using such a measure. For instance, these acuity tests often yield highly variable results between examinations due to, for instance, observer-based (i.e., by clinicians or experimenters) variability [5] and differences in recording settings, such as distances from chart and light conditions [6]. In addition, active cooperation of the observer is required: the observer has to actively report, for instance, the orientation of a C. This not only requires compliance of the observer, but also means that it is a subjective measure of visual function, in the sense that no strong conclusions can be drawn from an inability to read out the next line. Finally, with this type of acuity tests only a small subset of the sensitivity of the visual system is probed: objects with high spatial frequencies at very high contrast [7].

Several studies related visual acuity to optokinetic eye movements [8], or smooth pursuit eye movements [9], and did so by varying the spatial frequency of the stimulus. Optokinetic eye movements refer to the following of a moving pattern of dots or stripes in the full visual field. These studies used gaze and ocular following responses as a tool to assess visual function in visually impaired participants and reported that reduced visual acuities decreased the amplitude of the following response. However, these studies did not vary the contrast of the stimulus and, hence, did not determine the interaction between visual acuity and contrast sensitivity in more detail.

Contrast sensitivity is the ability to detect differences in contrast between shades of gray in a visual stimulus. This sensitivity varies with spatial frequency, that is, the level of visual detail of the stimulus. A contrast sensitivity test measures the smallest amount of contrast needed to detect a visual stimulus and provides a more complete quantification of a person's visual capabilities by taking two variables into account, spatial detail and contrast. Contrast sensitivity is measured by asking an observer to detect or discriminate gratings as targets instead of symbols [10, 11]. Sine-wave gratings possess useful mathematical properties and early stages of visual processing are optimally "tuned" to such targets [12, 13]. Each sine-wave grating consists of a given spatial frequency which is specified in terms of the size of the grating at the back of the eye considering the number of sinusoidal luminance cycles per degree (cpd) of visual angle. The contrast of the target grating at a specific spatial frequency is then varied while the observer's contrast detection threshold is determined.

The contrast sensitivity function has become a well-established tool to probe the functional integrity of the visual system [14]. Over the last decades many techniques, including psychophysics [15] and the recording of optokinetic nystagmus [8, 9], have been described to measure the contrast sensitivity function. Leguire et al. [14] compared the contrast sensitivity function based on psychophysics with optokinetic measurements in a small group of healthy subjects and found a good association between the two measures. Here we aim to determine the contrast sensitivity function in humans by measuring the gaze following response (GFR) in reaction to moving stimuli of varying contrasts and spatial frequencies. The GFR is an eye movement that drives the eye to follow stimuli in the visual field and may contain both voluntary and involuntary components. This technique was originally developed to determine contrast sensitivity in mice [16]. The present study is for proof of principle only and shows how foveally induced gaze following responses to moving Gabor patches are affected by contrast and spatial frequency of the stimulus. In addition, we studied how these eye movement responses are affected by aberrations in central visual acuity due to uncorrected refractive errors.

2. Materials and Methods

2.1. Subjects. We measured 30 healthy subjects (13 females) between 22 and 57 years of age (median of 27 years). One eye

was measured per subject without any refractive correction, while the other eye was patched. The study followed the tenets of the Declaration of Helsinki and informed consent was obtained from all subjects before the experiment.

2.2. Visual Acuity. Central visual acuity was assessed using a Landolt-C chart, which requires an observer to report the orientation of a gap in a ring. The size of the ring and gap is reduced every three rings. The visual acuity score of the observer was defined by the smallest visual angle of the ring for which the observer reported the orientation correctly at least two times. Variability was limited by using a fixed viewing distance of 6 meters (~20 feet) and by having one experimenter testing all subjects under identical light conditions. Subjects were divided into three groups based on these visual acuity scores: low (score of 20/200 and below), intermediate (scores between 20/200 and 20/20), and high (score of 20/20 and above) visual acuity.

2.3. Contrast Sensitivity Measurements. All experiments were performed in a darkened room. The gaze following response (GFR) was evoked by moving a visual stimulus horizontally. The stimulus was back-projected via computer-controlled movable mirrors (Laser2000, The Netherlands) on a transparent screen (135 by 99 cm) using a digital projector (Sanyo PLV-Z2) with a resolution of 1024 by 768 pixels (see Figure 1(a)). Viewing distance was 305 cm.

Each stimulus showed a circular Gabor patch with a standard deviation of 5 degrees of visual angle in diameter, thus covering the fovea and a substantial part of the parafoveal area when looked at. The Gabor patches were generated in Matlab (The Mathworks, Natick, MA, USA). A Gabor patch consisted of vertically oriented lines with a particular luminance that was determined by a sinusoid having a specific frequency (0.48, 0.96, 1.93, 3.87, or 7.74 cycles per degree) and a specific black and white contrast (1, 2, 4, 8, 16, 32, 48, 64, or 100%). Luminance of the bright (L_{\max}) and dark stripes (L_{\min}) in the center of the patch was measured with a luminance meter (LS-100; Minolta Camera, Osaka, Japan), after which contrasts were calculated according to the Michelson formula: $\text{Contrast} = (L_{\max} - L_{\min}) / (L_{\max} + L_{\min})$. Average luminance was 16 cd/m² in all stimulus conditions. For the stimuli with 100% contrast, the luminance of the dark stripes was 0.15 cd/m² and the luminance of the white stripes was 32 cd/m².

Combining these two variables yielded 45 unique Gabor patches and each was presented once in a random order (see Figure 1(b) for stimulus examples).

The movements of the mirrors were controlled by a computer running Spike-2 (version 4.20, Cambridge Electronic Design) in such a way that the stimulus moved sinusoidally in the horizontal plane (frequency of 0.1 Hz, peak velocity of 5 degrees per second, and peak to peak amplitude of 15.9 degrees) for three full cycles. Hence, each stimulus presentation lasted for 30 seconds. Between stimulus presentations there was a random blank interval of 5–15 seconds. The experimenter told the subject when the next

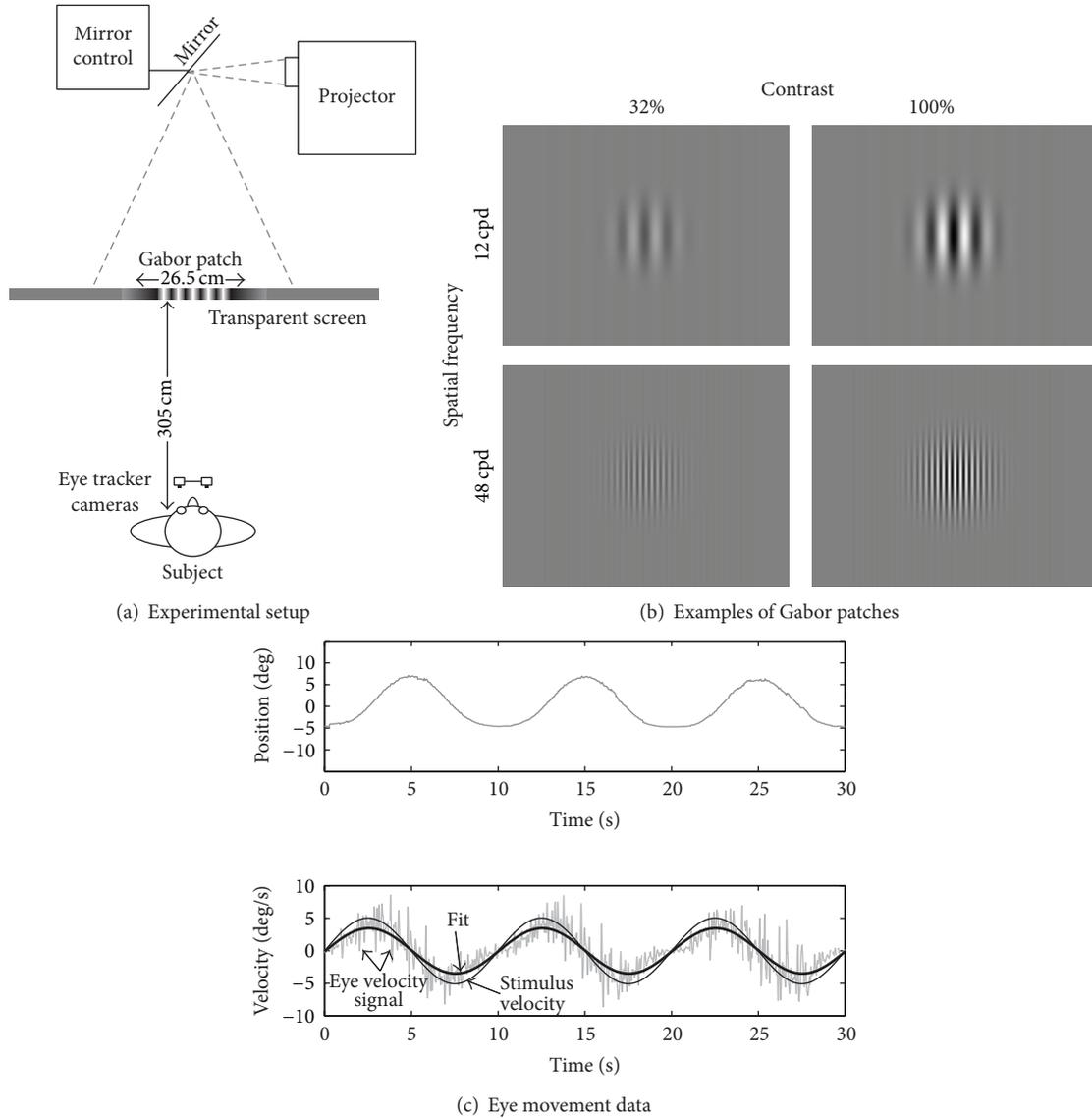


FIGURE 1: (a) shows a schematic drawing of the experimental setup. The stimulus, a Gabor patch, was back-projected via mirrors on a transparent screen. Movement of the mirrors induced a horizontal movement on the screen. (b) shows four examples of Gabor patches. Each stimulus contained a Gabor patch with a unique combination of spatial frequency and black-white contrast. (c) shows an example of the eye movements of an observer who explicitly followed the movement of the Gabor patch. This observer was not included in this experiment. The Gabor patch moved sinusoidally from left to right in the horizontal plane. The top plot of (c) shows the raw eye position trace. The bottom plot of (c) shows the corresponding eye velocity trace (gray line), the stimulus velocity trace (thin black line), and the fitted sinusoid through the eye velocity signal (thick black line).

stimulus was about to be presented. Subjects were instructed to keep their eyes open and look at the stimulus, without specific instructions. The whole experiment lasted for about 40 minutes.

