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Assistive Technology Innovations in Neurological Conditions

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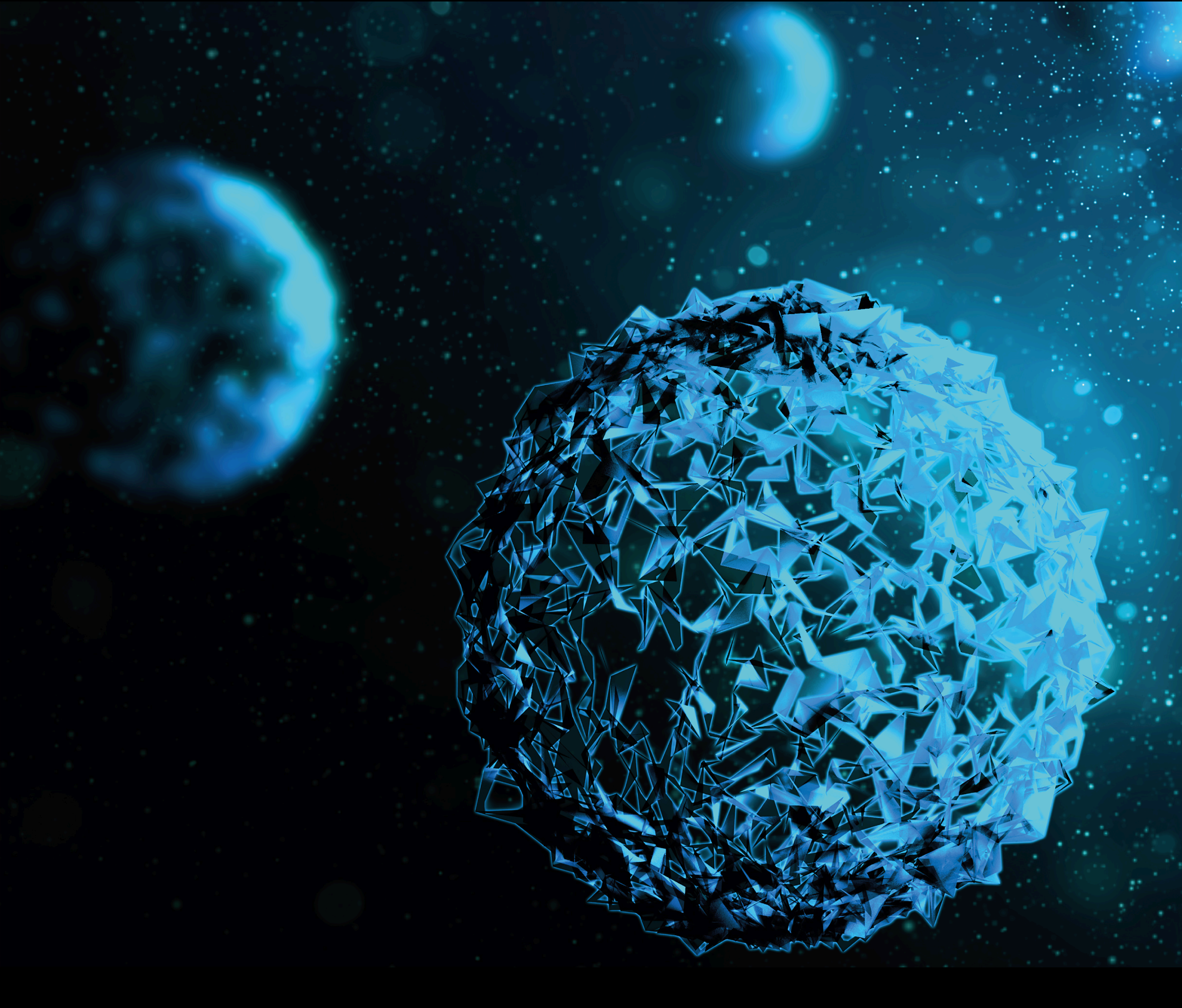
Guest Editors: Helen Dawes, Carlos B. De Mello Monteiro, Nancy Mayo, and Johnathan Collett



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Editorial Board

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Editorial

Assistive Technology Innovations in Neurological Conditions

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Advances in assistive technologies, aimed at maintaining or improving individuals' function and independence, thereby promoting their well-being [1, 2], have led to improvements in the autonomy and quality of life of people with neurological disabilities [3]. Nevertheless, the process of translating assistive devices from the laboratory bench to the manufacture of accessible products that meet the needs of people with neurological impairments is undoubtedly challenging as there is an ongoing need for reinvestment in science and technology and in the validation process [4].

This special issue provides recent developments in and summarizes studies of the development, testing, and application of assistive technology innovations in neurological conditions. High-quality research articles and systematic reviews strive to inform and investigate how assistive technologies can enable individuals with a variety of neurological conditions in many different aspects of their lives. Topics included in the issue address the use of assistive technology for improving health, psychological, and social status, as well as motor/cognitive learning and performance.

More specifically, the systematic review by B. Thordardottir et al. synthesized studies on facilitators and barriers related to the acceptance and use of innovative assistive technologies among people with cognitive impairments and their caregivers. E. Bartkiene et al. used sensory traits and face reading technology to analyse several factors (such as social status, age, gender, education, knowledge about healthy eating, and attitude to food) affecting consumer food choices. C. L. Kwan et al. investigated a wearable assistive device based on patterns of physiological signal changes and found it was able to successfully identify moments of significance experienced by individuals with dementia and their caregivers. The systematic review by A.V. L. de Araujo et al. evaluated the effectiveness of virtual reality-based rehabilitation interventions after spinal cord injury. C. Luque-Moreno et al. provided evidence for the reduction of spasticity and improvement of gait function in poststroke individuals who had traditional rehabilitation augmented with virtual reality reinforcing feedback. Finally, the results of A. H. Moliterno et al. suggested that applying computer game-based randomized training (compared to constant practice) might have superior effects on the motor performance of individual poststroke.

This special issue illustrates the wide variety of technologies that have been applied to assist people with various neurological conditions. Incorporating such a range of topics is certainly one of the strengths of this issue, which offers a broad overview on many different innovations in assistive technologies designed to improve physical functioning and promote well-being in neurologically impaired individuals. The included studies have all succeeded in addressing the potential of the technological aspects of different tools/devices, the methods used in their evaluation, and have provided results that advance the current knowledge of the mechanisms behind the associated conditions, which is a crucial role in developing understanding of the effects of the proposed interventions.

In conclusion, this special issue outlines recent developments in knowledge on many different aspects of assistive technologies and their application for individuals with neurological impairments. Future research must continue to focus on the development, evaluation, and application of assistive technology innovations in neurological conditions, to provide enhanced knowledge about the aspects involved in the associated conditions and hence pave the way to build successful strategies to improve an individual's function and independence.

Disclosure

The views expressed are those of the authors and not necessarily those of the NHS, the NIHR, or the Department of Health.

Conflicts of Interest

Nancy E. Mayo is the president of PhysioBiometrics Inc., an enterprise dedicated to the development of practical and accessible innovations for people with movement and posture vulnerabilities. Her role in the company did not influence the statements made in this editorial. Helen Dawes set up Clinical Digital Diagnostics limited, a spin-off company hosted by Oxford Brookes University. Her role in the company did not influence the statements made in this editorial. All other authors declare that there are no conflicts of interest regarding the publication of this editorial.

Carlos Bandeira de Mello Monteiro
Helen Dawes
Nancy Mayo
Johnny Collett
Fernando Henrique Magalhães

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Research Article

Effect of Contextual Interference in the Practicing of a Computer Task in Individuals Poststroke

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Objectives. Sensory and motor alterations resulting from stroke often impair the performance and learning of motor skills. The present study is aimed at investigating whether and how poststroke individuals and age- and sex-matched healthy controls benefit from a contextual interference effect on the practice of a maze task (i.e., constant *vs.* random practice) performed on the computer. *Methods*. Participants included 21 poststroke individuals and 21 healthy controls, matched by sex and age (30 to 80 years). Both groups were divided according to the type of the practice (constant or random) presented in the acquisition phase of the learning protocol. For comparison between the groups, types of practice, and blocks of attempts, the analysis of variance with Tukey's post hoc test ($p < 0.05$) was used. *Results*. Poststroke individuals presented longer movement times as compared with the control group. In addition, only poststroke individuals who performed the task with random practice showed improved performance at the transfer phase. Moreover, randomized practice enabled poststroke individuals to perform the transfer task similarly to individuals without any neurological impairment. *Conclusion*. The present findings indicated a significant effect of contextual interference of practice in poststroke individuals, suggesting that applying randomized training must be considered when designing rehabilitation protocols for this population.

1. Introduction

Stroke is a consequence of blood flow obstruction or hemorrhage in the encephalon [1], which often leads to neurological damage associated with functional limitations and/or disabilities [2] such as cognitive, sensorimotor, and/or language disorders [3].

