Visual warning signals optimized for human perception: What the eye sees fastest

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B. L. Gros, D. S. Greenhouse and T. E. Cohn

Group in Vision Science and Department of Bioengineering, University of California, Berkeley, CA 94720-2020, USA

Abstract: This study aimed to answer the question of how to design a visual warning signal that is most easily seen and produces the quickest reaction time. This is a classic problem of bionic optimization—if one knows the properties of the receiver one can most easily find a suitable solution. Because the peak of the spatio-temporal contrast sensitivity function of the human visual system occurs at non-zero spatial and temporal frequencies, it is likely that movement enhances the detectability of threshold visual signals. Earlier studies employing extended drifting sinewave gratings bear out this prediction. We have studied the ability of human observers to detect threshold visual signals for both moving and stationary stimuli. We used discrete, localized signals such as might be employed in aerospace or automotive warning signal displays. Moving stimuli show a superior detectability to non-moving stimuli of the same integrated energy. Moving stimuli at threshold detectability are seen faster than non-moving threshold stimuli. Under some conditions the speed advantage is over 0.25 seconds. Similar advantages have also been shown to occur for suprathreshold signals.

Key Words: Vision, reaction time, warning signals, psychophysics, bionic signals.

INTRODUCTION

The designer of a visual warning signal (e.g., a cockpit display, a brake light, or a rail crossing signal) aims to develop signals that convey information rapidly and accurately. In the case of warning signals, it is especially important that an observer be able to respond as fast as possible. How does one design a signal that is maximally effective?

The purpose of this investigation is to gather information relevant to the question of how best to signal a warning through the human visual system. We have made measurements aimed at identifying the nature of the visual stimulus that the eye might see the fastest. We have directed our attention at a class of visual stimuli that others have found the eye to be most sensitive to. Previous research has demonstrated that stimuli that move or that appear to move have lower detection thresholds, and thus are seen more easily (Gros et al 1996; Watson et al 1983). Our present experiments demonstrate that moving stimuli also produce faster reaction times than stationary targets. We find this to be true in a variety of tasks and viewing circumstances. Whether this advantage is due to more rapid transduction at the retina, to quicker conduction in the visual pathway, or even to cognitive effects, cannot be determined from our study, but our results point to an advantage that, close to visual threshold, averages at least 50 milliseconds (ms) and which under some circumstances can exceed 300 ms. We term these signals *motion-enhanced warning signals*.

What makes the inquiry of general interest is the accelerating understanding of the visual nervous system achieved over the past several decades. It has become clear that our own visual perception is mediated by a multiplicity of channels, with different properties, operating in parallel. The issue was first crystallized by the provocative finding that retinal ganglion cells in the frog mediating detection of time-important events, such as changing contrast or movement, were equipped with myelinated optic nerve fibers, the better to speed this time sensitive information to centers of higher processing (Maturana et al 1960).

It is now well accepted that two major ascending channels mediate the bulk of visual detection (Shapley 1990). The "M" system finds a way station in the magnocellular layer of the lateral geniculate nucleus, is specialized for moving stimuli, and is faster, though of poorer acuity. The other major system is the "P" system, so-named for its way station in the parvocellular layers of the lateral geniculate. The P system is specialized for color and detail vision, but is slower.

We took a new look at this constraint because of an interest in the problem of warning signal design. If one wanted to send a signal to be processed by the visual nervous system, which way of doing it would lead to the fastest conscious reaction? Based upon the results of the

Corresponding Author:
Theodore E Cohn, PhD
University of California
360 Minor Hall, Berkeley, CA 94720-2020, USA
Tel: 510-642-5076
Email: tecohn@uclink.berkeley.edu

foregoing studies, and mindful of the special features of the "M" pathway, we decided to examine a moving target as our candidate for fastest signaling. For a comparison stimulus we chose a non-moving target with much the same spatial features and approximately the same energy content, to avoid the obvious confound that more energy delivered almost always lessens reaction time.