Head movements were restrained using a bite board. Monocular eye movements were recorded using an EyeLink infrared camera system (EyeLink 1 Desktop, SensoMotoric Instruments GmbH, Teltow, Germany) at a 250 Hz sampling rate [17]. Calibration and calibration-accuracy validation were performed prior to each experiment using the standard EyeLink routine.

2.4. Analysis. Eye movement recordings were analyzed offline using custom-written software in Matlab. The first 3 seconds of data was discarded. Instantaneous eye velocity was calculated by taking the first derivative of horizontal eye position over time. Fast phases (saccades) were removed using a velocity threshold of 10 degrees per second (i.e., twice the stimulus velocity). A sine-wave was fitted to the remaining velocity signal, yielding a fitted peak eye velocity (see Figure 1(c) for an example).

The eye velocity gain was calculated for each subject, contrast, and spatial frequency by dividing the fitted peak eye

velocity by the peak stimulus velocity (fixed at 5 deg/s). Per subject, all gains were then normalized by setting the gain obtained in the highest contrast (100%) and lowest spatial frequency (0.48 cpd) to 1.

A multivariate repeated measures analysis (ANOVA) was carried out for the eye movement gains with three factors: "Group" (3 levels: low, intermediate, and high visual acuity), "Contrast" (9 levels), and "Spatial Frequency" (5 levels). Differences between groups were evaluated by subsequent planned comparisons (uncorrected). All statistical analyses were done in SPSS 20.

3. Results

In two subjects, not all responses could be reliably measured due to eye tracking failure; their data was discarded. Based on their visual score in the visual acuity test, the remaining 28 subjects were classified as having low (score of 20/200 and below, $N = 11$), intermediate (scores between 20/200 and 20/20, $N = 10$), or high (score of 20/20 and above, $N = 7$) visual acuity. Ages did not differ between the three groups (median test, $P = 0.75$).

Before normalization (see Methods), the gains across all 45 Gabor presentations and all 28 subjects ranged from 0.0 to 0.53 with a grand overall median of 0.25. After normalization, the GFR gains (averaged over the 45 Gabor presentations) ranged from 0.40 to 0.95 across subjects (median of 0.65). There was a positive correlation between acuity scores and the average normalized GFR gains (Spearman correlation of 0.78, $P < 0.001$).

Figure 2 shows the normalized GFR gain as a function of spatial frequency and contrast of the stimulus for the 3 groups separately. Differences can clearly be observed, most prominently at high spatial frequencies and low contrast.

In order to quantify these differences, the average normalized gains obtained for each contrast and each spatial frequency from each group are plotted in Figures 3(a) and 3(b), respectively.

Statistical analysis showed a significant main effect of "Group" ($F(2) = 21.4$, $P < 0.001$): high acuity subjects had on average higher GFR gains (0.80 ± 0.03 [Standard Error]) than the intermediate (0.69 ± 0.03 , $P < 0.001$) and low acuity subjects (0.53 ± 0.03 , $P < 0.001$). The difference in average gain between the low and intermediate acuity groups was also significant ($P = 0.024$).

The significant main effects of "Contrast" ($F(8) = 29.5$, $P < 0.001$) and "Spatial Frequency" ($F(4) = 48.4$, $P < 0.001$) showed that decreasing the contrast or increasing the spatial frequency of the visual stimulus reduced the GFR gain.

The interactions between "Group" and "Contrast" ($F(2, 8) = 3.62$, $P < 0.001$) and between "Group" and "Spatial Frequency" ($F(2, 4) = 3.79$, $P = 0.013$) were significant. Post hoc analyses showed that especially for lower contrasts (1%–8%) the low acuity group had significantly lower GFR gains than both the intermediate and high acuity groups (all $P < 0.01$; see Figure 3(a)). The average GFR gain was lowest in the low acuity group for all spatial frequencies. Furthermore, for low spatial frequencies (0.48 to 1.92 cpd)

the intermediate acuity group differed from the low acuity group, whereas for higher frequencies (3.84 and 7.68 cpd) the intermediate group differed from the high acuity group (see Figure 3(b)).

From these analyses, we observed that our groups were best separated using a moving Gabor patch with a spatial frequency of about 4 cpd and a contrast of about 8%. We found a positive correlation between visual acuity scores and the normalized GFR gains for this particular Gabor patch (Spearman correlation of 0.64, $P = 0.002$, Figure 3(c)). We did not compute the correlations for the other 44 stimuli.

4. Discussion

We observed that the gaze following response (GFR) is influenced by both the spatial frequency and the contrast of a sinusoidally moving sine grating. In addition, this eye movement response was affected by central visual acuity, as it varied between three groups of subjects with varying visual acuity scores. Reduced central visual acuity related to uncorrected refractive errors induced lower GFR gains. This suggests that the GFR response can be used to estimate human contrast-sensitivity function and to determine how well a stimulus is seen.

The method of measuring the GFR has several advantages over a central visual acuity test using, for instance, a letter chart or a Landolt-C chart. For instance, the latter does not cover the whole visual spectrum but only the high spatial frequency and very high contrast ranges [7], and, therefore, a 20/20 result in visual acuity will not always uncover loss of vision for other contrasts and spatial frequencies. Hence, tests in low vision patients (patients with impaired eye sight that cannot be corrected by conventional means) often depend on self-reported changes in visual function and acuity, which can be highly inaccurate [2, 18]. The eye movement response can provide useful additional information, for instance, an extra dimension of data: that of response magnitude. The gaze following responses measured with the contrast sensitivity test are not bimodal ("I can see it" or "I cannot see it," as in the common acuity test) but graded; the gain of the GFR decreases as stimuli become harder to see [16, 19]. This response sensitivity makes the GFR method suitable to use when screening for small changes in contrast sensitivity, which can be caused by degenerative diseases or by treatment methods that aim to improve visual function in low vision patients. With stimuli covering the whole range of human vision, small changes in contrast sensitivity could be detected using this approach. In addition, using the GFR reflex to test contrast sensitivity provides us with an objective test and without user bias, which often occurs in perception tasks when the stimulus is close to the perceptual threshold.

We tested a small range of spatial frequencies, because there are some technical challenges to measure all the way up to the maximum visible spatial frequency (about 60 cpd [20]) using a standard computer display. For instance, a 24-inch widescreen monitor is approximately 48 cm wide and has a horizontal resolution of 1920 pixels. This means that at most 20 black lines and 20 white lines, each being only

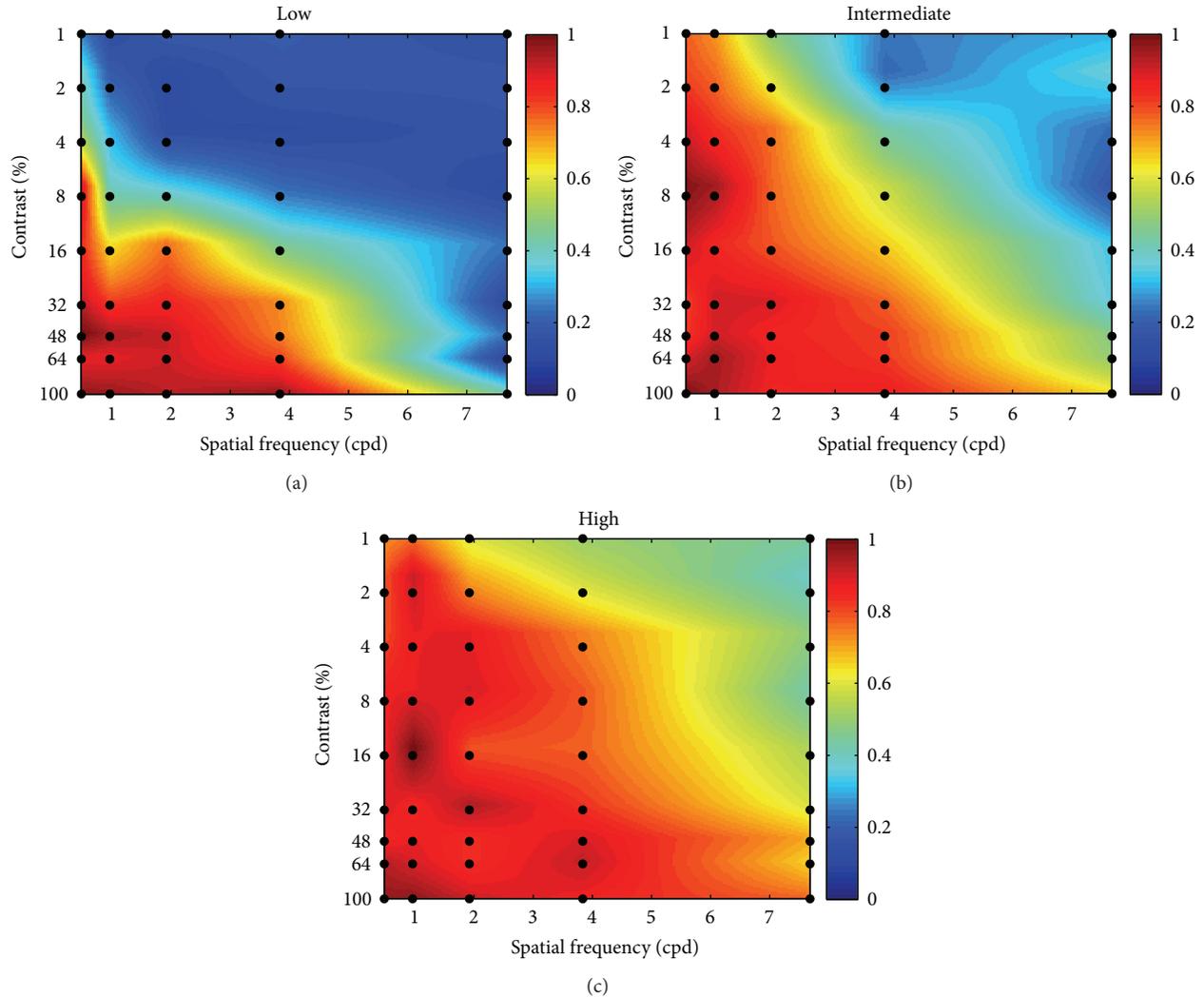


FIGURE 2: For each of the three groups (low, intermediate, or high visual acuity), the color reflects the averaged normalized GFR gains at 45 combinations of contrast and spatial frequency (indicated by black dots). The space between the measured points is linearly interpolated.