A variety of rehabilitation programs take advantage of knowledge from motor learning research to optimize the improvement of functional abilities in poststroke individuals [4–6]. Regardless of the approach or intervention technique, the rehabilitation program shall be designed to comprise a set of internal processes associated with practice, training, or experience that results in relatively permanent changes in the performance of motor skills [7, 8].

In a recent systematic review, Shishov et al. [5] pointed out that the very broad types of protocols and measurements used to assess motor learning in poststroke individuals make it difficult to synthesize research findings across studies. Therefore, the authors emphasize the need to promote more studies in order to improve the knowledge of the organization of practice during poststroke rehabilitation. The organization of practice is an important factor to be controlled in motor learning studies, as the type of practice (e.g., constant: always the same task sequence; or random: similar, but with variations on the task sequence) can significantly influence the extent at which motor learning techniques improve performance [9–11]. According to Porter and Magill [12], random tasks reduce performance during training, but enhance retention and transfer as compared with constant schedules, a phenomenon known as the contextual interference (CI) effect. Practicing in high contextual interference conditions (random practice) enforces the individual to use multiple processing strategies to optimize performance during acquisition, whereas no such multiple processing seems necessary for the low contextual interference condition (constant practice). As a consequence, high contextual interference context is associated with improved performance during the retention and transfer phases of the learning process of a motor task (see [13, 14]).

Different theoretical supports have been associated with the CI effect [15]. The first addresses the "forgetting-reconstruction" hypothesis, which consists of short-term forgetting between successive presentations of the same task during random training. This requires the learner to "reconstruct the action plan at each presentation," which might lead to stronger memory representations [16, 17]. A second theory suggests that the computational models play a crucial role of working memory in the CI effect. It has notably been proposed that motor adaptation occurs via the simultaneous update of a fast process that contributes to fast initial learning but quickly forgetting and a slow process that contributes to long-term retention but slow learning [18, 19]. A third possibility was proposed by Lee and Schweighofer [20], who considered multiple task adaptation. In this model, a single fast process is arranged in parallel with multiple independent slow processes switched via contextual cues. During adaptation, motor errors simultaneously update fast and slow processes in a competitive manner. In a situation in which tasks are interchanged during training, this model predicts that the decay in the fast process due to both time and interference from other tasks leads to the greater update of the slow process. Thus, random schedule training should induce less long-term forgetting than constant schedule training, as proposed in the CI effect.

Some studies have been carried out to address how CI affects motor learning in poststroke individuals [15, 21–23], with findings suggesting a slower change in performance during practice in random schedules as compared with constant schedules (but with retention due to CI effects). On the other hand, in a study with functional magnetic resonance imaging, Boyd et al. [24] showed that practice of a repeated sequence increased cortical activation (suggesting a functional reorganization of the contralesional motor cortex poststroke), whereas random sequence performance did not enhance motor learning.

Although most of the above studies presented a CI effect in agreement with Shishov et al. [5], there is a gap in the motor learning literature in poststroke individuals, as most studies did not use a retention or transfer phase to assess changes in motor performance. Motor learning is basically composed of three phases: (1) acquisition, the phase in which the individual, in a repeated manner, practices how to accomplish a task; (2) retention, defined as the act of retaining previously learned information; and (3) transfer, the moment at which the individual can demonstrate whether or not there was improvement in ability, after modification of the task [11, 25, 26]. Kantak et al. [27] suggested that retention and transfer tests, rather than solely the performance parameter during acquisition, should be implemented to control for transient performance changes and hence to assess motor learning precisely. Moreover, according to Shishov et al. [5], retention tests assess the extent to which performance has improved due to the motor plan that was established during practice (thereby indicating long-lasting changes and the strength of the motor memory built during the acquisition phase), whereas the transfer test would examine the adaptability of the newly acquired motor program. These features are putatively related to the superior performance expected at the retention and transfer phases of random practice schedules as compared to constant practice (i.e. CI effect).

As rehabilitation programs must be focused on gradually improve the performance of a recently practiced motor activity ([27] (which must not only involve improvements during practice but also lead to enhanced skills on retention and transfer), the present study is aimed at contributing to the empirical body of knowledge by addressing whether poststroke individuals benefit from a CI effect, considering all the three stages of the learning process, namely, acquisition, retention, and transfer phases.

For this purpose, we used a motor learning protocol with acquisition, retention, and transfer phases during a simple computer task (maze task) performed by poststroke individuals and by age- and sex-matched healthy controls in order to identify improvements in motor abilities (see [11]). The motor task was chosen to assess distal function motor ability (finger movement), which is considered an important target for poststroke individuals. According to Antunes et al. [28], a computer task that improves the use of the computer keyboard comprises a technological ability that increases poststroke individuals' function and interaction with society (i.e., participation).

Both groups (poststroke and control groups) were divided into two subgroups based on the type of practice: in the subgroup of constant practice, participants performed the acquisition phase by repeating the same maze several times, and in the subgroup using random practice (more CI), the participants performed the acquisition phase using different mazes. As mentioned previously, we were particularly interested in unraveling which type of practice would show better movement time, not only in the acquisition phase but also in considering retention and transfer testing.

We hypothesized that poststroke individuals would perform worse in comparison with individuals from the control group in all phases of the study protocol. Moreover, we hypothesized that individuals who performed the constant practice would show better performance in the acquisition phase of the task as compared to those who practiced randomly, whereas the random practice group would perform better at retention and transfer.

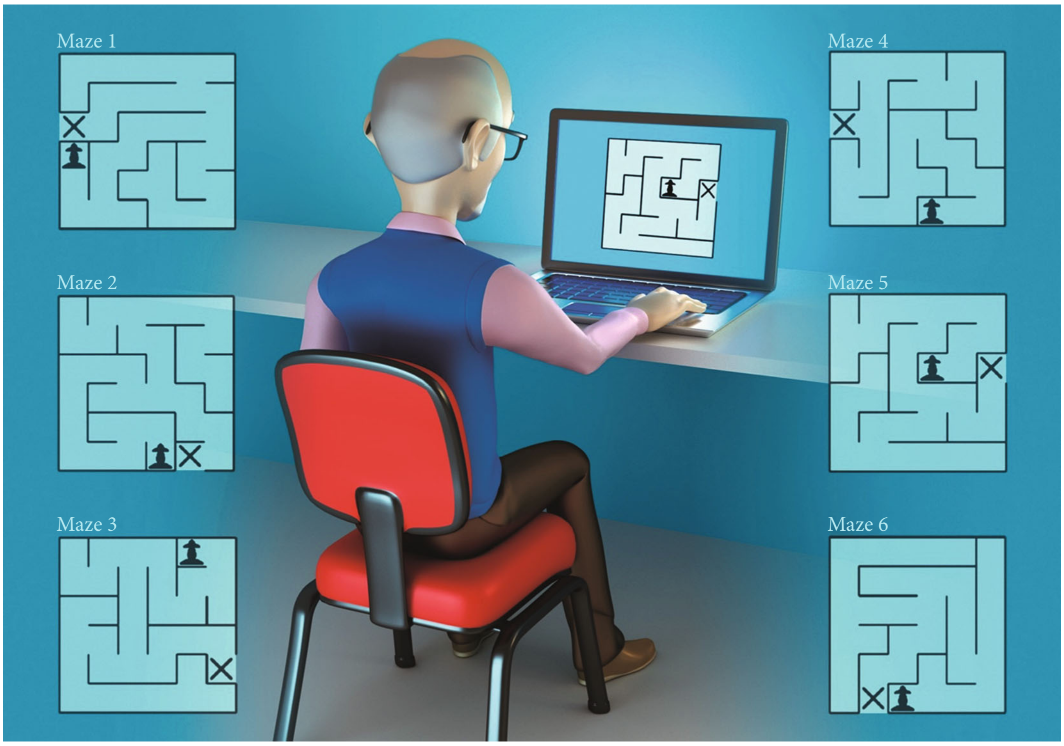

Figure 1: Representative example of a participant performing the maze task and the six different mazes used in the study.

2. Methods

2.1. Participants. This is a cross-sectional study, approved by the Research Ethics Committee under CAAE number 63123116.7.0000.5515. All participants signed the informed consent form. As the inclusion criterion of this study, individuals were required to present hemiparesis as a sequel of stroke for a minimum of 2 months. The exclusion criteria consisted of those who did not understand the proposed task after three attempts and those with comorbidities that precluded the performance of the activity (skeletal muscle deformity) [29].

Data collection was performed at a physiotherapy clinic in Presidente Prudente/SP (Brazil), and 42 individuals (between 30 and 80 years of age) were evaluated: 21 individuals after stroke (stroke group; SG) and 21 health individuals (control group; CG), matched by sex and age.