METHODS

Human observers, some naïve as to the purpose of the tests, were positioned, with head and chin rest, 1 meter (m) from the high resolution and ultrafast video monitor (Sony Multiscan ES20) connected to a PC. Observers wore normal optical correction and sat in a room with controlled photopic illumination (ambient illuminance approximately 40 lux). The monitor, capable of refresh rates of 100 Hz, was driven by a special-purpose graphics card (Cambridge Research Systems VSG 2/3) that allowed images to be altered rapidly and which gave 12 bit control over intensity. Observers viewed a luminous "**X**" on the video screen, the arms of which subtended 4.5 degrees (deg) in length. Fixation was either at the center of the **X** (pilot experiment) or a spot on the monitor 9.1 deg directly above the center of the **X** (remaining experiments), simulating a situation where the observer would not be expected to be looking directly at potential warning signals. Fixation instructions were given to observers, but actual fixation direction was not monitored.

In each test, there were two possible types of targets. In the first case (the motion-enhanced signal), a pair of gaussian intensity profile spots (0.5 deg at half height, centers separated by 0.5 deg) were ignited in sequence to give the appearance of oscillatory motion (on-time 100 ms, off-time 10 ms, sequence repeated for up to 2.5 s). The motion was radial towards and away from the point of fixation, and just past the termination of the arm of the **X**. (The choice of which of the four arms of the **X** varied depended upon the experiment; see details below.) The second possible target (the stationary stimulus) was a single such spot ignited for 2.5 s. The single spot was at the location of the closer of the two spots used in the motion signal.

Except in the pilot experiment (see below), the target luminance pattern (either steady or 100 ms on, 10 ms off) was ramped on over a period of 250 ms. This temporal profile was meant to simulate the gradual onset of luminance from a typical incandescent bulb, as is commonly used in automobile warning signals today. Intensity integrated over time and space was thus nearly identical for test (motion) and comparison (stationary) stimuli, with the former having a 9% disadvantage owing to the off period, conveying a conservative bias to our tests. The spatio-temporal energy profiles of the two stimuli overlapped, with both having a similar spatial distribution of light and of strong DC components. The main difference was in the temporal components, with the motion stimulus showing a peak corresponding to a velocity of 2.2 deg/s that was not present for the stationary stimulus.

First, we measured the threshold contrast of our targets using a standard psychophysical staircase routine. (This routine adjusts the contrast of each trial based on responses to previous trials, narrowing in on the 79% correct point.) In all cases, the threshold contrast proved to be less for the motion-enhanced signal. We then ran our reaction time trials at this approximate "threshold" level but with two features intended to make the test a good comparison between moving and non-moving targets. Reaction times were measured using software delivered with the VSG board, and the resolution was 10 ms.

Trials of moving and stationary targets were randomly interleaved, with the subject not knowing in advance what sort of stimulus to look for. Also, with stimuli near detection threshold, the subject could not be very certain of what he/she saw. Additionally, we presented stimuli at a randomly determined time (after at least an initial delay period of 0.5 s which was followed by a period during which one or the other stimulus could occur at one of six points in time: 0.0, 0.35, 0.95, 1.97, 3.7, or 5.5 s) following the call for the stimulus by the observer. Observers were instructed to press any button on a custom button box to indicate that they were ready for a trial, and then press a second button to indicate detection of a target presentation and, for the latter, to do so as fast and accurately as possible. In all experiments, the trial ended and the stimulus was extinguished after 2.5 s if the observer did not respond. We tested under several different viewing circumstances intended to reveal properties of speed of visual processing with a simple detection task, with a choice task, and with either distractors or with an attention-grabbing auxiliary "loading" task.