1 pixel wide, can be drawn per cm, resulting in a square wave grating of 20 cycles per cm. At a viewing distance of about 170 cm, this would yield a spatial frequency of 60 cpd. For sine gratings, requiring 4 (or even more) visible lines with different contrasts, the viewing distance has to be doubled (at least) to accommodate the entire stimulus. In our setup, the maximum spatial frequency of projected sine-wave grating was limited by viewing distance (305 cm), screen width (135 cm), and projector resolution (1204 pixels), resulting in a projection of about 41 pixels per degree, that is, a maximum spatial frequency of 10 degrees. However, we already observed a decrease in GFR gain for moderate spatial frequencies up to 10 degrees; higher frequencies would have most likely led to negligible eye movement responses. This observation can be exploited in future studies by modifying the experiment into an adaptive procedure which allegedly restricts the number of required trials, thereby reducing the total time of the test substantially. At present, measuring the GFR at all possible combinations of spatial frequencies and

contrasts took about 40 minutes, whereas a regular visual acuity test takes only a few minutes to complete.

In the present study, the nonnormalized GFR gains were rather low. This was probably related to the instruction given to the subject. We told them to look at the stimulus, without explicitly instructing them to fixate at the center of the moving Gabor patch.

Our study suggests that measuring the GFR provides insight into the sensitivity of spatial frequency and contrast in healthy adult subjects. In addition to measuring central visual acuity (preferably by means of a logMAR chart) it may have several clinical applications. For instance, it is known that contrast sensitivity decreases with age [21, 22], which is, however, generally not picked up with an acuity test. In elderly persons, decreased contrast sensitivity contributes to a poor postural stability which leads to a doubling of the already increased likelihood of falling [23]. As a note, the Landolt-C chart measures central visual acuity and we did not assess peripheral visual function. There are many

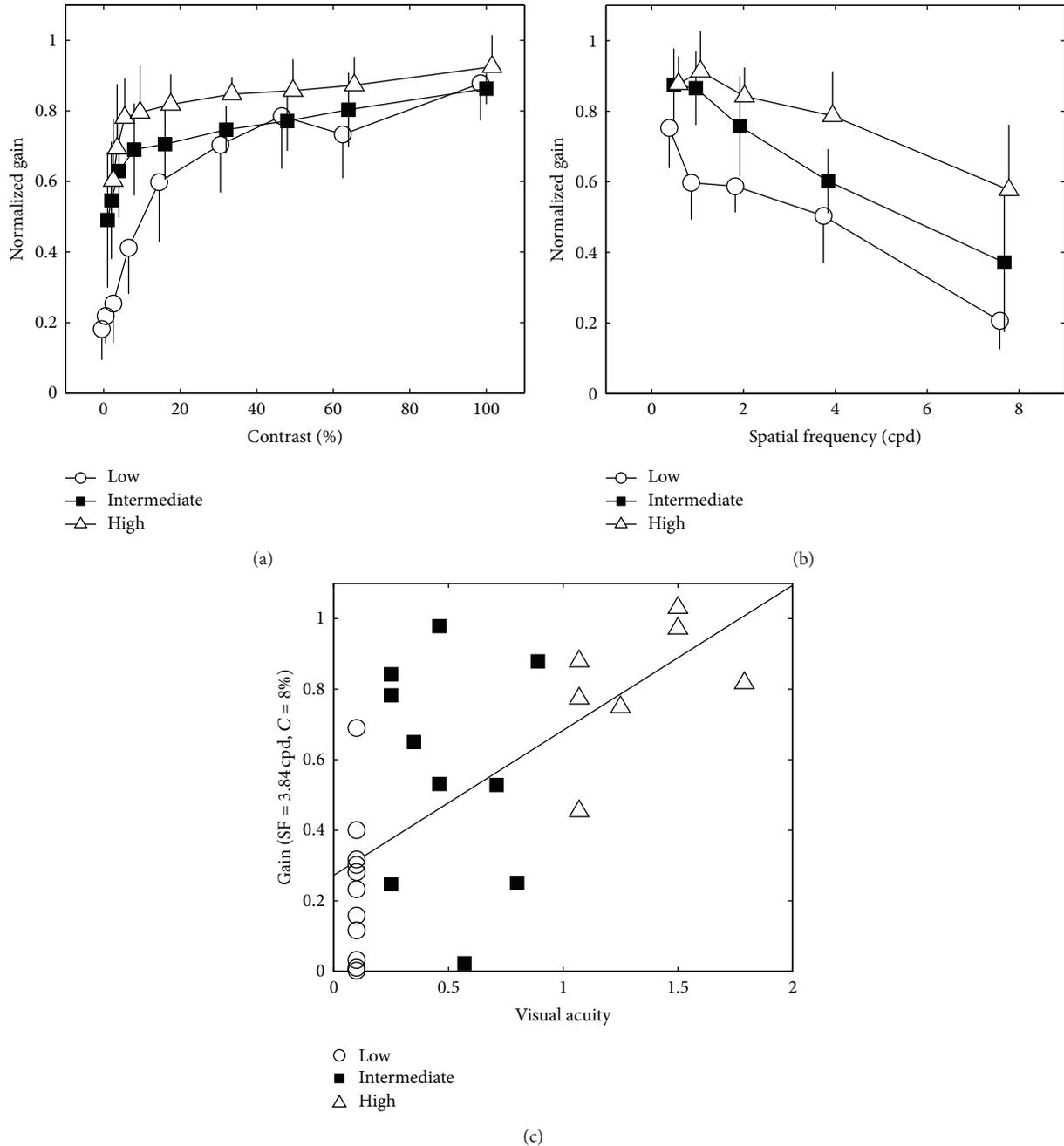


FIGURE 3: For each of the three groups (low, intermediate, or high visual acuity), the averaged normalized GFR gains are pooled over the 5 levels of spatial frequency and plotted against contrast in (a) and pooled over the 9 levels of contrast and plotted against spatial frequency in (b). The error bars represent standard error of the mean. The normalized GFR gain in response to a moving Gabor patch with a spatial frequency of 3.84 cpd and a contrast of 8% is plotted against the visual acuity score in (c); each symbol represents a single subject.

complex ocular conditions; some conditions affect central visual function, like macular degeneration, whereas others result in macular sparing and induce tunnel vision. Moreover, there is a difference between peripheral and central contrast sensitivity. Future studies using the GFR as a measure for contrast sensitivity might use stimuli that target the peripheral retina in particular.

5. Conclusion

We conclude that measuring the gaze following response (GFR) for a wide range of stimulus contrasts and spatial frequencies is useful for observing changes in contrast sensitivity. We observed that worse central visual acuity affects this eye movement response. Measuring the GFR may contribute

to a better estimate of changes in visual function as a result of ageing, disease, or treatments meant to improve visual function.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

The authors would like to thank Junior Med School students Saskia van Grondelle and Simone Dijkland for their assistance in data collection. The authors would also like to thank the reviewers for providing valuable feedback on their work. This study was supported by HFSP (Marcella Spoor), NWO 813.07.002 (Bart van Alphen), the Prinses Beatrix Fund (Jos N. van der Geest), Marie Curie ITN Programme C7 (Maarten A. Frens) and the EUR Interreg Initiative TC2N (Maarten A. Frens and Jos N. van der Geest).

References

- [1] A. M. Armbrecht, P. A. Aspinall, and B. Dhillon, "A prospective study of visual function and quality of life following PDT in patients with wet age related macular degeneration," *The British Journal of Ophthalmology*, vol. 88, no. 10, pp. 1270–1273, 2004.
- [2] K. J. Warrion, U. Altangerel, and G. L. Spaeth, "Performance-based measures of visual function," *Survey of Ophthalmology*, vol. 55, no. 2, pp. 146–161, 2010.
- [3] P. T. V. M. de Jong, "Age-related macular degeneration," *The New England Journal of Medicine*, vol. 355, no. 14, pp. 1474–1485, 2006.
- [4] A. Compston and A. Coles, "Multiple sclerosis," *The Lancet*, vol. 372, no. 9648, pp. 1502–1517, 2008.
- [5] R. A. Gibson and H. F. Sanderson, "Observer variation in ophthalmology," *The British Journal of Ophthalmology*, vol. 64, no. 6, pp. 457–460, 1980.
- [6] J. C. Pandit, "Testing acuity of vision in general practice: reaching recommended standard," *British Medical Journal*, vol. 309, no. 6966, p. 1408, 1994.
- [7] A. P. Ginsburg, "Contrast sensitivity and functional vision," *International Ophthalmology Clinics*, vol. 43, no. 2, pp. 5–15, 2003.
- [8] S. T. Wester, J. F. Rizzo III, M. D. Balkwill, and C. Wall III, "Optokinetic nystagmus as a measure of visual function in severely visually impaired patients," *Investigative Ophthalmology and Visual Science*, vol. 48, no. 10, pp. 4542–4548, 2007.
- [9] C. M. Schor and D. M. Levi, "Disturbances of small-field horizontal and vertical optokinetic nystagmus in amblyopia," *Investigative Ophthalmology and Visual Science*, vol. 19, no. 6, pp. 668–683, 1980.
- [10] K. Arundale, "An investigation into the variation of human contrast sensitivity with age and ocular pathology," *The British Journal of Ophthalmology*, vol. 62, no. 4, pp. 213–215, 1978.
- [11] N. Kara Jr., R. F. Espindola, B. A. F. Gomes, B. Ventura, D. Smadja, and M. R. Santhiago, "Effects of blue light-filtering intraocular lenses on the macula, contrast sensitivity, and color vision after a long-term follow-up," *Journal of Cataract and Refractive Surgery*, vol. 37, no. 12, pp. 2115–2119, 2011.
- [12] L. Maffei and A. Fiorentini, "The visual cortex as a spatial frequency analyser," *Vision Research*, vol. 13, no. 7, pp. 1255–1267, 1973.
- [13] A. B. Watson and J. G. Robson, "Discrimination at threshold: labelled detectors in human vision," *Vision Research*, vol. 21, no. 7, pp. 1115–1122, 1981.
- [14] L. E. Leguire, B. S. Zaff, S. Freeman, G. L. Rogers, D. L. Bremer, and N. Wali, "Contrast sensitivity of optokinetic nystagmus," *Vision Research*, vol. 31, no. 1, pp. 89–97, 1991.
- [15] J. R. Drover, L. M. Wyatt, D. R. Stager, and E. E. Birch, "The teller acuity cards are effective in detecting amblyopia," *Optometry and Vision Science*, vol. 86, no. 6, pp. 755–759, 2009.
- [16] B. van Alphen, B. H. J. Winkelman, and M. A. Frens, "Age- and sex-related differences in contrast sensitivity in C57Bl/6 mice," *Investigative Ophthalmology and Visual Science*, vol. 50, no. 5, pp. 2451–2458, 2009.
- [17] J. N. Van der Geest and M. A. Frens, "Recording eye movements with video-oculography and scleral search coils: a direct comparison of two methods," *Journal of Neuroscience Methods*, vol. 114, no. 2, pp. 185–195, 2002.
- [18] R. L. Skeel, A. Nagra, W. Vanvoorst, and E. Olson, "The relationship between performance-based visual acuity screening, self-reported visual acuity, and neuropsychological performance," *Clinical Neuropsychologist*, vol. 17, no. 2, pp. 129–136, 2003.
- [19] H. Cahill and J. Nathans, "The optokinetic reflex as a tool for quantitative analyses of nervous system function in mice: application to genetic and drug-induced variation," *PLoS ONE*, vol. 3, no. 4, Article ID e2055, 2008.
- [20] D. R. Williams, "Aliasing in human foveal vision," *Vision Research*, vol. 25, no. 2, pp. 195–205, 1985.
- [21] H. A. Greene and D. J. Madden, "Adult age differences in visual acuity, stereopsis, and contrast sensitivity," *American Journal of Optometry and Physiological Optics*, vol. 64, no. 10, pp. 749–753, 1987.
- [22] R. Sekuler, L. P. Hutman, and C. J. Owsley, "Human aging and spatial vision," *Science*, vol. 209, no. 4462, pp. 1255–1256, 1980.
- [23] K. Turano, G. S. Rubin, S. J. Herdman, E. Chee, and L. P. Fried, "Visual stabilization of posture in the elderly: fallers vs. nonfallers," *Optometry and Vision Science*, vol. 71, no. 12, pp. 761–769, 1994.