2.2. Instruments and Procedures. For characterization of the sample, the following instruments were applied: the Orpington Scale to classify the severity and estimate the prognosis of functional improvement [30, 31], the Fugl Meyer Evaluation Scale (FMS) to assess motor and sensory impairment [32], and the Berg Balance Scale to evaluate balance ability [33]. In addition, hand muscle function was evaluated through palmar grip dynamometry (Saehan® brand dynamometer) [34], and unilateral manual dexterity was measured with the Box and Block Test (BBT) [35].

2.2.1. Maze Task. The main tool used in the present study to evaluate motor learning was the maze task, which consists of six different mazes. The task was performed on a notebook positioned on a table, and the participants sat in a chair so that they would feel comfortable to perform the task on the computer (Figure 1). Participants were then given the instruction to perform the task with their preferred upper limb, which was also the limb commonly used to perform fine motor activities in daily life (all individuals chose the nonaffected arm). In addition, the participants also received information about the activity that they should follow the maze path as fast as possible until the end of the maze (signaled with an "X"), using the arrows displayed on the computer (up, down, right, and left), requiring perception and spatial memory during the execution [11]. When the participant finished each trial, a feedback message with the information about the time (in seconds) used to complete the maze was displayed at the monitor screen, thereby providing participants with the knowledge of their performance.

In the present protocol, the individuals in the SG and CG were divided into subgroups according to the type of task (random or constant practice) (Figure 2). In the acquisition phase, individuals who performed constant practice carried out 30 repetitions of Maze 1, whereas the participants of the random practice subgroup randomly performed 30 repetitions involving 5 different mazes (Mazes 1, 2, 3, 4, and 5, which were randomly presented). After 5 min of rest, retention was performed in which all individuals performed Maze 1 five times (the same maze used in constant practice acquisition and also part of the random practice). This protocol was used by Prado et al., [11], and Maze 1 was chosen for the retention test for both groups in order to allow appropriate comparisons between types of practice (constant *vs.*

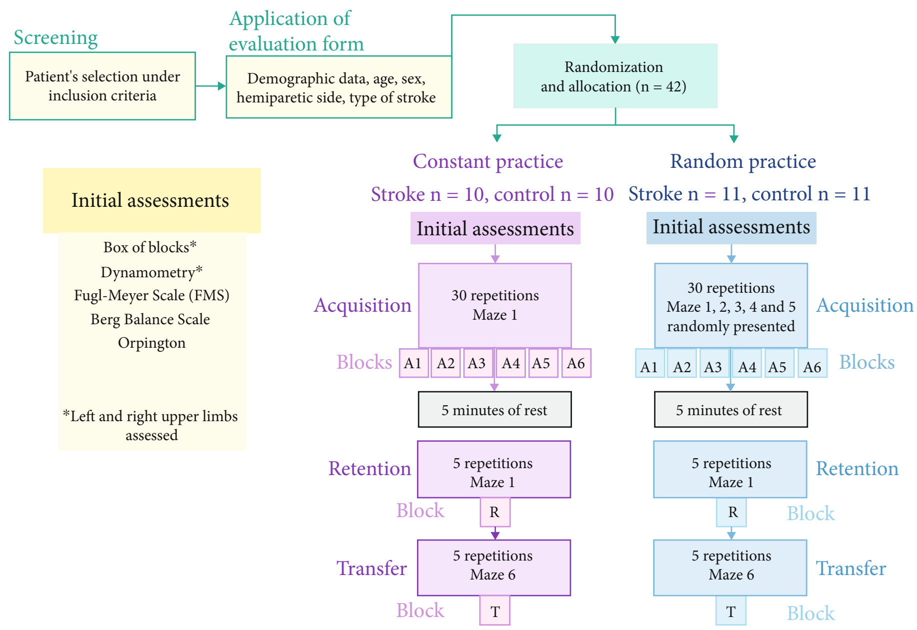

Figure 2: Depiction of the experimental protocol, showing sample selection and the presentation of the 6 different mazes according to the type of practice (constant *vs.* random) during acquisition, retention, and transfer phases of the training.

random). For the retention phase, 5 repetitions of Maze 1 were performed in constant and random practices. In the transfer phase, participants performed 5 attempts of maze 6 (new maze, i.e., not presented before), with no resting time between retention and transfer. In summary, all participants performed 30 attempts of acquisition, 5 attempts for retention, and 5 attempts for transfer. These attempts were divided into blocks with five trials each, yielding 6 blocks of acquisition (A1 to A6), 1 block of retention (R) and 1 block of transfer (T) (see Figure 2).

In this study, three important choices should be explained:

(1) Upper limb and fine movements: in this study, all participants used the more functional upper limb (i.e., participants of the control group used the preferred arm whereas poststroke participants used the nonaffected arm). For the poststroke participants, the nonaffected arm corresponded to the dominant side after stroke (commonly used for daily manual activities). In a recent systematic review, Shishov et al. [5] summarized a set of studies in which learning associated with a given intervention was inferred by examination of the nonaffected limb, which seems to be the appropriate choice to distinguish motor execution impairments due to hemiparesis (as the pathological condition, *per se,* might mask motor learning) (see [36]).

(2) Task used: to verify motor learning, we used a computer maze task which has been already used for similar studies on cerebral palsy [11] and Duchenne muscular dystrophy [37, 38]. According to Souza et al. [39], this is a simple task with the possibility of evaluating various neuropsychological issues, such as executive function, implicit memory, and spatial learning. The maze activity continuously challenges the individual's ability to process the new information related to the execution of the movement and the motor planning, since this task involves mechanisms such as memory, perception, sensory processing, feedback circuits, and effective execution of the movement [40–44]. Moreover, examining a simple task in motor learning is recommended to avoid movement compensations and was used in most of the previous studies [5].

(3) Computer task: another important choice for this protocol was the use of a computer task. Assessing the ability of poststroke patients to use a keyboard is important as effective use of computer tools is essential for poststroke patients in order to socialize, access their bank account, have fun, and so on. When considering new approaches for rehabilitation, technology has become an innovative resource, as it establishes a stimulating and pleasurable relationship between individuals, assists with functional evaluation, and possibly improves day-to-day function [45–47]. Thus, the use of a technological device (i.e., computer keyboard) provides new forms of evaluation and intensifies the rehabilitation process, with the aim of minimizing dysfunction in participation [48]. According to Wearden [49] and Milot et al. [50]; the individual tends to pay more attention when challenged by a task with a higher index of difficulty

2.3. Data Analysis. The subgroups of poststroke individuals (constant *vs* random practice) were compared with Student

Table 1: Identification characteristics and clinical aspects of the individuals participating in the study, with values expressed as the mean and standard deviation ($n = 39$).

	Experimental: Stroke constant ($n = 10$)	Experimental: Stroke random ($n = 11$)	p	Control: Control constant ($n = 10$)	Control: Control random ($n = 11$)	p
Age (years)	55.9 ± 12.6	52.7 ± 11	0.240	56.2 ± 12.7	52.6 ± 10.6	0.487
Box of blocks (R) (units)	26.8 ± 20.2	29.9 ± 21.2	0.162	73.7 ± 8.2	70.4 ± 10.7	0.398
Box of blocks (L) (units)	24.2 ± 14.4	23.2 ± 22.5	0.270	71.4 ± 8.1	66.4 ± 10.7	0.353
Dynamometry (R) (kg)	29.2 ± 26.1	36.3 ± 23.5	0.762	71.3 ± 15.0	68.3 ± 22.8	0.200
Dynamometry (L) (kg)	26.2 ± 19.9	27.7 ± 29.3	0.043*	67 ± 17	62.3 ± 22.8	0.374
Time of injury (months)	67.7 ± 108.5	38.1 ± 72	0.684	—	—	
FMS (points)	74.2 ± 14.4	69 ± 14	0.377	—	—	
BBS (points)	39.9 ± 11.9	46.1 ± 7.5	0.083	—	—	
Orpington (points)	3.4 ± 1.5	3.3 ± 1.1	0.403	—	—	
Sex (n)						
Masculine	6	5	0.500	7	7	0.562
Feminine	3	4		3	4	
Hemiparetic side (n)						
Right	3	3	0.690	—	—	
Left	6	6		—	—	
Side used for task	Opposite of paresis			Dominant arm		
Dominant side						
Right	—	—		8	9	
Left	—	—		2	2	
Type of stroke (n)						
Ischemic	4	8	0.066	—	—	
Hemorrhagic	5	1		—	—	

Note. R = right; L = left; FMS = Fugl Meyer Evaluation Scale; BBS = Berg Balance Scale; n = number of individuals. *Level of significance ($p < 0.05$).

t-test to investigate for possible differences in age, FMS, Berg scale, dynamometry, BBT, and date of injury, whereas a chi-square test was used to compare sex, hemiparetic side, and type of stroke. A Bonferroni post hoc test was used to compare the proportions in the intragroup and intergroup analyses of type of stroke.