We performed a pilot experiment and then five additional experiments. In both the pilot and the first experiment, termed "1-of-1 detection," we sought to minimize observer uncertainty by presenting the target at the same position every time, at the end of the upper right arm of the **X**. In this case, the observer always knew where the target would be presented. In the second experiment, "1-of-4 detection," we added uncertainty by randomly choosing on each trial one of the four arms of the **X** to be the location of the signal. Again, observers had to react as fast as possible to the presentation of the target, but they were not required to indicate which of the four targets were presented. In the third experiment, the trials were identical to the 1-of-4 detection trials, but this time the observer had to indicate *which* of the four possible target locations the target was actually presented by pressing the appropriate button on the button box. In this task, observers could press any button to indicate the appearance of the target, whereupon the target was extinguished (just as in the other experiments). Observers could then take their time before reporting which of the four targets they had seen. With this method, RTs were not spuriously increased due to observer searching for the correct button

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to press. This experiment was termed 1-of-4 identification. Three observers, two of whom were naïve as to the purpose of the study, were employed in these first three experiments.

Finally, we ran two additional experiments. In one, the "distractor experiment," we superimposed the targets on a large screen television using a half-silvered mirror. The **X** and the targets were imaged at the bottom of the screen, similar to the way that warning signals might be displayed with a Heads-Up display in a vehicle or cockpit. Observers passively watched a video of a simulated drive down an Interstate highway. They were instructed to watch the "highway" as if they were driving, but no attempt was made to monitor fixation during the experiment. While watching the scene, they performed the 1-of-1 detection experiment. In the second additional experiment, termed "sensory loading," the targets and the **X** were again optically superimposed on a television monitor, but this time the observers were instructed to play a simple "video game" that appeared on that monitor. An circle of several degrees diameter was displayed on it, and an easily seen spot, seen within or near the circle, was moved with Brownian unpredictability using a random number routine operated in a second computer. The observer used a joystick to keep the spot within the circle. When the joystick was moved, the motion of the spot was the vector sum of the joystick deflection and the computer-generated random motion signal. In this way, the observers were obligated to concentrate on the moving spot, but were still responsible for responding to the presentation of the warning signal detection target. Four observers were used in these two experiments, two of whom were naïve. In both experiments, the optical distance to both the television and the computer monitor was 1 m, and the average luminance of the display on the television was 25 candelas per square meter.

RESULTS

Our results were quite robust across subjects, and were repeatable.

Pilot test

Prior to our first experiment, we ran a pilot experiment. In this experiment, a 1-of-1 detection experiment, observers fixated the center of the **X**, and the target (either moving or stationary) appeared with a sudden onset. The results, listed in Table 1, confirmed our predictions based on previously reported detection experiments: for all three observers, the target that included motion was seen faster on average than the stationary target (average reaction time advantage of 112 ms). A one-tailed paired *t*-test on the difference in RT for each observer was performed, and the probability is listed at the bottom of Table 1. The *p*-value indicates that our reaction times are not significantly different at the 0.05 level, perhaps due to observer S2, who showed only a small advantage for motion under these conditions.

Table 1 **Reaction times, 1-of-1 detection, pilot experiment**

	Mean RT (s) ± SD	*N*	Misses
S1 motion	0.511 ± 0.119	43	0
S1 no motion	0.689 ± 0.397	33	0
S2 motion	0.296 ± 0.032	37	0
S2 no motion	0.316 ± 0.057	41	0
S3 motion	0.680 ± 0.192	47	0
S3 no motion	0.812 ± 0.441	32	3
One-tailed paired *t*-test on difference of the means	$p = 0.072$		

The distributions of reaction times for one observer are shown in Figure 1; they are typical of those for all observers. From these data, it is evident that occasionally the stationary target is seen as quickly as the motion target, but on many trials, observers responded much later, more than 1.0 s after presentation. Responses to the motion target, however, are clumped much closer together around the mean, a trend reflected in the lower standard deviations of reaction time to the motion target for all three observers. Finally, there were often many trials for the stationary target where observers did not respond to the target at all during the trial (2.5 s). These data are indicated in Figure 1 by the rightmost bar in each histogram. These trials where the observer missed the target are not included in the RT averages for all experiments as they were not coded beyond 2.5 s and would thus have distorted the average differences. Similarly, trials in which the observer responded premature to the presentation of the stimulus (false alarms) were excluded from the RT averages, and they are not shown in the figures. False alarm rates were typically 5–10%.