Research Article

The Influence of Attention and Target Identification on Saccadic Eye Movements Depends on Prior Target Location

David R. Hardwick, Timothy R. H. Cutmore, and Trevor J. Hine

Behavioural Basis of Health, Griffith Health Institute, and School of Applied Psychology, Griffith University, Mt Gravatt, QLD 4122, Australia

Correspondence should be addressed to Trevor J. Hine; t.hine@griffith.edu.au

Received 11 October 2013; Revised 17 December 2013; Accepted 6 January 2014; Published 27 February 2014

Academic Editor: Arvid Herwig

Copyright © 2014 David R. Hardwick et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Saccadic latency is reduced by a temporal gap between fixation point and target, by identification of a target feature, and by movement in a new direction (inhibition of saccadic return, ISR). A simple additive model was compared with a shared resources model that predicts a three-way interaction. Twenty naïve participants made horizontal saccades to targets left and right of fixation in a randomised block design. There was a significant three-way interaction among the factors on saccade latency. This was revealed in a two-way interaction between feature identification and the gap versus no gap factor which was only apparent when the saccade was in the same direction as the previous saccade. No interaction was apparent when the saccade was in the opposite direction. This result supports an attentional inhibitory effect that is present during ISR to a previous location which is only partly released by the facilitative effect of feature identification and gap. Together, anticipatory error data and saccade latency interactions suggest a source of ISR at a higher level of attention, possibly localised in the dorsolateral prefrontal cortex and involving tonic activation.

1. Introduction

Saccadic latencies are not simply explained by physiological processes like neural conduction: both task instructions and attention also play important roles [1]. The present study focused on three such factors (among several known to have influence) that have each been shown to reduce saccadic latency: a saccade to a new location that has a shorter latency relative to a saccade that immediately returns to a previously fixated location (known as inhibition of saccadic return, “ISR” [2]), the “gap effect” which is the disappearance of the fixation point before target appearance [3–5], and the need to identify high-resolution detail at the saccadic endpoint [6, 7].

ISR is a specific form of the more general construct of inhibition of return (IOR) which can be applied to many behavioural responses. For example, key-press responses to targets in new locations produce shorter RTs than targets in the same location [8–10]. The ISR effect is thought to contribute to efficiency of visual search [11, 12], such that the observer does not make an unnecessary immediate

saccade to previously viewed locations [8, 9, 13, 14]. This is reflected in the neurology: Prime and Ward [15] found reduced amplitude of occipital event related potentials (ERPs) for targets at cued locations when compared to targets at uncued new locations and Van der Lubbe et al. [10] concluded that their ERP, electrooculography (EOG), and button-press RT data excluded a bottom-up premotor response theory of ISR. On the other hand, Hunt and Kingstone [8] proposed that there are both top-down (goal-directed and attention mechanisms) and bottom-up (stimulus-driven) influences on ISR. It should be noted that the shorter latencies due to ISR are not always reported in experimental paradigms. When participants are required to make a series of saccades either towards a target (“prosaccades”) or in the opposite direction to a target (“antisaccades”), saccades were executed more quickly when the saccade in the penultimate trial was in the same direction [16]. This was attributed to low-level phenomenon of “directional plasticity,” where on a given trial it is easier for activity in the superior collicular neurons to

reach a threshold to trigger a saccade in the same direction as the prior saccade.

To saccade to a new location, visual attention needs to be released from the previous location and this requires some time [5, 17]. The operation of this process has been revealed in the “gap effect” paradigm. The gap refers to a delay (between 100 and 300 ms) that is introduced between the fixation point offset and the onset of a new target [4]. Gap trials have been shown to markedly reduce saccadic latency and in some studies, a second peak at 120 ms has been noted in the latency distributions in addition to the usual 200 ms peak [17, 18].

Reuter-Lorenz et al. [19] considered the gap effect to be partly due to the cueing component of fixation-offset. They showed that a warning tone by itself prior to fixation-offset in the gap condition, or during fixation in the no gap (temporal “overlap” condition), produced significant reduction in saccade latency. Following this, Pratt et al. [20] cued visual attention to various parts of a fixation cross. When participants were attending to part of the fixation cross that disappeared at the beginning of a gap, they showed significantly reduced latency compared to when they were attending to another part of the cross that did not disappear. Both Hutton [21] and Jin and Reeves [5] concluded that these results support an attentional component in the gap effect. However, there is some dispute as to the neural circuitry underlying this component [22, 23]. Attentional control could be exerted from a number of higher cortical centres to the fixation neurons in the superior colliculus (SC) that generate the saccade. This neural control centre could include the dorsolateral prefrontal cortex (DLPFC) which is involved in saccadic suppression, the frontal eye fields (FEF), and/or the lateral-intraparietal area of the posterior parietal cortex (LIP, [22, 23]).

Trottier and Pratt [7] found that saccadic latency is reduced during discrimination of high-resolution detail at the target location (*identification*), without the gap delay described above. Terminological note: Trottier and Pratt [7] used *look-obtain* (feature of target) versus *look* (without obtaining feature), while others [24, 25] used *identification* versus *glance*. We used *identification* versus *no identification*. Specifically, when naive participants were asked to identify the pixel offset at the centre of a target during fixation overlap trials, saccade latencies were in the very fast range ($M = 135$ ms) and were significantly shorter than no identification fixation overlap trials ($M = 185$ ms). They stated that these very fast latencies could be the norm in naturalistic settings where identification of a new target is the purpose of a saccade and that saccade latencies over 150 ms were in fact abnormally slowed by simplistic laboratory paradigms. Trottier and Pratt [7] proposed that there is increased facilitation producing shorter saccade latency via top-down input to SC from the frontal cortex (including the PFC) during the identification task.

During behavioural studies in which participants were instructed to make pro- and antisaccades (a saccade to an opposite location where the targets appear), Guyader and colleagues [24, 25] replicated Trottier and Pratt’s [7] results in showing that removal of gaze fixation object prior to target presentation (the gap paradigm) produced extremely small

saccadic latencies when there was a requirement for target identification. However, the effect of identification that was observed during prosaccades (i.e., prosaccade latency was reduced during identification task) was not observed during antisaccades [24]. Guyader and colleagues [24, 25] explained these results as being due to the fact that antisaccades require extra executive processes compared to prosaccades: first, an inhibition of a reflexive saccade to a suddenly appearing target by a signal originating in the prefrontal cortex (PFC), and second, a voluntary saccade to look at the mirror position. They proposed that the identification effect occurs at a high executive level in the saccadic neural pathway but is a different signal from that used in antisaccades. The present study extends the results of these two studies by examining how these attentional factors—gap and identification—interact with contextual ISR, a factor that involves high-level cognitive processes that are sensitive to expectations accumulated over a period of time [2]. In summary, evidence supports the hypothesis that each of the three factors—identification, gap, and ISR—may exert their influence in reducing saccadic eye movement latency through neural activity involving the PFC. However, if these mechanisms converge in a common functional pathway their effects may not be simply additive. In fact, Guyader et al. [24] claimed that they may “cancel” each other. There are studies that have combined two of these three attentional effects, with a reduction in saccade latency greater than in each effect alone [7, 8, 14]. Trottier and Pratt [7] used both a feature identification task and the gap effect and found a significant interaction, such that the reduction in saccadic latency due to correct identification was greater for overlap trials than for gap trials, a result replicated by Guyader et al. [24]. A possible basis for this could be that the gap effect and target identification facilitate saccadic latency via a shared neural pathway from the PFC that disinhibits SC. On the other hand, the identification effect was not present in antisaccades and Guyader et al. [24] surmised that the additional executive processes required for the antisaccades “cancelled out” the effect completely.

It follows that if ISR is the result of an attentional top-down mechanism similar to that required in antisaccades, then it would be expected that Trottier and Pratt’s [7] feature identification task, which decreases saccade latency in fixation overlap conditions, might also interact with ISR (cf. results of Terry et al. [26] in motor tasks). For example, on a trial in which the gaze “returns” to the previous location and also requires target identification, ISR may cancel the facilitating effect of the identification process. However, if there is an oculomotor bottom-up component to ISR, then top-down attentional decision tasks may not be affected by this “hard-wired” effect. Therefore, when considered together, the top-down pathway proposed by Van der Lubbe et al. [10] for ISR could have a mediating influence over the top-down pathway proposed for target identification [7, 24, 25] and over the gap effect, producing a three-way interaction. Thus, the strength of the interaction between identification and gap found by Trottier and Pratt [7] would depend on ISR influence. In effect, ISR is implicit in any saccade latency study that randomly presents targets to a few locations that are on either side of a central fixation: about half the trials

will be ipsilateral to the previous saccade and half will be contralateral. Trottier and Pratt's [7] results are an average of these trials: the present study makes this laterality an independent variable to determine the ISR effect.