The results of motor learning analyses were obtained through blocks of five trials for all phases of the study (acquisition, retention, and transfer). We used an Analysis of Variance (ANOVA) with the factors "group" (Stroke *vs.* Control), "type of practice" (Constant *vs.* Random), and "block," with repeated measures on the factor ("block"). In addition, for the factor block, separate comparisons were made for the study phases: the first block of acquisition versus the last block of acquisition (A1 versus A6), the last block of acquisition versus the retention block (A6 versus R), and the last block of acquisition versus the transfer block (A6 versus T). To identify the differences, the least significant difference (LSD) post hoc test was performed. Partial eta-squared (η_p^2) was reported to measure the effect size and was interpreted as small (effect size > 0.01), medium (effect size > 0.06), or large (effect size > 0.14) [51]. A linear regression analysis was carried out considering the improvement in time in seconds from the first to the final block of the acquisition to identify which factors (age, sex, hemiparetic side, date of injury in months, type of stroke, FMS, right-side BBT, left-side BBT, right-side dynamometry, left-side dynamometry, Berg Scale, and Orpington Scale) influenced the improvement in performance. A significance level of $p < 0.05$ was considered.

3. Results

Table 1 depicts the characterization of the participants of this study, indicating the homogeneity of the sample as assessed by the absence of significant differences between the factors (age, sex, hemiparetic side, and type of stroke). Individual data from each patient (such as age, gender, hemiparesis, months from lesion, type of lesion, Fugl Meyer Scale, box of blocks, dynamometry, and Berg and Orpington Scales) are attached as Supplementary Material (available here).

For the analysis of performance, separate ANOVAs were performed for each phase of the study, presented below.

3.1. Acquisition

3.1.1. Main Effects. A main effect for the group was found ($F(1, 35) = 19.3$, $p < 0.001$, $\eta_p^2 = 0.36$), in which the SG presented worse performance ($M = 39$ s) when compared with the CG ($M = 15$ s).

3.1.2. Interactions. The results are presented in Figure 3. Considering the acquisition, there was a significant interaction for blocks by groups ($F(1, 35) = 16.7$, $p < 0.001$, $\eta_p^2 = 0.32$). This result demonstrates that the groups improved performance from the first ($M = 37$ s) to the final block ($M = 17$ s) of the acquisition; however, the post hoc test demonstrated that this performance improvement was only for the SG ($M = 56$ s for 22 s, $p < 0.001$), since the CG did not present significant improvement ($M = 19$ s for 12 s, $p = 0.155$). No effects or interactions for type of practice were found.

3.2. Retention

3.2.1. Main Effects. The main effect for groups remained present ($F(1, 35) = 12.6$, $p = 0.001$, $\eta_p^2 = 0.27$), in which the SG presented a longer time ($M = 22$ s) than the CG ($M = 12$ s).

3.2.2. Interactions. There were no effects or interactions for blocks, suggesting that the performance acquired in the practice of the task was retained. Similarly, no effects or interactions for type of practice were found.

3.3. Transfer

3.3.1. Main Effects. A main effect for groups remained ($F(1, 35) = 14.2$, $p = 0.001$, $\eta_p^2 = 0.29$). This result demonstrates that the SG presented a longer time to perform the task ($M = 23$ s) when compared with the CG ($M = 12$ s).

3.3.2. Interactions. No effect was found for blocks; however, there were interactions for blocks by type of practice ($F(1, 35) = 22.4$, $p < 0.001$, $\eta_p^2 = 0.39$) and blocks by type of practice by groups ($F(1, 35) = 14.2$, $p = 0.001$, $\eta_p^2 = 0.29$). The post hoc test showed that the constant SG presented a worse performance in the transfer test ($M = 32$ s) when compared with the final acquisition block ($M = 23$ s), while the random SG improved performance in the transfer test ($M = 14$ s), in relation to the final acquisition block ($M = 21$ s). In the CG, all participants maintained the same performance, regardless of the type of practice. That is, only the SG with constant practice did not present transfer of performance.

Also, a (marginal) interaction between groups and type of practice ($F(1, 35) = 3.13$, $p = 0.085$, $\eta_p^2 = 0.08$). The post hoc test presented an interesting result in the transfer phase: the random SG did not demonstrate differences in relation to the CG ($M = 18$ s in the SG; $M = 12$ s in the CG), and there were differences between only the groups that performed the constant practice ($M = 28$ s in the SG; M = 11 s in the CG).

3.4. Regression Analysis. To understand which factors may influence performance improvement during practice, a regression analysis was performed between the improvement in movement time from the first to the last acquisition block (Δ between blocks). The analysis revealed a significant regression model for the CG ($F(1, 20) = 5.3$, $p = 0.032$, $r^2 =$ 0.22), resulting in the following equation: improved movement time = −0.202 × points in the right-side BBT. In other words, the points in the BBT on the right side influenced the improvement during the practice of the task. In the SG, there was no significant regression model.

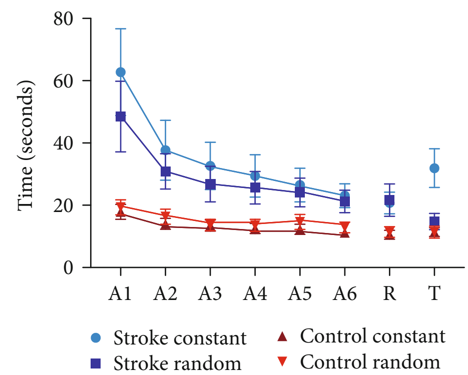

Figure 3: Graphical representation of the mean and standard error of the performance of groups in all phases of the study, in both types of practice. A1 = acquisition 1; A2 = acquisition 2; A3 = acquisition 3; A4 = acquisition 4; A5 = acquisition 5; A6 = acquisition 6; R = retention; T = transfer.

4. Discussion

The present study assessed motor learning in poststroke individuals as compared with healthy controls using a computer maze as the movement task. Individuals in the SG took more time to perform the maze task as compared with the CG in most stages of the practice. This finding is interpreted as a consequence of the lesion in brain areas (e.g., the cerebral cortex) [52] that might negatively affect the planning and execution of motor tasks that requires spatial memory and organization [39]. It is well known that the ability to find the right way into a novel or familiar environment (such as in the maze task) is a multifactorial function [53]. General deficiencies in attention, memory, and perceptual skills lead to an inability to find the correct path in known and unknown places, in addition to preclude the execution of the task in a short time [54].

Previous research evaluated motor learning using a computer maze task in individuals with Duchenne muscular dystrophy [37], while Prado et al. [11] and De Paula et al. [55] used the same task to evaluate individuals with cerebral palsy. Similarly, Possebom et al. [56] and Menezes et al. [57] studied individuals with Down syndrome, Santos et al. [58] investigated the motor learning effects in individuals institutionalized in shelters, and Souza et al. [39] involved university students in a very similar maze protocol. All the mentioned studies verified that participants in the experimental group (i.e., with the pathology/condition under study) presented a longer time of task execution as compared to their paired controls. The authors interpreted that the longer time was probably associated with loss of function and incapacity inherent to the pathologic conditions, which can also be found in the nonaffected arm of poststroke individuals [59].

The present study also showed that poststroke individuals demonstrated significant improvement in performance during acquisition, reducing the movement time from the first to the final block of the acquisition phase, regardless of the type of practice. Additionally, in the present study, the SG demonstrated retention of practice after the training period, regardless of the type of practice (random or constant). These findings are somewhat different from previous reports that evidenced a better performance during acquisition with constant practice as compared to ramdom practice [7, 14, 60, 61] and also differ from previous studies that showed the application of random practice as an essential feature to improve performance at the retention phase [62]. Such an apparent contradiction between the present and some previous results is probably associated with the specificity of the task used in the present study, as training a very simple task as the computer maze might had been sufficient for this population to improve performance during the acquisition and retention, regardless of the type of practice [62–64].

On the other hand, the general improvement in performance of the SG group during acquisition is in line with the study of Malheiros [38], which reported participants with Duchenne muscular dystrophy performed better than typically developed individuals at the final block of the computer maze task as compared to the first block of the acquisition phase. Additionally, the present study and that from Malheiros [38] observed that the control group did not improve performance during the motor learning protocol (acquisition, retention, and transfer phases), which is probably associated with the nature of the task, which is very easy to perform and probably not challenging for participants without cognitive and/or sensorimotor impairments.