In the remaining five experiments, two changes were made in order to more closely mimic real-world situations. We smoothed the onset characteristic of the targets (both moving and stationary) and also placed them further from fixation. Both of these changes were intended to mimic conditions found in real viewing situations. Our targets in the pilot experiment had been sudden onset (rise time under 1 ms) produced by the excellent phosphor characteristics and rapid refresh of the monitor. But signaling in the real world is often realized with incandescent bulbs (as for example in automobile brake lights or tell-tales). We simulated the onset characteristic of incandescent signaling by linearly increasing the luminance of the target on each trial from zero to the peak over a period of 250 ms. We also required observers to fixate a distant point (9.1 deg directly above the center of the **X**), so that targets would be imaged well out of the fovea, because in real life, a warning signal is likely to be first seen in peripheral vision. Since the motion system is thought to be especially well represented in the periphery, we expected a further improvement in the reaction time advantage for the moving target over the results of our pilot experiment. After these manipulations,

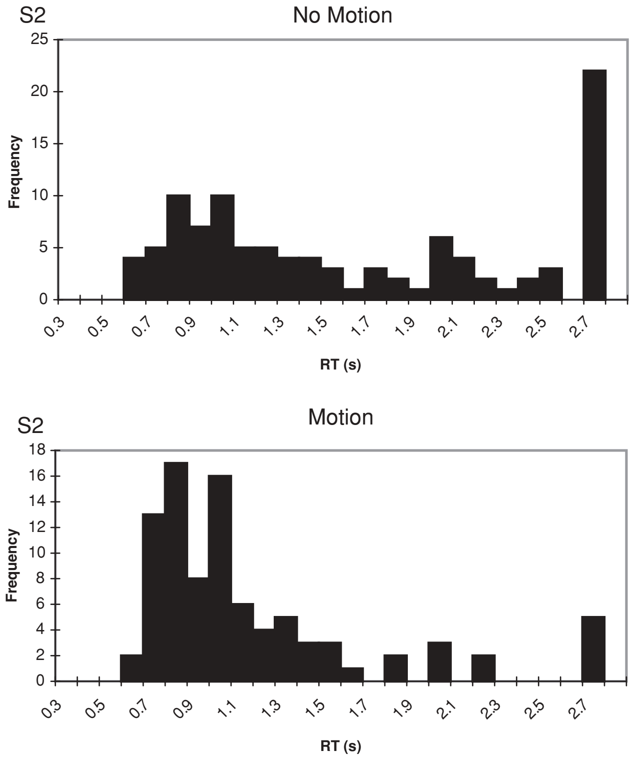

Figure 1 Distribution of reaction times for both stationary (upper panel) and moving (lower panel) stimuli in the pilot experiment (1-of-1 detection task, sudden stimulus onset). Ordinate is frequency of occurrence. Abscissa is reaction time in millisecond separated into bins of 100 ms. Reaction time is defined as the time elapsed between the onset of the first frame in which the stimulus occurs and the time at which the observer depresses a button. For the observer shown, RTs are between half a second to over 2 s, and the average is larger for the stationary target. Note that there is much overlap in the distributions to the two targets at short reaction times, but RTs to the stationary target contain many trials with long reaction times and trials where the target was not seen at all (right most bin).

we determined new thresholds for all observers to the new stimuli.

Simple detection task

In the first experiment, the 1-of-1 detection experiment, the target always appeared at a consistent, known location. Our results, similar to those in the pilot, were that observers showed a slower reaction time to the stationary target. Analysis of reaction times (see Table 2) showed that the mean reaction times were 170–381 ms slower to the stationary target for three observers (average 276 ms). Figure 2 shows these distributions for one observer; they are similar to the distributions shown in Figure 1, but reflect a shift to the right and a broader spread due to the gradual onset of the target. In Figure 2, the observer shows a peak in RT near 1.0 s for both targets, but the stationary target shows many more trials with RTs great than 1.5 s.