If they are wholly independent, then combining all the factors would result in simple additive main effects with the possibility of at least one of these (e.g., the gap effect) being due to bottom-up control mechanisms. Less than additive effects, that is, some type of two- or three-way interaction, would support the notion that a shared resource is being used and this could help to circumscribe how these attentional factors might be linked to the underlying neural mechanisms. While it is clear that behavioural data alone are insufficient to identify a brain source associated with a limited shared resource, such data may be used to suggest possible places to examine with electrophysiological recording methods. Certainly, Malsert et al. [25] theory allows for sharing of such top-down control resources, but only for what they describe as "tonic" PFC activation—a slow change in neural response due to identification as opposed to "phasic" PFC activation which only lasts for fractions of a second at the onset of a task.

Finally, anticipatory errors occur when participants move their eyes prior to appearance of the target (either during fixation or during the gap) or move their eyes after appearance of the target but before they could possibly have processed the target. Such errors have been assumed to be an important indicator of disinhibition of top-down control of SC circuits [27]. For example, Trottier and Pratt [7] reported a greater anticipatory error rate during identification and gap trials compared to other trials and assumed this disinhibition increased during target feature identification resulting in a faster subsequent saccade. Attentional disengagement is also facilitated by both the gap effect and by there being an opposite location (contralateral) to the previous target [8, 14, 28], that is, in the presence of an ISR effect. This disengagement toward new locations is partly mediated through the SC, permitting it to more freely initiate an eye movement, even in the absence of a target as occurs in antisaccades [24] and particularly if the frontal eye field (FEF) is contributing to anticipatory errors [29].

Bearing this in mind, one contribution of the present study is that it predicts that conditions facilitating this disengagement (e.g., during identification versus no identification) will result in more anticipatory saccadic errors, but particularly when the previous target appeared in a contralateral location to the current target, the conditions of ISR. Further, depending on whether the previous target is contralateral or ipsilateral to the current target, significant differences are also predicted for the type of anticipatory saccades. For contralateral prior location during identification trials, anticipations towards the target (protarget anticipations) would be greater than anticipations away from the target (antitarget anticipations). Furthermore, for ipsilateral prior location, during identification trials, antitarget anticipations would be greater than protarget anticipations. However, we propose that when PFC disinhibition of saccades does not identify a target feature (during no identification trials), protarget and direction anticipation rates will be approximately equal for contralateral and ipsilateral target prior location.

2. Materials and Method

2.1. Participants. Twenty naïve first-year psychology students with normal vision, 11 females and 9 males (age $M = 22$ years, $SD = 6$, and range = 17 to 35 years), participated in the study in exchange for course credit. Six other participants did not complete the trials.

2.2. Design. The main experiment was a five-way "gap" \times "identification" \times "target prior location" \times "direction" \times "eccentricity" repeated measures factorial design. There were two levels each of temporal "gap" (200 ms gap/no gap), "identification" (identification/no identification), "target prior location" (ipsilateral/contralateral), and "direction" (left/right) and three levels of "eccentricity" (4° , 6° , or 8°), giving 48 within-subject data cells. Saccadic latency, the percent of anticipatory saccades, and key-press reaction time (RT) from target onset were all measured, as was accuracy in the pixel offset discrimination task (Figure 1). Both gap levels and identification levels were blocked.

2.3. Apparatus. Each eye was sampled at 1000 Hz with an IRIS infrared eye tracker [30, 31] with spatial accuracy $<0.25^\circ$. Head position was stabilised at 57 cm viewing distance with a custom-built chin and cheek rest. Stimuli were displayed on a 21-inch CRT monitor running at 85 Hz horizontal refresh and 1600×1200 pixel resolution and were aligned horizontally half-way down the screen. Stimulus luminance was approximately 17.5 cd/m^2 . The display background luminance was adjusted upward until the phosphor decay was not visibly noticeable (a little less than 0.20 cd/m^2). The start of the raster at the top left of the screen was synchronised with the eye trace record and corrected offline for scanning delay (5 ms). A PC running Neurobehavioural Systems Presentation program was used to display and collect data.

The infrared eye tracker centre position was adjusted for each participant prior to stimulus calibration. There were nine calibration trials at the beginning of each trial block, followed by six practice trials. Calibration targets with pseudorandom positions had the dimensions depicted in Figure 1(b) and were shown across 9 locations ranging from -10° to $+10^\circ$, in 2.5° intervals. Each calibration target remained on for 2000 ms, with a 1000 ms interval between each target. Due to the controlled head movement and shortness of the trial blocks, no further calibrations were necessary.

2.4. Stimulus Parameters. Identification was operationalised as discrimination of target centre pixel lateral displacement similar to Trottier and Pratt ([7]; Figure 1). The central fixation crosshair was $0.8^\circ \times 0.8^\circ$ and 0.05° line width.

The sequence of saccades for *contralateral prior location* and *ipsilateral prior location* (Figure 2) was operationalised in a similar manner to Carpenter [14]. Each second target in a sequence pair became a first target for the next sequence pair, so in a block of 120 trials there were 119 possible pairs.

In general, increased randomisation results in reduced predictability, thus producing higher probability of very fast

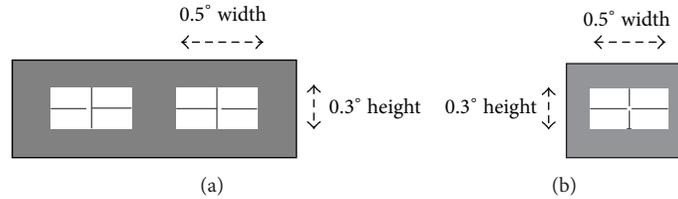


FIGURE 1: Saccadic stimuli for identification of fine features (after [7]). For a *feature identification* task, one of two stimuli (a) was presented with a single pixel offset either left or right, either target being presented randomly left or right of central fixation. In a *no identification* task, stimulus on the right (b) with a central pixel was presented in the same manner.

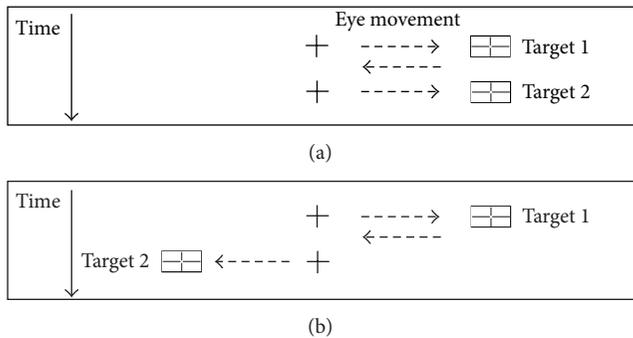


FIGURE 2: Operationalisation of target prior location for inhibition of saccadic return. Centre cross is fixation. Dashed arrows represent eye movements, with time down the page. (a) is ipsilateral prior location and (b) is contralateral prior location.

exogenous reflexive saccades [32]. Therefore, consistent with [8, 33], in order to increase uncertainty and ensure fast exogenous saccade production, targets were both temporally and spatially randomised. Accordingly, right and left direction from fixation, target eccentricity, duration of intertrial interval, and duration of fixation cross were all continuously randomised. Multiple locations were presented along the horizontal plane in randomised order: $\pm 4^\circ$, $\pm 6^\circ$, and $\pm 8^\circ$ eccentricities.

2.5. Procedure. There were four Latin square counterbalanced trial blocks, each with 120 trials: no identification, no identification-gap, identification, and identification-gap. If the no identification and identification trials had been interleaved this would have introduced a third choice (press left, press space bar, or press right), without any control task. Separating them into blocks largely reduced this effect, although there was probably a short-lasting carryover effect of identification when the counterbalanced order called for the identification block to occur first. The only way to control this carryover, apart from counterbalancing, would be to conduct a much larger between-subject study. These were conducted in one session in the laboratory. The ISR factor was derived post hoc. For identification trials (Figure 1(a)), participants were instructed to “immediately look at the centre of the peripheral target and identify the direction in which the central pixel is offset” and then “press the appropriate arrow key, left arrow for left offset and right arrow

for right offset.” For no identification trials (Figure 1(b)), participants were instructed to “immediately look at the centre of the peripheral target” and then “immediately press the space bar.”

Response instructions were displayed on the screen prior to the calibration, prior to the practice trials, and prior to the main trials for each block of trials. Each participant was instructed to keep their head as still as possible on the chinrest during testing. Participants were instructed that accuracy and speed were equally important across all conditions for both eye movement and key-press response.

Each trial started with a white crosshair at central fixation. Both fixation duration and intertrial interval continuously randomly varied between 500 and 1000 ms. A new intertrial interval, which also determined the beginning of the interstimulus interval, began once a response key was pressed. These values were greater by 200 ms in gap trials due to the delay in stimulus onset. If a key-press response was not made within 1500 ms of target presentation the trial timed out and the message “Press key to continue” appeared. Note that the interstimulus interval for presentation of the target also defined the intersaccade interval for ISR and was well within the range for the ISR effect to occur, which has been estimated to be between 500 and 3500 ms [9].

Anticipatory saccades were identified offline. An accepted method of finding within-subject criteria for anticipations is to determine the particular saccade latency at which direction errors cease to occur for each participant [7, 32]. Hence, saccades made opposite to target direction were counted as anticipations, as were saccades that were made toward the target within the same unacceptably short latency range. Terminal position inaccuracy and double saccades are also indicative of anticipatory saccades. For example, when an initial saccade terminal position was far from the target (defined here as horizontally greater than 1.5°), it was usually followed by a corrective saccade within 50 to 60 ms; the initial saccade was therefore coded as anticipatory. Moreover, trials on which anticipatory key-presses occurred were excluded automatically during testing, as each trial was terminated by a key-press.

3. Results

Because it was prerequisite that participants have normal vision, the eye trace data for each eye was compared for each participant to ensure that there were no anomalies. After

choosing the eye with the cleanest signal the vertical-axis voltage signal was calibrated to obtain approximate position in degrees. This normally resulted in the right eye trace being analysed. Saccadic latency onset after target presentation was automatically determined using a Matlab © routine as that time at which eye velocity was approximately $20^\circ/s$. These values were scanned for anomalies, and in very rare cases saccade onset was manually coded or the trial coded as an error. Data were obtained for all legitimate trials: saccadic latency, anticipations, landing position inaccuracy, and blinks. Anticipations and other exclusions were further analysed. Exclusion of saccadic latencies as slow outliers was based on being beyond 3.29 z-scores above the mean. Only 0.5% (51/9600) saccadic latencies met the slow outlier criterion. Although the saccadic latency threshold for anticipations varied among participants and among conditions, it was found to occur between 65 and 85 ms. Anticipatory key-press prior to target presentation (0.2%) and blinks (1.7%) appeared to be randomly distributed across conditions.