In the present study, poststroke participants that trained under random practice showed effective motor learning at the transfer phase, whereas those that trained under constant practice did not. Such a better performance at the transfer phase for random practice as compared to constant practice might be associated with the fact that the randomly performed training required motor reorganization with multiple processing strategies [14, 15, 65] in the recruitment of upper limb muscles at each attempt of the acquisition phase. Consequently, the participants subjected to random practice could probably adapt to these changes [21] and hence demonstrated a superior performance at the transfer phase. Furthermore, it is necessary to constantly create a plan of action in the face of the frequent changes in the task [17], which favors the performance of the random practice group at the transfer phase, whereas the participants with constant practice were not adapted to modifications and hence could not reorganize the plan of action necessary for transfer. This result has a strong practical implication, as the main goal of practicing motor tasks (acquisition phase), especially for individuals in the rehabilitation process, is the transfer of the improved performance to similar tasks, which is indeed the most difficult goal to reach and rarely addressed in motor learning research [66].

Lastly, and rather interesting, no difference could be observed between the performance of the SG (trained with random practice) and the CG (trained with both random and constant practice) at the transfer phase. This finding indicates that the randomized practice enabled poststroke individuals to perform the transfer task similarly to individuals without any neurological impairment. This finding is probably due to CI effects, so the reorganization of motor action necessary at each attempt demanded the participants to constantly apply task-appropriate motor strategies, which is known to facilitate learning [67]. In the case of poststroke individuals, this may possibly improve motor ability to perform as well as healthy subjects [17, 21]. Further studies must be carried out (e.g., using different tasks) to investigate CI effects in poststroke individuals, to confirm whether considering random practice as an important component of intervention programs shall be indicated for this population.

5. Limitations and Future Directions

One of the limitations of the present study was that the participants with stroke performed the maze task with their nonaffected arm (which was eventually the "original" nondominant arm before stroke for some participants), whereas the healthy control participants performed the task with their dominant arm. Although this might have influenced the present results somehow, it is worth noting that most of the participants of the SG were chronic patients (67.7 months after injury for the constant practice group and 38.1 months for the random practice group). Thus, the poststroke participants were used to perform daily tasks using their nonaffected arm, regardless of their original handedness.

Additionally, the present study involved a relatively small number of participants; i.e., a larger sample could have provided more detailed data about time of injury, strength, and comparison between sides (right and left). Regardless of the small number of participants, the large effect sizes associated with the present results suggest the sample was large enough to provide reliable results.

This study used a short-term protocol and a specific computer maze task, so that the present results cannot be generalized to different tasks and/or long-term effects. Moreover, the present study did not directly investigate the neurological or physiological mechanisms associated with the present findings. Although previous studies suggest mechanisms such as cortical reorganization, adaptive changes in the functional organization of the motor system and plasticity due to motor learning intervention (e.g., [68]) might be associated with the behavioral outcomes observed here; the effects of the short-term protocol used in the present study might only be associated with these mechanisms in a speculative way. Thus, considering the promising results, future studies with long-term learning protocols and direct neurological assessments are warranted in order to provide more conclusive results about the mechanisms and the clinical applicability associated with motor learning by random practice in poststroke individuals.

Finally, further clinical assessments (besides gender, hemiplegic side, age, and functional classification), such as visual and cognitive measurements, could have been useful to better characterize the sample and interpret the results. Nevertheless, despite the limitation pointed above, the present results suggest that motor training of poststroke patients can be more effective with the implementation of random practice rather than constant practice. Thus, the findings presented herein provide useful insights on tasks for fine movements of the upper limbs, which are important for the accomplishment of activities of daily living and are generally impaired in poststroke patients [63].

6. Conclusion

Poststroke individuals presented lower performance on the maze task as compared with healthy controls. In addition, only poststroke individuals who performed the task with random practice showed improved performance at the transfer phase, which suggests an effect of contextual interference of practice. Moreover, randomized practice enabled poststroke individuals to perform the transfer task similarly to individuals without any neurological impairment. This finding might be considered an indication of the importance of applying randomized training in the rehabilitation of poststroke individuals, as the type of practice in the acquisition phase significantly influenced overall motor learning.

Data Availability

All relevant data are within the paper. Any other data concerning the results communicated herein will be freely available upon request.

Conflicts of Interest

The authors state no conflict of interest.

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Supplementary Materials

"Demographic data for each patient included in the study". *(Supplementary Materials)*

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Research Article

Reinforced Feedback in Virtual Environment for Plantar Flexor Poststroke Spasticity Reduction and Gait Function Improvement

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Background. Ankle spasticity is a frequent phenomenon that limits functionality in poststroke patients. *Objectives*. Our aim was to determine if there was decreased spasticity in the ankle plantar flex (PF) muscles in the plegic lower extremity (LE) and improvement of gait function in stroke patients after traditional rehabilitation (TR) in combination with virtual reality with reinforced feedback, which is termed "reinforced feedback virtual environment" (RFVE). *Methods*. The evaluation, before and after treatment, of 10 hemiparetic patients was performed using the Modified Ashworth Scale (MAS), Functional Ambulatory Category (FAC), and Functional Independence Measure (FIM). The intervention consisted of 1 hour/day of TR plus 1 hour/day of RFVE (5 days/week for 3 weeks; 15 sessions in total). *Results*. The MAS and FAC reached statistical significance ($P < 0.05$). The changes in the FIM did not reach statistical significance ($P = 0.066$). The analysis between the ischemic and haemorrhagic patients showed significant differences in favour of the haemorrhagic group in the FIM scale. A significant correlation between the FAC and the months after the stroke was established ($P = -0.711$). Indeed, patients who most increased their score on the FAC at the end of treatment were those who started the treatment earliest after stroke. *Conclusions*. The combined treatment of TR and RFVE showed encouraging results regarding the reduction of spasticity and improvement of gait function. An early commencement of the treatment seems to be ideal, and future research should increase the sample size and assessment tools.

1. Introduction

Stroke patients suffer several deficits that affect (mildly to severely) the cognitive, psychological, or motor areas of the brain, at the expense of their quality of life [1]. Although rehabilitation techniques do not only act on the motor deficits [2], the effects associated with the interruptions of the corticospinal tract, as well as the subsequent adaptive changes, commonly require specific interventions. Among them, the most important changes are muscle weakness, loss of dexterity, cocontraction, and increased tone and abnormal postures [3].

Hemiparesis is the most common problem in poststroke patients, and its severity correlates with the functional capabilities of the individual [4], being that impairment of gait function is one of the most important limitations. Furthermore, weakness of the ankle muscles caused by injury to supraspinal centres and spasticity are the most frequent phenomena that limit functionality [5]. The degree of spasticity of the affected ankle plantar flex (PF) muscles primarily influences gait asymmetry [6], which is, in addition to depression, another independent factor for predicting falls in ambulatory stroke patients [7]. Physiological changes in the paretic muscles, passive or active restraint of agonist activation, and abnormal muscle activation patterns (coactivation of the opposing lower extremity (LE)) have been shown to occur after a stroke and can lead to joint stiffness (foot deformities are present in 30% of stroke patients) [8], deficits in postural stabilization, and reduced muscle force generation [9]. To enhance this postural stability during gait, it seems that poststroke patients with impaired balance and paretic ankle muscle weakness use a compensation strategy of increased ankle muscle coactivation on the paretic side [10].

Scientific evidence shows that the use of mixed techniques with different physiotherapy approaches under very broad classifications (i.e., neurophysiological, motor learning, and orthopaedic) provides significantly better results regarding recovery of autonomy, postural control, and recovery of LE in the hemiparetic patient (HP) as compared to no treatment or the use of placebo [11]. Within the latter techniques, we may emphasize the relearning of motor-oriented tasks [12], as well as other approaches based on new technologies (e.g., treadmill [13], robotics [14–16], and functional electrical stimulation (FES) [17]), which are often used as additional treatments to traditional rehabilitation (TR). However, some of these emerging therapies, such as vibratory platforms [18], have not been shown yet to produce as positive results as the prior ones. Thus, obtaining better results with mixed and more intensive rehabilitation treatment has been demonstrated [19, 20]. Therefore, we propose to add the use of virtual reality (VR) techniques to TR to optimize results. We can use the label "VR-based therapy" because it acknowledges the VR system as the tool being used by the clinician in therapy, not as the therapy itself. It is essential to transfer the obtained gains in VR-based therapy to better functioning in the real world [21]. In this way, the intersection of a promising technological tool with the skills of confident and competent clinicians will more likely yield high-quality evidence and enhanced outcomes for physical rehabilitation patients [22].

The application of VR to motor recovery of the hemiparetic LE (HLE) has been addressed by several authors in the last decade [23–28], obtaining satisfactory results, in general terms, in the increase of walking speed [22, 24, 25], cortical reorganization, balance, and kinetic-kinematic parameters. Other authors have reported improvements in the balance of patients treated with nonimmersive VR systems based on video games, using specific software and with the guidance of a therapist [29]. A recent study showed that VR-based eccentric training using a slow velocity is effective for improving LE muscle activity to the gastrocnemius muscle and balance in stroke [30]; however, the spasticity of PF muscles was not analysed in any of these studies.