Table 2 **Reaction times, 1-of-1 detection**

	Mean RT (s) $\pm$ SD	N	Misses	d′
S4 motion	0.719 ± 0.152	124	0	5.23
S4 no motion	1.10 ± 0.412	129	7	3.59
S2 motion	0.993 ± 0.376	90	5	2.33
S2 no motion	1.27 ± 0.552	103	21	1.56
S3 motion	1.01 ± 0.422	35	0	4.12
S3 no motion	1.18 ± 0.538	36	13	1.23
One-tailed paired t-test on difference of the means	$p = 0.023$			

This trend is indicated in Table 1 as well, where all observers show larger variance in RT for the stationary targets. The t-test shows that the differences in RT in this experiment are statistically significant ($p = 0.023$) and do support our hypothesis that the motion target is seen faster than the stationary target.

Based upon prior published studies (Watson et al 1983), we were expecting that a signal containing motion would be more detectable than one without. The expectation was

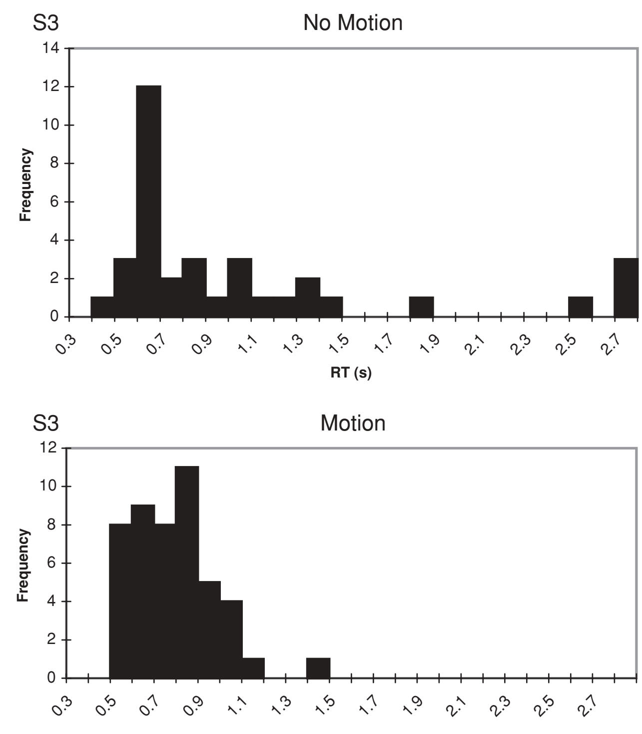

Figure 2 Distribution of reaction times for both stationary (upper panel) and moving (lower panel) stimuli in Experiment 1. Methods are identical to those of the results shown in Figure1 except that the target luminance was ramped on linearly over 250 ms to simulate the gradual onset of an incandescent bulb, and fixation was peripheral. The distributions show that reaction times to the stationary stimulus extend to much longer times than those of the motion stimulus, and there are many more trials where the observer did not respond at all to the stationary stimulus.

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Table 3 **Reaction times, 1-of-4 detection**

	Mean RT (s) ± SD	*N*	Misses	d′
S4 motion	0.945 ± 0.306	283	2	4.44
S4 no motion	1.213 ± 0.463	312	40	2.85
S2 motion	1.125 ± 0.467	290	46	1.64
S2 no motion	1.247 ± 0.549	240	80	0.58
S3 motion	1.055 ± 0.374	133	12	1.60
S3 no motion	1.374 ± 0.512	157	44	0.89
One-tailed paired *t*-test on difference of the means	$p = 0.028$			