3.1. Saccadic Latency. A five-way repeated measures factorial ANOVA for the main experimental design was conducted with gap (2) \times identification (2) \times prior location (2) \times direction from fixation (2) \times target eccentricity (3), on saccadic latency. Main effects for the following conditions were significant: 200 ms gap < no gap, $F(1, 19) = 87.46$, $MSE = 843.71$, $P < .001$; identification < no identification, $F(1, 19) = 24.92$, $MSE = 740.48$, $P < .001$, contralateral < ipsilateral $F(1, 19) = 26.83$, $MSE = 275.05$, $P < .001$, and target eccentricity, linear effect $F(1.5, 28.39) = 23.34$, $MSE = 186.03$, $P < .001$ (Greenhouse-Geisser corrected), and target eccentricity quadratic $F(1, 19) = 7.73$, $P = .012$, $MSE = 64.24$. The two-way interaction of gap \times identification was significant, $F(1, 19) = 10.31$, $MSE = 220.47$, $P = .005$ and was similar to previous results ([7], their Figure 2; [24] their Figure 3) and is shown in our Figure 3. These two factors were also involved in a significant three-way interaction of gap \times identification \times prior location, $F(1, 19) = 5.13$, $MSE = 58.32$, $P = .035$, which is shown in Figure 4.

This three-way interaction of gap \times identification \times prior location was further analysed by a two-way repeated measures ANOVA for gap \times identification for each of the two ISR levels. There was a significant two-way interaction of gap \times identification for ipsilateral targets, $F(1, 19) = 15.98$, $MSE = 132.03$, $P = .001$, but not for contralateral targets, $F(1, 19) = 3.33$, $MSE = 63.44$, $P = .084$. The left (ipsilateral) panel of Figure 4 shows this two-way interaction. Bonferroni corrected paired comparisons, for the pairs of conditions connected by a line in the graph, showed that identification was significantly faster than no identification for all but the ipsilateral 200 ms gap condition (mean difference = 5.2, $SEM = 2.7$ ms, $P = .067$).

The two-way interaction of identification \times direction from fixation was significant, $F(1, 19) = 5.68$, $P = .028$, $MSE = 88.43$ (Figure 5). Right direction from fixation was significantly greater than left under identification (mean difference = 4.5 ms, $P = .016$), but not under no identification. The three-way interaction of gap \times prior

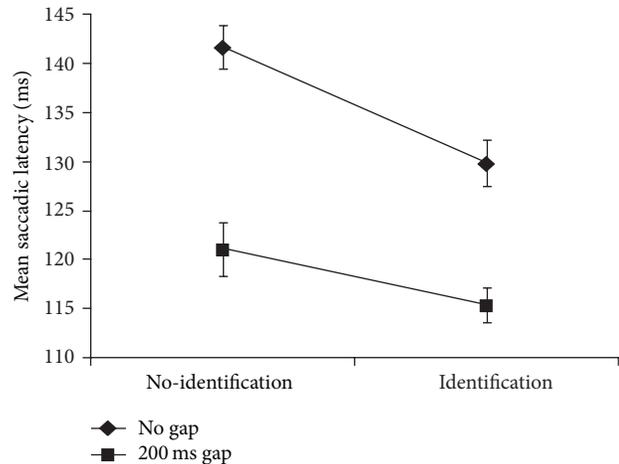


FIGURE 3: Significant two-way interaction of gap \times identification of target feature for saccadic latency. Error bars = ± 1 SEM.

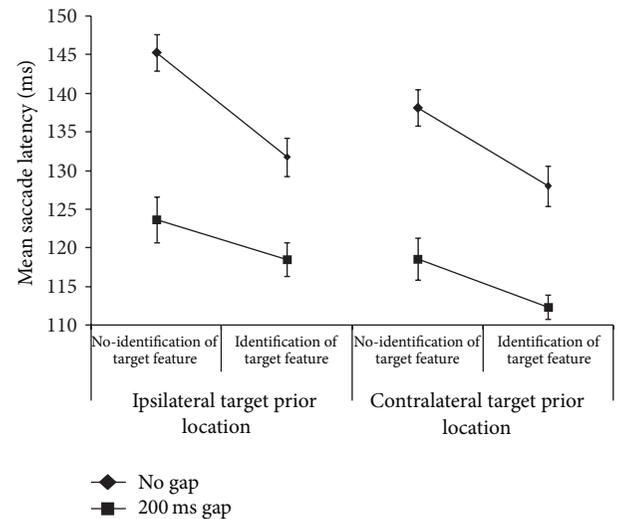


FIGURE 4: Mean saccadic latencies for $n = 20$ collapsed across eccentricities. Main effects and interactions are described in the text: note the three-way interaction for gap \times identification \times target prior location. Error bars = ± 1 SEM.

location \times direction from fixation was significant, $F(1, 19) = 5.01$, $P = .037$, $MSE = 34.97$ (Figure 6). When testing the simple effects of direction from fixation, the only significant post hoc paired comparison was for 200 ms gap under ipsilateral prior location, with left being significantly quicker than right (mean diff. = 4.3 ms, $P = .049$). This comparison is represented by the lower line in the left panel of Figure 6. The other three pairs were not significant.

3.2. Anticipation. Anticipatory saccades had low frequencies in no gap condition levels, with no anticipations for some participants, and therefore the comparison of no gap with 200 ms gap was initially explored with Wilcoxon-signed-ranks test. This test found that there was a significantly greater probability of anticipatory saccades for gap trials compared to

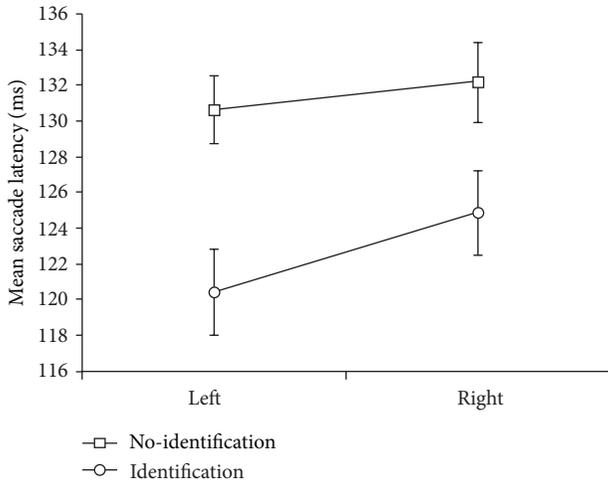


FIGURE 5: Mean saccadic latencies for the two-way interaction of identification × direction from fixation. Error bars = ±1 SEM.

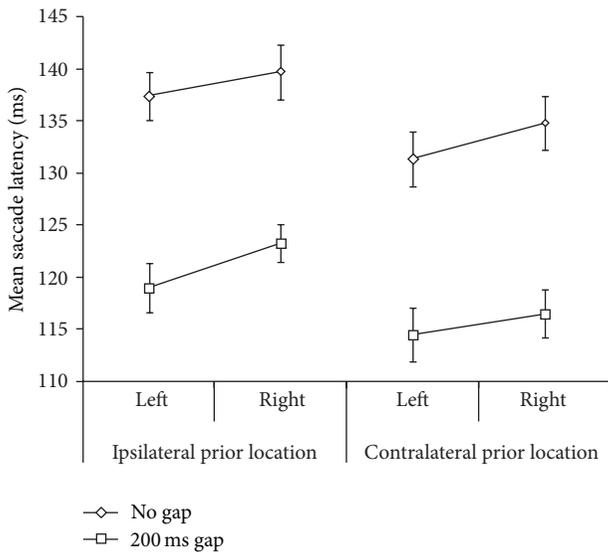


FIGURE 6: Mean saccadic latencies for the three-way interaction of gap × prior location × direction from fixation. Error bars = ±1 SEM.

no gap trials, $z = 3.92, P < .001$ (two-tailed). No gap trials median was 3.6% (min. = 0.18%, max. = 7.5%) and 200 ms gap trials median was 8.0% (min. = 2.6%, max. = 17.0%) anticipatory errors.

A repeated measures ANOVA was performed on percent of anticipatory saccades collapsed across gap levels. There was a significant two-way interaction of target prior location × anticipatory type (protarget versus antitarget anticipations), $F(1, 19) = 9.79, MSE = 53.45, P = .006$. Examination of Figure 7 reveals a crossover interaction between target prior location and anticipatory type. Hence, protarget anticipations were more likely when the previous target was in the contralateral location to the current target, whereas antitarget anticipations were significantly more likely when the previous target was in the ipsilateral location.

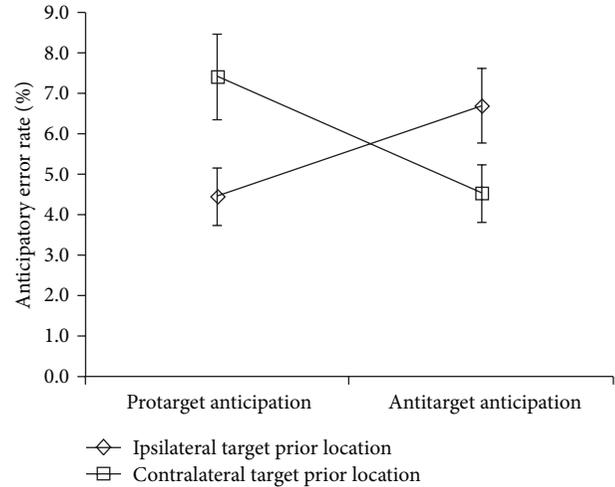


FIGURE 7: Mean percent of anticipatory eye movements under ISR conditions. Anticipatory eye movement two-way interaction for target prior location × anticipatory type. Note: Prototarget = anticipation in same direction as target. Antitarget = anticipation in opposite direction from target. Ipsilateral = same direction target prior location. Contralateral = opposite direction target prior location. Error bars = ±1 SEM.

There was a significant three-way interaction of identification × target prior location × anticipatory type, $F(1, 19) = 5.48, MSE = 52.59, P = .030$. Figure 8 shows mean percent anticipation rates. Two-way repeated measures ANOVA across identification levels showed a significant interaction for target prior location × anticipation-type under identification, $F(1, 19) = 7.40, MSE = 102.19, P = .014$, but not under no identification. Examination of Figure 8 reveals a crossover interaction between target prior location and anticipatory type for identification (right panel) which is not present in the no identification condition. Hence, under the identification condition, protarget anticipations were more likely when the previous target was in the contralateral location to the current target, whereas antitarget anticipations were significantly more likely when the previous target was in the ipsilateral location.

3.3. Feature-Discrimination Accuracy during Identification. Incorrect key-press for feature discrimination between left and right centre pixel offset comprised 2.8% of trials (93/3200), with relatively even distribution across gap and target prior location condition levels.