Virtual reality acts as an augmented environment where feedback can be delivered in the form of enhanced information about knowledge of results and knowledge of performance (KP) [31]. There are systems that use this KP through the representation of trajectories during the execution of the movement, as well as visualizing these once performed, to visually check the amount of deviation from the path proposed by the physiotherapist. Several studies demonstrated that this treatment enriched by reinforced feedback in a virtual environment (RFVE) may be more effective than TR to improve the motor function of the upper limb after stroke [31, 32]. In our study, the use of a VR-based system, together with a motion capture tool, allowed us to modify the artificial environment with which the patient could interact, exploiting some mechanisms of motor learning [33, 34], thus allowing greater flexibility and effective improvement in task learning. This system has been highly successful in the functional recovery of the hemiparetic upper extremity [31, 33–36], but its combined effect with TR on the LE has not yet reported conclusive data [37]. The continuous supply of feedback during voluntary movement makes it possible to continuously adjust contractile activity [38], thus mitigating increments in spasticity and cocontraction processes of the patient. These settings are of great significance in motor control, and certain variables (such as the speed of the movement) can be controlled, having a direct influence on spasticity. In this line, the aim of this study is to determine if there is a decrease in the spasticity of the PF muscles and improved gait function, following a program that includes the combination of TR and VR with reinforced feedback, which is called "reinforced feedback virtual environment" (RFVE).

Moreover, as a complementary aim, we analysed the modulatory effects of demographic and clinical factors on the recovery of patients treated with TR and VR. The analysis of the influence of these modulatory variables was focused on better highlighting what type of patients would benefit most from the combined treatment of TR and VR. Particularly, we looked into the effects of age and time elapsed from the moment the stroke occurs until the patient starts neurorehabilitation. As shown in various studies, a better outcome for treatment can be expected for younger patients and for those who start the treatment earlier [39]. Also, comparisons were made between patients with an ischemic and haemorrhagic stroke, since differences in their recovery prognostic have been reported elsewhere, with better outcomes for the latter group [40].

2. Materials and Methods

2.1. Sample. In the present study, the sample consisted of 10 male poststroke patients (5 with right hemisphere injury and 5 with left hemispheric injury; 6 with ischemic strokes and 4 with haemorrhagic strokes). The demographic and clinical characteristics of both groups of patients are presented in Table 1. Human experimentation was approved by the Ethical Committee of the University of Seville (Spain). Each patient provided written consent allowing the use of their demographic and clinical information for research purposes. Any personal information that could identify them was removed to preserve their anonymity.

The inclusion criteria were as follows: patients with a single stroke (ischemic or haemorrhagic) included in a physiotherapy program (1 hour/day, 5 days/week) and never

Table 1: Median (25th—75th percentiles) for age, months after stroke, and scores on the scales before and after the treatment are presented. Calculated *differential variables* are also included. Mann–Whitney's U and Z values are indicated along with the corresponding P values.

Scales	Ischemic ($n = 6$)	Haemorrhagic ($n = 4$)	U	Z	P
Age	62.47 (55.82–75.3)	63.47 (52.29–72.33)	10	−0.4	0.76
Months after stroke	7.34 (3.98–12.07)	4.6 (3.11–6.74)	8	−0.85	0.39
FAC pre	3.5 (1.5–4.75)	1.5 (0–3)	5	−1.25	0.13
FAC post	3.5 (2.25–4.75)	2 (1–3.25)	7	−1.08	0.27
FIM pre	112 (88–125)	81 (73.8–91.3)	3	−1.93	0.05
FIM post	109 (86.5–125)	67 (61.3–80.8)	5	−1.5	0.13
MAS pre	2.5 (1–4)	1.5 (0.75–2.5)	9.5	−0.57	0.57
MAS post	3.5 (3–4)	3.5 (3–4.25)	8.5	8.5	−0.78
Diff. FAC	0 (0–.25)	1 (.25–1)	5	−1.75	0.08
Diff. FIM	0 (0–1.5)	11 (0–14)	3.5	−2.05	0.04
Diff. MAS	0 (-2.5–.25)	−1.5 (−4.25, to −0.25)	6.5	−1.22	0.22

treated before with RFVE. The exclusion criteria were as follows: evidence of cognitive impairment (patients underwent a cognitive screening before inclusion in the study), De Renzi test score of below 62 or receptive aphasia that would alter the understanding of tasks, and conducting additional rehabilitation with other technologies that could influence the results (e.g., robotics, FES, and vibration platforms) (Figure 1).

2.2. Assessment and Intervention. A preintervention evaluation, an intervention based on the objectified deficits, and a postintervention evaluation were performed on the 10 patients described above. It is important to highlight that before the date of the first assessment, they all had received TR in the initial period following the stroke.

2.2.1. Assessment of Spasticity

(i) Spasticity of PF muscles of the hemiparetic ankle was assessed using the Modified Ashworth Scale (MAS), with the patient resting in supine position. The MAS is the most widely used and extended measure to quantify hypertonia of any joint [41, 42], testing the resistance of muscles to fast manual stretching, and providing reliable measurements of spasticity when patients are evaluated by a single examiner [41]. Data obtained with the MAS have been statistically rescaled so that a score of 1 + on the MAS corresponds to a numerical score of 2, 2 corresponds to a numerical score of 3, 3 corresponds to a numerical score of 4, and 4 corresponds to a numerical score of 5 (thus, we consider a numerical category 1 +, which includes such a scale).

2.2.2. Assessment of Functionality

(i) Functional Ambulatory Category (FAC) [43]: it was designed to examine the levels of assistance required for walking along a 15-meter corridor, without receiving any technical help. It is divided into 6 categories, ranging from 0 (does not walk) to 5 (normal).

(ii) Functional Independence Measure (FIM) [44]: it is a scale constructed from 7 levels of performance. Eighteen items have been defined within 6 performance areas: self-care, sphincter control, mobility, strolling, communication, and social knowledge. The maximum score for each item is 7, and the minimum score for each item is 1. So, the maximum score obtained would be 126, and the minimum score obtained would be 18.

According to the VR intervention, patients underwent 1 hour/day of treatment based on RFVE, in addition to the TR already performed for 1 hour/day, 5 days/week for 3 weeks (a total of 15 sessions). Subsequently, a clinical evaluation (MAS, FAC, and FIM) pre- and post-intervention, comparing the results with specified statistical methods, was performed.

Moreover, the TR session was focused on the overall functional recovery of the patient (including the upper limb) [2, 45–48]. Patients allocated to the TR group received specific rehabilitation of the LE consisting of passive, assisted, and active exercises in many directions in the lower limb workspace (e.g., coxofemoral joint flexion and extension, abduction and adduction, internal and external rotation, knee flexion, and extension) and mixed techniques with different approaches [11]. Exercises were performed in the sitting and standing positions, and each of the training programmes was personalized to the motor capacities of patients. The individual task-oriented exercises were selected for each patient in accordance with their current mobility conditions (e.g., exercises for postural control in the standing or sitting position instead of gait training). Then, the exercise programme was progressively increased in terms of complexity by the physiotherapist in charge of the treatment (e.g., go up and downstairs or exercises to improve dynamic balance), according to results from the functional assessment. Thus, exercises performed by patients in the TR group were addressed to achieve the best functional skills for balance and walking autonomy.

The treatment based on RFVE was specifically centred on the recovery of the HLE [28, 43]. The RFVE equipment used consisted of a computer workstation connected to a 3D motion tracking system (Polhemus 3Space FasTrak Vermont, USA) and a high-resolution LCD projector that

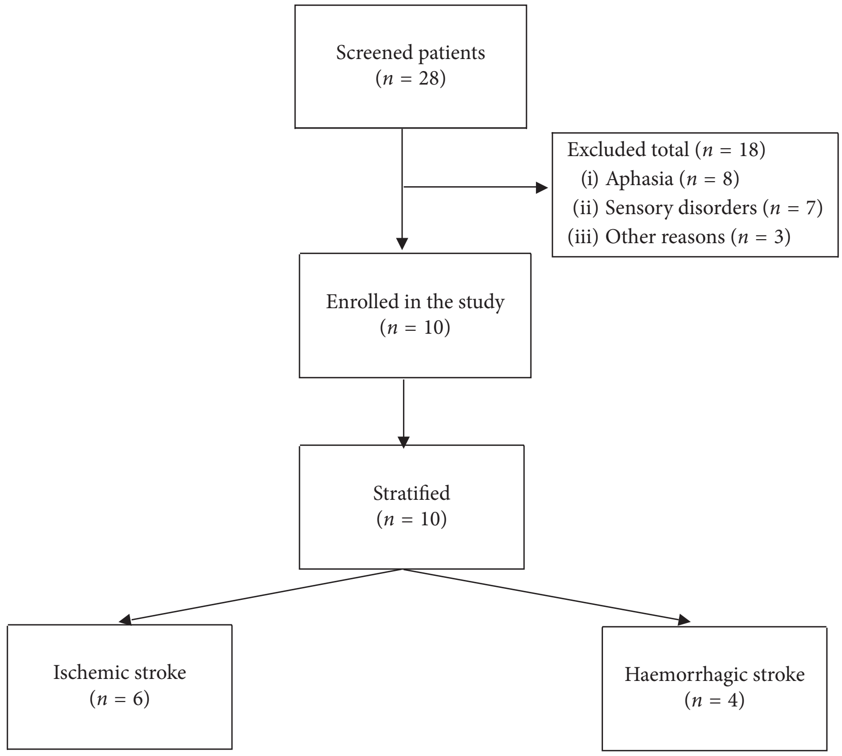

Figure 1: Flowchart of participants through the study.