Table 4 **Reaction times, 1-of-4 identification**

	Mean RT (s) ± SD	*N*	Misses	d′
S4 motion	1.049 ± 0.364	217	2	4.15
S4 no motion	1.335 ± 0.484	244	25	3.80
S2 motion	1.075 ± 0.451	184	28	1.25
S2 no motion	1.294 ± 0.592	145	60	0.41
S3 motion	1.118 ± 0.394	101	9	2.52
S3 no motion	1.445 ± 0.531	114	35	2.08
One-tailed paired *t*-test on difference of the means	$p = 0.006$			

realized as may also be seen in Table 2. Detectabilities (abbreviated d′, Green and Swets 1988) were calculated from false alarms and misses recorded in the runs for each subject. d′ for motion signals exceed those for non-motion signal for each subject. No-motion signals show a d′ that averages about 55% of that for motion signals. It should be pointed out that our main endpoint measure, that of reaction time, is known to improve (lessen) with detectability. However, in the literature, that improvement is obtained by the use of additional luminance (Mansfield 1973) or additional contrast (Lupp et al 1976), which supplies both additional detectability and lessened reaction time. In the present case, the integrated contrast is actually less (by a small amount) in the case of motion signals. Thus, improved detectability is itself counterintuitive. Nonetheless, we cannot demonstrate that the finding is new in this sense. If detectability advantage, from whatever cause, leads to an RT improvement, then the RT result is not itself surprising; what may be new is that a non-contrast manipulation gives the same advantage as a contrast manipulation. However, surprising or not, we have demonstrated that signals with motion are seen better by two methods of reckoning: their detectability is higher and their reaction time is lower.

In tables showing data where targets appeared at multiple locations, detectabilities were not homogeneous with respect to location (d′ was higher for targets closer to fixation, as would be expected). Thus, in Tables 3 and 4 we present d′ averaged over the four possible locations of target presentation. Consistently, motion targets retain the detectability advantage a well as the RT advantage.

Detection with uncertain location

In the 1-of-4 detection experiment, we arranged to make the target location unknown to the observer, to see if the resulting spatial uncertainty would increase the difference in reaction times for the stationary and motion targets. The data were averaged over the four spatial locations for each type of target. This spatial uncertainty increased reaction times for both conditions, as expected, but the advantage for motion was slightly reduced. Still, the reaction times for all three observers were an average of 240 ms slower to the stationary target (see Table 3) and the *t*-test shows that the differences were statistically significant ($p = 0.028$). Again, the variance in RTs was larger for the stationary target for all observers. The distribution of RTs is very similar to those shown in Figure 1.

Detection and identification with location uncertainty

Another manipulation that could alter the disparity between reaction times to stationary and moving stimuli was the addition of complexity to the cognitive aspects of the task. In the 1-of-4 identification experiment (a "choice" reaction time task), the observer had to respond to the target presentation as before, but in this experiment the observer was also instructed to report which of the four targets was presented. RTs for both targets increased with the increased complexity of the task. Average reaction times for the motion enhanced target, however, still show a significant ($p = 0.006$) advantage over the stationary target, from 219 to 376 ms (average of 277 ms, see Table 4). As in the other two experiments, the data also show larger variances in RT for the stationary target, and more misses of the stationary target than the motion target.

Simple detection with distractors

In the distractor experiment, we repeated the 1-of-1 detection experiment, but now the warning signal target was superimposed on a video of a simulated drive down an interstate highway, viewed on a computer monitor superimposed upon the signal by means of a half-silvered mirror. Both stationary and motion-enhanced targets in these experiments were ramped on over 250 ms as described above, to mimic the on-time of incandescent bulbs. Reaction times were again greater for the stationary targets for three of four observers (see Table 5), and the advantage for moving targets averaged 128 ms. Variances were up for both moving and stationary targets, but they were again greater for the stationary targets for three of the four observers. The differences in RT in this task were not statistically significant, reflecting the performance of Observer S5, who showed a slight increase in RT for the motion target.