3.4. Key-Press RT. Repeated measures factorial ANOVA was conducted on the key-press RT data using the same factors as the saccadic latency data. Unsurprisingly, key-press RT for identification requiring discrimination was significantly longer than for no identification trials, $F(1, 19) = 216.82, MSE = 78556.55, P < .001$ (mean difference = 266 ms). Key-press RT for target eccentricity was significant, $F(1.48, 28.15) = 52.32, MSE = 4261.70, P < .001$ (Greenhouse-Geisser corrected); target eccentricity quadratic was also significant,

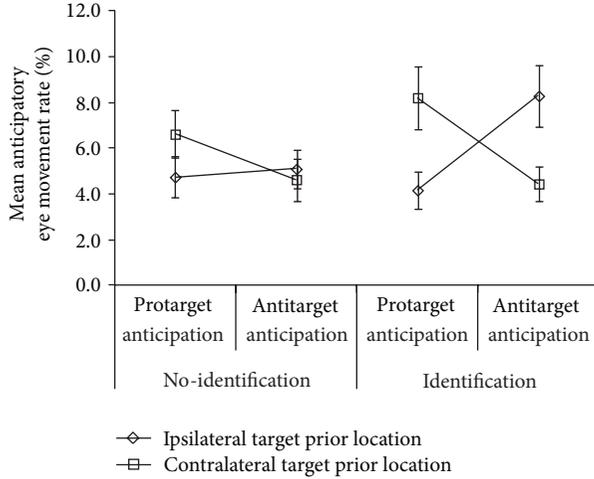


FIGURE 8: Mean frequency of anticipatory eye movements under ISR conditions. Anticipatory eye movement three-way interaction for identification \times target prior location \times anticipatory type for 200 ms gap trials. Error bars = ± 1 SEM.

$F(1, 19) = 4.76$, $MSE = 1314.08$, $P = .042$. However, key-press RT for target eccentricity was involved in a significant two-way interaction with identification, $F(1, 19) = 5.94$, $MSE = 1995.93$, $P = .025$ and quadratic $F(1, 19) = 4.50$, $MSE = 884.86$, $P = .047$. Table 1 shows mean key-press RT for this interaction. There was a significant curvilinear effect of eccentricity under identification, but not under no identification for key-press RT, as shown in the difference scores (Table 2).

There was a significant two-way interaction of identification \times target prior location, $F(1, 19) = 5.63$, $MSE = 2063.55$, $P = .028$. This was due to key-press RT for no identification being longer for ipsilateral prior location ($M = 566$ ms, $SEM = 25$) than contralateral ($M = 559$ ms, $SEM = 24$), whereas key-press RT for identification was shorter for ipsilateral prior location ($M = 825$ ms, $SEM = 17$) than contralateral ($M = 833$ ms, $SEM = 18$). That is, the saccadic-IOR (ISR) effect for contralateral locations reducing latencies was *reversed* for manual RT only under the identification discrimination task.

There was a significant two-way interaction of identification \times direction from fixation, $F(1, 19) = 5.72$, $MSE = 1900.18$, $P = .027$ (see Table 2). Key-press RT to the right of fixation was quicker under no identification, while key-press RT to the left was quicker under identification.

4. Discussion

The primary purpose of this study was to measure the interaction of three factors associated with saccadic latency: a temporal gap between the fixation and the target, identification of target feature, and ISR. It was hypothesized that an inhibitory influence by the PFC due to ISR could account for the less than additive effects [7] of gap and identification factors. Overall, results support this hypothesis as revealed in nonadditivity of the individual factors when ISR was present but not when it was absent (i.e., a three-way interaction was

TABLE 1: Mean key-press RT (KPRT) in milliseconds (ms) for the two-way interaction of target-feature-identification \times eccentricity with standard errors (SEM). Columns to right show Bonferroni corrected mean differences for paired comparisons of 4° to 6° and 6° to 8° .

	Eccentricity	KPRT (ms)	SEM	Mean diff.	SEM
No-identification	Four	544	23		
	Six	563	25	19*	4
	Eight	580	25	17*	4
Identification	Four	799	18		
	Six	835	18	37*	5
	Eight	852	17	17*	5

* Paired comparison significant at Bonferroni corrected $P < .05$.

TABLE 2: Key-press RT in milliseconds (ms) for the two-way interaction of target-feature-identification \times direction from fixation.

	Direction	KPRT (ms)	SEM	Mean diff.
No-identification	Left	564	24	
	Right	560	25	+4.1
Identification	Left	824	18	
	Right	834	17	-9.4

observed, Figure 4). Thus, while the individual factors can produce additive shortening of saccade latency, ipsilateral trials must be considered as having a moderating inhibitory (i.e., ISR) effect on the shortening of 200 ms-gap-identification trials. A simple explanation in terms of a floor effect in latencies of the saccadic oculomotor system is unlikely since the contralateral 200 ms-gap-identification saccadic latency is significantly quicker (a very short mean of approximately 112 msec) than the ipsilateral comparison ISR condition (see Figure 4).

4.1. Saccadic Latency Interactions. It can be noted that the two-way interaction of gap \times identification replicates the results of both Trottier and Pratt [7] and Guyader et al. [24]. In the present experiment, we separated the trials on this additional ISR factor and demonstrated that the two-way interaction only manifests itself when ISR is present, producing a three-way interaction—compare the left (ISR present) and right (no ISR) sections of Figure 4. Trottier and Pratt [7] implicate a top-down mechanism (identification) as responsible for reduced saccadic latency when a target feature is to be identified; however they do not pursue explanation of the two-way interaction. There appears to be a unique effect occurring in the ipsilateral 200 ms-gap-identification condition such that the facilitating top-down effect of instruction-type to identify a target feature is reduced. This functional effect could be due to reduced efficacy in PFC saccadic disinhibition of SC, a mechanism proposed by Trottier and Pratt [7] to account for shorter saccadic latency when the task requires fine target detail identification. With the visual attention disengaged due to the 200 ms gap, when a target appears in a previously fixated location this disinhibition fails

to exert the degree of influence it does if the target appears in the ipsilateral location.

A common mechanism for gap and ISR in the frontal cortex, possibly the FEF, could be the basis of this interaction. In fact, an FEF stimulation study conducted with monkeys by Opris et al. [34] concluded that the gap effect may lower the FEF threshold required for initiating a saccade. On the other hand, the locus of the interaction may well be in “tonic” activation of the PFC [25]. According to these authors, tonic activation is required to maintain identification in working memory when saccadic tasks are blocked into instruction types as they are in the current study (2 (identification) \times 2 (gap) = four blocks). Only phasic activation is required when there is no such memory requirement and the saccadic task is cued within each trial in a completely mixed trial paradigm. Only tonic activation admits of resource sharing and interaction. Following this line of argument, in the Malsert et al. [25] study, the interaction between antisaccade/prosaccade and identification did not occur in their mixed trial paradigm, whereas in our blocked trial paradigm the interaction between ISR, gap, and identification did occur. Therefore, one possible explanation of the three-way interaction is as follows: when a gap-trial and identification instruction require the participant to identify a target feature, a phasic PFC mechanism common to the gap effect and ISR is activated. The inhibitory ISR influence dominates at this locus negating the facilitating influence in general agreement with [10]’s top-down pathway.

4.2. Anticipatory Saccadic Errors. Gap trials produced significantly more anticipatory saccades than the no gap trials. This finding supports the theory that there is a greater state of SC disinhibition in preparation for a saccade during the gap, as found in direct neuronal recording from monkey SC during gap tasks [35, 36]. According to Fischer and Weber [17], freeing fixated attention during the gap releases voluntary control of bottom-up processes and allows initiation of search for a target, which can produce a higher rate of anticipatory saccades.

There was also a greater probability of anticipations during the identification trials as predicted. However, this was subsumed in a three-way interaction of anticipatory type (protarget versus antitarget anticipation), target prior location, and identification. Anticipatory errors were significantly more probable in the direction that the oculomotor system favours, that is, away from the previous target being the expected response (the crossover interaction, right side of Figure 8) that only occurs during the identification condition. The two-way interaction under identification is occurring before the targets can be adequately processed because anticipatory errors by definition occur at a very early stage. This anticipatory saccade three-way interaction may have its basis in an interaction of top-down and bottom-up processes. One possible explanation is that the top-down endogenous effect of target identification during overt discriminatory planning disinhibits reflexive motor mapping and spatial planning, and in this case the effect appeared to allow these areas to trigger anticipatory saccades to *expected* locations

in the absence of top-down inhibition from DLPFC and FEF. The anticipatory effect found here is consistent with the oculomotor corollary of Pierrot-Deseilligny et al. [29] finding of increased anticipatory saccades in patients with recently damaged DLPFC. However, this needs to be verified by direct neurophysiological investigation, for example, in monkeys.

Together, the saccadic latency and anticipatory saccade results appear to support a theory of ISR that may be low-level reflexive but certainly involves an expectancy effect that manifests as a shared top-down disinhibitory control during identification. This could allow FEF/supplementary eye fields spatial planning areas to have an anticipatory IOR effect [37]. Further, top-down disinhibition from DLPFC could allow SC saccadic mapping [38] or FEF spatial planning neurons to inadvertently anticipate a target, thus causing an involuntary anticipatory error (e.g., [10, 29]).

The accuracy rate for identification was higher than that found by Trottier and Pratt [7]. They found accuracy of 80% to 90%, whereas in this study pixel offset discrimination accuracy was 97%. The randomisation of multiple aspects of the experimental design most likely contributed to this improvement in accuracy. That is, making the task more unpredictable encouraged participants to respond more carefully (due to increased uncertainty). Furthermore, if being able to predict what was going to happen next had been a factor in causing anticipations, then this would have showed an increased anticipation rate across all types of trials. This was not the case; trials without 200 ms gap and without identification of target feature had very low to zero anticipation rates for some participants.

Moreover, changing temporal and spatial certainty of the upcoming target might change some of the other exogenous effects observed in this study. In particular, anticipatory saccades would likely decline and the three-way interaction for anticipatory error type \times prior location \times identification could change under more predictable conditions. For example, overlap condition levels were not included in this study. Hunt and Kingstone [8] found an increased ISR effect during fixation overlap tasks compared to no gap tasks. Further, Weber et al. [32] found an increased probability of very fast saccades during randomisation of fixation fore-period (i.e., intertrial interval) for fixation overlap trials. Taken together, these findings suggest that the inclusion of fixation overlap could magnify the interaction effect with gap, identification, and ISR. Also note that while Weber et al. [32] found decreased express saccades when the fixation duration was randomly varied, they used durations of one, two, or three seconds; we used a random variation between 500 and 1000 ms. Hence, our manipulation may not have had the same effect as that of Weber et al. [32].