displayed virtual scenarios on a large screen (Figure 2). The 3D motion tracking system detected the position of the electromagnetic sensor placed on the LE. The flexible software, developed at the Massachusetts Institute of Technology (Cambridge, MA, U.S.), was used to create several motor tasks for the LE. The nature and complexity of the motor tasks were adapted to the previously evaluated deficiencies, gradually increasing the difficulty and providing the variability that boosted motor learning.

In the virtual scenario, the starting position and the features of the target were determined to facilitate the perception of errors and their correction by the subject (learning by imitation) [37, 49], enabling the acquisition of motor skills [43] and employing artificially reinforced feedback. While performing the task, subjects obtained information on the movement of their limb (KP) through the virtual representation of the trajectory carried out by the sensors (Figure 3). Amplification of the visual and auditory feedback was controlled, providing calculations of the score for each trial of the task and the use of the "virtual teacher" (T). The latter gives the patient continuous guidance on the ideal speed at which the movement should be carried out. It was possible to modulate the rate of the T, controlling spasticity while performing the given task and performing a higher-quality motion [4], as well as the reduction of the ankle muscle coactivation on the paretic side [10]. In line with previous studies focusing on the motor rehabilitation of the upper limb [31], the differences in muscle activation patterns of the LE were considered. Because the motor control mechanisms for both LEs are affected during poststroke gait [5], specific interventions were carried out for

Figure 2: Patient carrying out a task set out by the physiotherapist in front of the RFVE equipment.

their normalization. When the exercises were performed in a standing position, the patient was asked to stand on the nonparetic limb and perform open kinetic trajectories with the paretic limb to improve the oscillation phase. When asked to stand on the paretic limb, a sensor was placed on the dorsal side of the nonparetic foot (this was performed to optimize the proprioception of the paretic side induced by the movement of the centre of pressure on the supporting foot when moving the nonparetic side towards different trajectories in open kinetic chain). This exercise in a closed kinetic chain over the paretic LE could be an effective treatment method to improve gait patterns in stroke patients, since it would provide constant sensory input from the affected foot [50]. Besides, the associated eccentric work of these exercises would have a direct relationship with the

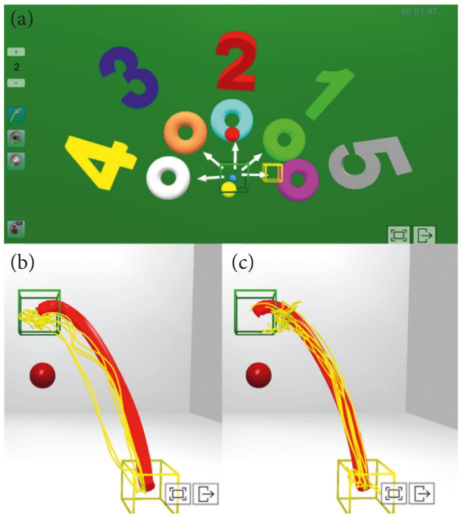

Figure 3: Different trajectories proposed to patients in the virtual scenario. (a) Star of numbers with different directions to follow, moving the foot on the ground without losing contact with the plant. In (b) and (c), the ideal path proposed by the physiotherapist (red) and the different tests performed by the patient (yellow) are shown. As can be seen, the executed trajectories (yellow) approximate the proposed ideal trajectory (red) from pretraining (b) to posttraining (c).

reduction of the best activation of the gastrocnemius muscle, as long as it is conducted at the low speed [38], which in our case was controlled by using the T guide [37]. In linear paths, dragging the foot on the ground from the starting point to the arrival point (different numbers), additional feedback (especially the speed of realization through the T) was provided for the realization of the different directions in which the spasticity of the FP musculature (speed-dependent) had to be modulated to perform a correct FD movement. At the same time, it was important to repeat more specific tasks that included the effect of gravity until reaching the point of arrival, providing visual-auditory feedback to achieve better performance until approaching the ideal trajectory. Theoretically, the best movement should be repeated, emulating a reference model as exactly as possible, with the aim to achieve the best motor performance [34]. Afterwards, it was possible to show the patient the performance of the task (Figures 3(b) and 3(c) offered the patient the possibility to visualize, in 3D, the ideal trajectory (red lines) and the different repetitions (yellow lines) to see at what point and in which direction the real trajectory moved further away from the ideal, thus being able to perform a more specific training of specific points of the trajectory) to obtain feedback that could help in its correction (KP). PF weakness is a determinant of kinetic asymmetry during gait in poststroke individuals walking with high levels of effort [51]. For that reason, it was paramount to perform exercises aimed at enhancing muscle strength while avoiding spasticity and cocontraction phenomena by continuously providing feedback to the patient. For example, controlled exercises (in trajectory, distance, and speed) of heel lift in load to improve the maximum peak of plantar flexion during take-off (sensor in the heel) [37].

2.3. Statistical Analysis. Mean and median scores on the different scales for each group are represented in Figure 4. Pre- and post-treatment comparisons were performed by using repeated-measures ANOVAs after having confirmed the parametricity of the different variables.

Additionally, the treatment effects on the ischemic ($n = 6$) and haemorrhagic ($n = 4$) groups were also analysed in light of previous studies reporting differences in their responsiveness to the rehabilitation treatment [40]. Both groups' scores on the different scales pre- and post-treatment were compared by using Mann–Whitney tests. Moreover, *differential variables* (henceforth "*Diff variables*") were calculated by subtracting the pretreatment scores from the posttreatment scores for each of the scales (i.e., *Diff. FIM*, *Diff. FAC*, and *Diff. MAS*). Both groups were compared on these variables by using Mann–Whitney tests to account for differences in their response to the treatment.

Finally, correlation analyses between the *Diff variables* and the different demographic and clinical variables collected were conducted to account for the modulatory effect of these variables on the effect of the treatment. Nonparametric Spearman analyses were used.

3. Results

3.1. Pretreatment and Posttreatment Comparisons. Individual and group scores on each scale pre- and post-treatment are represented in Figure 3. The repeated-measures ANOVAs revealed significant changes in the FAC ($F(1, 9) = 6$; $P = 0.03$; partial eta-squared = .4) and MAS ($F(1, 9) = 5{,}12$; $P = 0.04$; partial eta-squared = .36) scales. As shown, the mean FAC scores increased from 2.5 (SE = .6) pretreatment to 2.9 (SE = .5) posttreatment, indexing an improvement in ambulation functionality. Conversely, mean MAS scores decreased from 3.4 (SE = .34) pretreatment to 2 (SE = .56) posttreatment, thus indicating reduced spasticity posttreatment. Besides, increases in the overall scores on the FIM scale were observed, although it did not reach the significance level ($F(1, 9) = 5$; $P = 052$; partial eta-squared = .36).

3.2. Modulatory Effects of Age, Months after the Stroke, and Stroke Aetiology. Correlation analyses showed no linear associations between age and any of the *differential variables* (i.e., *Diff. MAS, Diff. FAC,* and *Diff. FIM*). However, a significant positive correlation was observed between the number of months after the stroke and *Diff. FAC* (rho = −0.71, $P = 0.05$). Those patients who started the treatment earlier after the stroke showed a greater recovery in ambulation functionality. Comparisons between ischemic and haemorrhagic patients on the *differential variables* revealed significant differences in *Diff. FIM* (Table 1), with greater values for the latter group indicating more significant improvements in their independence functionality.