Table 5 **Reaction times, 1-of-1 detection with distraction**

	Mean RT (s) ± SD	N	Misses	d′
S4 motion	1.07 ± 0.480	79	2	2.79
S4 no motion	1.17 ± 0.532	71	22	1.34
S1 motion	0.861 ± 0.295	48	0	4.89
S1 no motion	1.02 ± 0.429	32	3	2.96
S5 motion	1.13 ± 0.420	42	0	4.43
S5 no motion	1.03 ± 0.397	40	1	3.14
S6 motion	1.29 ± 0.429	40	12	1.75
S6 no motion	1.44 ± 0.520	37	8	2.01
One-tailed paired t-test on difference of the means	$p = 0.142$			

Simple detection with sensory loading

Finally, in the sensory loading experiment, we again repeated the 1-of-1 detection experiment. Like the distractor experiment, the targets were again superimposed on a television screen, but this time, observers were engaged in a task designed to approximate a vehicle steering task, but still required to respond when they noticed a target appear. The data reflect the same trends as the initial experiments (see Table 6). Reaction times for all four observers were shorter for the motion target by an average of 223 ms, and the variance of the reaction times is smaller for the motion targets for all four observers. A t-test again showed the differences in the mean RTs was significant ($p = 0.013$). In addition, the number of no-motion trials in which the target was missed was greatly increased in this task. One observer, S4, missed nearly 65% of the no-motion targets, while missing only 14% of the motion targets.

DISCUSSION

The applied psychology literature has ample reference to phenomena that might have been used to predict these results, at least qualitatively, though, to our knowledge, no explicit test without confounding variables has been performed prior to this one. Flashing targets, for example, are known to have special features that attract attention, and moving targets are thought to be even more salient. Engineers have long built these features into their warning devices, as for example at railway crossings or on emergency vehicles. But evidence as to their superiority is not obvious.

Table 6 **Reaction times, 1-of-1 detection under sensory loading**

	Mean RT (s)	N	Misses	d′
S4 motion	1.15 ± 0.541	113	15	1.88
S4 no motion	1.30 ± 0.596	92	58	0.43
S1 motion	0.970 ± 0.364	40	1	2.92
S1 no motion	1.19 ± 0.515	41	8	1.83
S5 motion	0.957 ± 0.297	49	8	4.70
S5 no motion	1.28 ± 0.427	37	8	4.51
S6 motion	1.19 ± 0.417	42	6	2.18
S6 no motion	1.39 ± 0.512	42	31	0.47
One-tailed paired t-test on difference of the means	$p = 0.013$			

Rationale for using motion-enhanced signals

The most compelling predictive evidence comes from the basic vision science literature. The measured spatio-temporal contrast sensitivity function in humans has a peak sensitivity at non-zero spatial and temporal frequencies (Kelly 1979). This means that a moving target should be seen best, which is exactly what Watson et al (1983) reported in an investigation of gray scale targets. Our own results in the tests described above show a similar trend, in that moving targets lead to fewer errors of detection or identification than the stationary target (though only reaction time data are reported herein). Apparently, based on the reaction time data, this same target is also seen fastest, presumably because it is signaled in a fast neural pathway specialized to the detection of motion. That may also explain why our stationary target sometimes achieved reaction times as fast as those of the motion target, in that the initial onset of the stationary target, which has the same time course for as the motion-enhanced target, may also be signaled in the fast, "M" pathway of the visual system. However, because a moving stimulus is continuously stimulating the "M" pathway, the motion target is generally more effective in eliciting fast responses, and thus the average reaction time for the motion target is less than for the stationary target. While our stimuli were designed to preferentially stimulate either the M or P pathway, these are physiologically defined and thus we could not confirm which neural pathways our observers actually used.