The anticipatory error data appeared to be particularly sensitive to changes in top-down inhibitory control [27]. It has previously been hypothesised that executive frontal inhibitory deficits are associated with eye movement dysfunction in people diagnosed with schizophrenia, and increased anticipatory saccade rates in the antisaccade task have been used to measure eye movement dysfunction [39, 40]. Our task is far easier to participate in compared to the antisaccade task, which is an important factor for people who

are psychologically distressed. Further exploration of our anticipatory error data interaction could see the development of a new tool to compare schizophrenia participants with controls especially as it relates to different levels of tonic PFC activation, and this would add to work already published on pro- and antisaccade latencies [16]. Finally, higher-order interactions between response systems may also occur. The present experiment may be considered to be a dual task in the sense that both saccadic and manual responses are being executed. While it was beyond the scope of this study to investigate possible higher-order “cross-talk,” Huestegge and Koch [41] have shown that such cross-talk may occur under certain conditions. In essence, our data for the three-way interaction of gap \times identification \times target prior location incorporates cross-talk, but from a different perspective, because it includes (by default during identification trials) analysis of the participant pressing a right or left arrow key on the keyboard, immediately after looking at the target which can also be to the right or the left of fixation.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

This work was funded in part by the Griffith University Applied Cognitive Neuroscience Research Centre and the School of Applied Psychology. Thanks are due to Mark Ferguson for technical assistance and Neil Davey for programming.

References

- [1] R. H. S. Carpenter and M. L. L. Williams, “Neural computation of log likelihood in control of saccadic eye movements,” *Nature*, vol. 377, no. 6544, pp. 59–62, 1995.
- [2] C. J. H. Ludwig, S. Farrell, L. A. Ellis, and I. D. Gilchrist, “The mechanism underlying inhibition of saccadic return,” *Cognitive Psychology*, vol. 59, no. 2, pp. 180–202, 2009.
- [3] M. G. Saslow, “Effects of components of displacement-step stimuli upon latency for saccadic eye movement,” *Journal of the Optical Society of America*, vol. 57, no. 8, pp. 1024–1029, 1967.
- [4] M. G. Saslow, “Latency for saccadic eye movement,” *Journal of the Optical Society of America*, vol. 57, no. 8, pp. 1030–1033, 1967.
- [5] Z. Jin and A. Reeves, “Attentional release in the saccadic gap effect,” *Vision Research*, vol. 49, no. 16, pp. 2045–2055, 2009.
- [6] A. Montagnini and L. Chelazzi, “The urgency to look: prompt saccades to the benefit of perception,” *Vision Research*, vol. 45, no. 27, pp. 3391–3401, 2005.
- [7] L. Trottier and J. Pratt, “Visual processing of targets can reduce saccadic latencies,” *Vision Research*, vol. 45, no. 11, pp. 1349–1354, 2005.
- [8] A. R. Hunt and A. Kingstone, “Inhibition of return: dissociating attentional and oculomotor components,” *Journal of Experimental Psychology*, vol. 29, no. 5, pp. 1068–1074, 2003.
- [9] R. M. Klein, “Inhibition of return,” *Trends in Cognitive Sciences*, vol. 4, no. 4, pp. 138–147, 2000.
- [10] R. H. J. van der Lubbe, S. F. W. Neggers, R. Verleger, and J. L. Kenemans, “Spatiotemporal overlap between brain activation related to saccade preparation and attentional orienting,” *Brain Research*, vol. 1072, no. 1, pp. 133–152, 2006.
- [11] M. I. Posner and Y. Cohen, “Components of visual orienting,” in *Attention and Performance*, H. Bouma and D. G. Bouwhuis, Eds., vol. 10, pp. 521–556, Erlbaum, Hillsdale, NJ, USA, 1984.
- [12] J. Pratt and J. McAuliffe, “Inhibition of return in visual marking? The importance of the interstimulus interval and the type of search task,” *Visual Cognition*, vol. 9, no. 7, pp. 869–888, 2002.
- [13] R. A. Abrams and R. S. Dobkin, “The gap effect and inhibition of return: interactive effects on eye movement latencies,” *Experimental Brain Research*, vol. 98, no. 3, pp. 483–487, 1994.
- [14] R. H. S. Carpenter, “Express saccades: is bimodality a result of the order of stimulus presentation?” *Vision Research*, vol. 41, no. 9, pp. 1145–1151, 2001.
- [15] D. J. Prime and L. M. Ward, “Cortical expressions of inhibition of return,” *Brain Research*, vol. 1072, no. 1, pp. 161–174, 2006.
- [16] J. J. S. Barton, D. C. Goff, and D. S. Manoach, “The inter-trial effects of stimulus and saccadic direction on prosaccades and antisaccades, in controls and schizophrenia patients,” *Experimental Brain Research*, vol. 174, no. 3, pp. 487–498, 2006.
- [17] B. Fischer and H. Weber, “Express saccades and visual attention,” *Behavioral and Brain Sciences*, vol. 16, no. 3, pp. 553–610, 1993.
- [18] B. Fischer and E. Ramsperger, “Human express saccades: extremely short reaction times of goal directed eye movements,” *Experimental Brain Research*, vol. 57, no. 1, pp. 191–195, 1984.
- [19] P. A. Reuter-Lorenz, H. M. Oonk, L. L. Barnes, and H. C. Hughes, “Effects of warning signals and fixation point offsets on the latencies of pro- versus antisaccades: implications for an interpretation of the gap effect,” *Experimental Brain Research*, vol. 103, no. 2, pp. 287–293, 1995.
- [20] J. Pratt, C. M. Lajonchere, and R. A. Abrams, “Attentional modulation of the gap effect,” *Vision Research*, vol. 46, no. 16, pp. 2602–2607, 2006.
- [21] S. B. Hutton, “Cognitive control of saccadic eye movements,” *Brain and Cognition*, vol. 68, no. 3, pp. 327–340, 2008.
- [22] J. W. Bisley and M. E. Goldberg, “Neuronat activity in the lateral intraparietal area and spatial attention,” *Science*, vol. 299, no. 5603, pp. 81–86, 2003.
- [23] C. Pierrot-Deseilligny, R. M. Müri, T. Nyffeler, and D. Milea, “The role of the human dorsolateral prefrontal cortex in ocular motor behavior,” *Annals of the New York Academy of Sciences*, vol. 1039, pp. 239–251, 2005.
- [24] N. Guyader, J. Malsert, and C. Marendaz, “Having to identify a target reduces latencies in prosaccades but not in antisaccades,” *Psychological Research*, vol. 74, no. 1, pp. 12–20, 2010.
- [25] J. Malsert, N. Guyader, A. Chauvin, and C. Marendaz, “Having to identify a target reduces antisaccade latencies in mixed saccadic paradigms: a top-down effect released by tonic prefrontal activation?” *Cognitive Neuroscience*, vol. 3, no. 2, pp. 105–111, 2012.
- [26] K. M. Terry, L. A. Valdes, and W. T. Neill, “Does ‘inhibition of return’ occur in discrimination tasks?” *Perception & Psychophysics*, vol. 55, no. 3, pp. 279–286, 1994.
- [27] J. Halliday and R. H. S. Carpenter, “The effect of cognitive distraction on saccadic latency,” *Perception*, vol. 39, no. 1, pp. 41–50, 2010.
- [28] M. Rolfs and F. Vitu, “On the limited role of target onset in the gap task: support for the motor-preparation hypothesis,” *Journal of Vision*, vol. 7, no. 10, article 7, pp. 1–20, 2007.

- [29] C. Pierrot-Deseilligny, R. M. Müri, C. J. Ploner, B. Gaymard, S. Demeret, and S. Rivaud-Pechoux, "Decisional role of the dorsolateral prefrontal cortex in ocular motor behaviour," *Brain*, vol. 126, no. 6, pp. 1460–1473, 2003.
- [30] J. P. H. Reulen, J. T. Marcus, D. Koops et al., "Precise recording of eye movement: the IRIS technique part 1," *Medical & Biological Engineering & Computing*, vol. 26, no. 1, pp. 20–26, 1988.
- [31] Skalar Medical, *Instruction Manual: Iris IR Light Eye-Tracker Model 6500*, Skalar Medical BV, Delft, The Netherlands, 2002.
- [32] H. Weber, M. Biscaldi, and B. Fischer, "Intertrial effects of randomization on saccadic reaction times in human observers," *Vision Research*, vol. 35, no. 18, pp. 2615–2642, 1995.
- [33] A. M. Bronstein and C. Kennard, "Predictive eye saccades are different from visually triggered saccades," *Vision Research*, vol. 27, no. 4, pp. 517–520, 1987.
- [34] I. Opris, A. Barborica, and V. P. Ferrera, "On the gap effect for saccades evoked by electrical microstimulation of frontal eye fields in monkeys," *Experimental Brain Research*, vol. 138, no. 1, pp. 1–7, 2001.
- [35] M. C. Dorris, M. Paré, and D. P. Munoz, "Neuronal activity in monkey superior colliculus related to the initiation of saccadic eye movements," *The Journal of Neuroscience*, vol. 17, no. 21, pp. 8566–8579, 1997.
- [36] D. Sparks, W. H. Rohrer, and Y. Zhang, "The role of the superior colliculus in saccade initiation: a study of express saccades and the gap effect," *Vision Research*, vol. 40, no. 20, pp. 2763–2777, 2000.
- [37] J. H. Fecteau and D. P. Munoz, "Exploring the consequences of the previous trial," *Nature Reviews Neuroscience*, vol. 4, no. 6, pp. 1–9, 2003.
- [38] J. H. Fecteau and D. P. Munoz, "Salience, relevance, and firing: a priority map for target selection," *Trends in Cognitive Sciences*, vol. 10, no. 8, pp. 382–390, 2006.
- [39] M. E. Calkins, W. G. Iacono, and C. E. Curtis, "Smooth pursuit and antisaccade performance evidence trait stability in schizophrenia patients and their relatives," *International Journal of Psychophysiology*, vol. 49, no. 2, pp. 139–146, 2003.
- [40] N. Smyrnis, I. A. Malogiannis, I. Evdokimidis et al., "Attentional facilitation of response is impaired for antisaccades but not for saccades in patients with schizophrenia: implications for cortical dysfunction," *Experimental Brain Research*, vol. 159, no. 1, pp. 47–54, 2004.
- [41] L. Huestegge and I. Koch, "Dual-task crosstalk between saccades and manual responses," *Journal of Experimental Psychology*, vol. 35, no. 2, pp. 352–362, 2009.