In the search for what one sees fastest, one might seek stimuli specialized to stimulate one, though not necessarily the other of these two pathways. Breitmeyer (1975) was the first to study such differential effects. He showed that stimuli of high spatial frequency, which he presumed to be processed in the slower "sustained" system, exhibited slower reaction times. Tolhurst (1975) has also undertaken such an investigation. For Tolhurst, the issue was whether the time to react could reveal evidence that one stimulus was stimulating one system. His results suggested so and added to Breitmeyer's. He found that the reaction time to a suddenly flashed low frequency grating (one designed to stimulate the "transient system") was bimodal with responses occurring time locked to either the onset or the offset. High frequency gratings, to the contrary, gave rise to a unimodal reaction time distribution that occurred later, indicative of a slower acting "sustained" system. Hence one

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might suspect that what is seen fastest is anything seen by the fastest of the parallel pathways.

The experiments described here show that, if a warning signal is designed in such a way as to elicit a perception of motion in the observer, the observer is more likely to respond to it than if the signal was static. The advantage that motion gives to the signal is shown in two ways. First, reaction times to the motion signal are on average shorter, sometimes up to a third of a second shorter. The distributions of the reaction times show many more trials where the static signal was not noticed until one or two seconds after it appeared (see Figure 1). Second, the static signal is more likely to be missed: many times the observer did not respond at all to the appearance of the static signal during the 2.5 s trial. The motion signal, however, was rarely missed.

These advantages for motion persist even when the observer is confronted by target spatial uncertainty or higher cognitive demand. In a task where the field of view was filled with distracting elements, we measured virtually the same advantage for the motion-enhanced warning signal as in tasks where full observer attention was allocated to the detection task. Likewise, when the observer was obligated to attend to a separate, ongoing steering task, motion-enhanced signals were again seen on average roughly 1/4 second faster than comparable static signals.

APPLICABILITY

If motion-enhanced signals are seen more quickly in the lab, what can we expect in real world settings based upon the narrow range of data that we have collected? Our present data do not permit an answer to the question of whether or not a fully briefed, alert observer would exhibit any difference in time to react between motion-enhanced and stationary signals. That is because we made no measurements under those conditions. One might expect a small difference favoring the motion-enhanced signal owing to speedier neural transmission and greater sensitivity in the M-system. What is more interesting in our view, however, is what transpires when the visual system is pressed to its limits. To find that out, we arranged for our signals to be barely visible as might occur in any of a number of circumstances.

The rationale for exploring near-threshold targets stemmed from our desire to develop understanding of worst-case scenarios. The attributes of motion in signaling matter most when the signal is hard to see. Reduced visibility as in fog for extra-vehicle signals, or due to observer inattention, blinking, head movement, or to saccadic eye movement would tend to place easily seen signals nearer to threshold, the regime to which our results directly apply. Under those circumstances, when signals are hard to see, we have demonstrated that placing a signal in motion (motion-enhanced signaling) leads to superior speed of detection.

Moreover, our results also show that implementation is not difficult. The motion need not be real, it can be apparent. Two or more sampled signals, while stationary themselves, can appear to be in motion. The perception of motion can be due strictly to nervous system interpretation, and cortical neurons have been shown to respond robustly to both real and apparent motion (Mikami et al 1986). Thus, a variety of warning signals could be fashioned, at their simplest, with two similar lit signals that are separated from each other in space and in time. Sequential ignition, with the appropriate parameters of separation, leads to the percept of motion, as has been long known, and of pragmatic importance, to the fastest signaling to the observer.

A recent study (Cohn and Nguyen 2002) had examined speed of response for motion-based signals in comparison to stationary signals in suprathreshold situations. Results obtained are qualitatively the same. The signal that employs motion is seen more rapidly on average than the stationary signal. The advantage has been measured to average over 30 ms. But the average obscures a finding also seen in the present study. On between 10 and 20% of trials, the reaction time to the stationary signal is 100–300 ms longer than that for the moving signal. Hence, suprathreshold findings portray the very same insight. Bionic considerations appear to require, and our data confirm, that motion needs to be inserted in visual signals to optimize both detectability and speed of seeing.

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