4. Discussion

Once the analysis was performed, the results could be considered satisfactory. In this way, significant data pointing to an

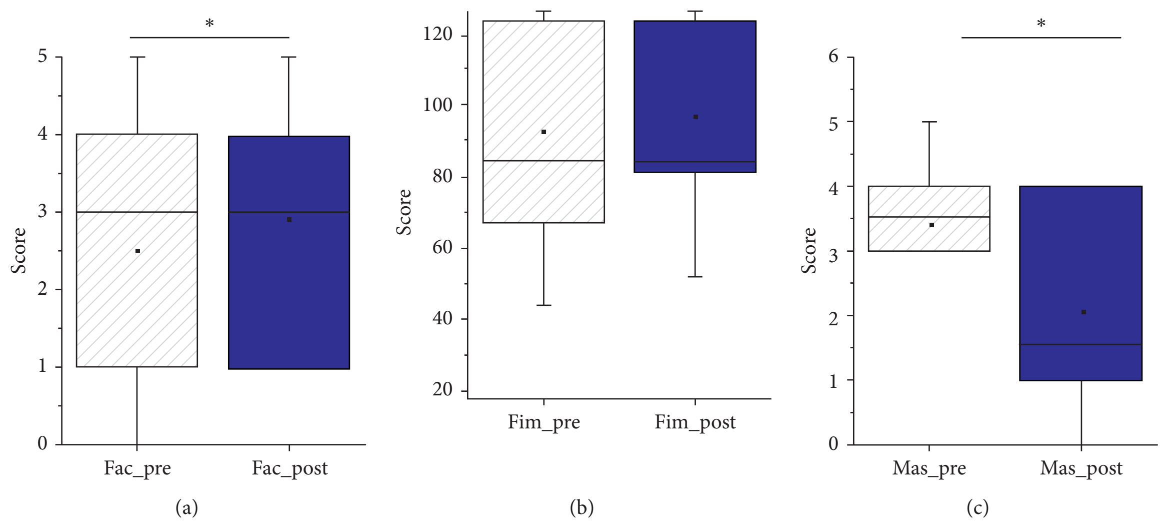

Figure 4: Boxplots showing the group scores pre- and post-treatment on each scale. Means are also represented by a square. Individual scores from each patient have also been included.

improvement in gait function measured by the FAC was obtained. Similar results were obtained by other authors that included the use of other VR systems applied to the HLE [23–28]. Although the variability of assessment tools used in this work did not allow us to establish full parallelism, in a study conducted by You et al. [24] in which the FAC was included as the assessment tool into the VR system "IREX VR system," similar results were obtained. In general terms of overall functionality measured by the FIM, despite some improvements being observed in a group, this change did not reach statistical significance. Since the FIM includes 18 categories (of which only 2 are closely related to gait function), we suggest that this is not adequate to measure its evolution.

Despite the well-known effect of botulinum toxin on the reduction of spasticity, no associated positive effects on the functionality of gait were observed in terms of reduction spasticity [52, 53]. Since the treatment intensity, as well as the learning of new motor skills, promotes cortical reorganization [34], it becomes necessary to implement therapies aimed at optimizing the effects of TR. An interesting finding is the improvement of spasticity in the PF muscles of the HP. In that sense, any of the authors mentioned above reported this deficiency with the use of VR systems applied to the HLE. The reason may be the lack of flexibility of the software of some VR systems used in these studies that, despite being optimal for learning motor tasks, are more limited to control some parameters related to the selective control of the motion. In our case, the ability to continuously monitor and change parameters (such as trajectory and speed of execution), which is closely related to spasticity, could influence the positive results; however, it would be necessary to carry out studies that analysed the specific effect of VR. Furthermore, the degree of improvement in spasticity was higher in the acute patients as compared to chronic patients. This may be due to the gradual establishment of the spasticity in stroke patients, increasing from the first months.

Results suggest that the RFVE system can contribute to TR improving ankle spasticity, besides other interventions, and this may contribute to reducing the risk of falls in patients [7]. However, some limitations of this study should be mentioned here. For example, the sample size was quite small (only 10 patients). Nevertheless, this limitation is not specific to this study and is rather common in the literature, as it affects the generalizability of our results. Another limitation is that no control group was used, that is, a group of patients who only underwent regular physiotherapy (without VR). Finally, since the eccentric exercise, when performed at low speeds, significantly improves the function of the gastrocnemius muscle [30], future research should consider comparing the spasticity measurements obtained through the MAS and the muscle activation pattern from EMG in order to account for spasticity improvements associated with the reciprocal innervation pattern.

With regard to other studies, better results were obtained in patients who started the treatment earlier (fewer months poststroke) [39, 54], with a significant improvement in gait function. This finding would reinforce the idea that early neurorehabilitation may potentiate different physiological processes underlying spontaneous recovery of the brain after an injury. Moreover, no modulatory influence of age on the treatment effect was observed, thus contradicting previous work [39]. Probably, a sample of patients with a wider range of ages would have better highlighted the influence of this variable on neurorehabilitation treatment. Last, in line with other studies [39], the results showed greater functional recovery in the haemorrhagic patients as compared to the ischemic patients. In this respect, similar results have been reported by Paolucci et al. [40] in conventional physical neurorehabilitation treatment.

VR, just as robotics, are consolidated tools for the functional rehabilitation of the upper limb poststroke. The use of the LE to promote locomotor relearning is more recent and presents unique challenges under the complex multisegmental mechanics of gait [55]. For this reason, it is crucial to invest efforts in adapting the reinforced feedback systems to the reeducation of the poststroke gait and find synergies between robotics and VR in order to develop more effective systems.

5. Conclusions

Although this study does not present evidence on the additional effects of VR and TR, the combined treatment of TR and RFVE showed encouraging results regarding the reduction of spasticity and improvement of gait function. Early commencement of the treatment seems to be ideal, and future research should increase the sample size and evaluation tools as well as provide two comparison groups between TR and VR.

Rehabilitation treatment could be enriched with the use of RFVE systems. Nevertheless, this tool is not a suitable substitute for an expert professional, since clinical experience is essential for effective use of the system. Therefore, physiotherapists are required to select the most appropriate strategies for each patient and the time of the process, executing them by adapting the parameters related to reinforced feedback to enhance motor learning. Future research is needed to determine the specific additional effects of this treatment.

Abbreviations

PF: Plantar flexor
LE: Lower extremity
TR: Traditional rehabilitation
RFVE: Reinforced feedback virtual environment
MAS: Modified Ashworth Scale
FAC: Functional Ambulatory Category
FIM: Functional Independence Measure
HP: Hemiparetic patients
FES: Functional electrical stimulation
HLE: Hemiparetic lower extremity
VR: Virtual reality.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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Review Article

Efficacy of Virtual Reality Rehabilitation after Spinal Cord Injury: A Systematic Review

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Background. Spinal cord injury (SCI) is often associated with long-term impairments related to functional limitations in the sensorimotor system. The use of virtual reality (VR) technology may lead to increased motivation and engagement, besides allowing a wide range of possible tasks/exercises to be implemented in rehabilitation programs. The present review aims to investigate the possible benefits and efficacy of VR-based rehabilitation in individuals with SCI. *Methods*. An electronically systematic search was performed in multiple databases (PubMed, BVS, Web of Science, Cochrane Central, and Scielo) up to May 2019. MESH terms and keywords were combined in a search strategy. Two reviewers independently selected the studies in accordance with eligibility criteria. The PEDro scale was used to score the methodological quality and risk of bias of the selected studies. *Results*. Twenty-five studies (including 482 participants, 47.6 ± 9.5 years, 73% male) were selected and discussed. Overall, the studies used VR devices in different rehabilitation protocols to improve motor function, driving skills, balance, aerobic function, and pain level, as well as psychological and motivational aspects. A large amount of heterogeneity was observed as to the study design, VR protocols, and outcome measures used. Only seven studies (28%) had an excellent/good quality of evidence. However, substantial evidence for significant positive effects associated with VR therapy was found in most of the studies (88%), with no adverse events (88%) being reported. *Conclusion*. Although the current evidence is limited, the findings suggest that VR-based rehabilitation in subjects with SCI may lead to positive effects on aerobic function, balance, pain level, and motor function recovery besides improving psychological/motivational aspects. Further high-quality studies are needed to provide a guideline to clinical practice and to draw robust conclusions about the potential benefits of VR therapy for SCI patients. Protocol details are registered on PROSPERO (registration number: CRD42016052629).

1. Background

Spinal cord injury (SCI) is a common neurological condition that often results in long-term impairments in physical function and psychological and socioeconomic status [1]. Because of functional limitations in the sensory and motor systems [2], which may involve both lower and upper limb functions [3], SCI drastically affects independence and quality of life [4]. Different types of training and stimulation protocols are commonly used to induce or facilitate processes of neural regeneration and plasticity, which might lead to significant functional recovery after SCI [5]. Therefore, appropriate rehabilitation strategies are highly needed to regain sensorimotor function and reduce symptoms such as spasticity, imbalance, and neuropathic pain.

Recently, studies have used virtual reality (VR) as a promising tool for clinical rehabilitation in a variety of neurological disorders. For instance, VR-based technologies have been demonstrated to improve cognitive function after traumatic brain injury [6] and to promote balance control and gait recovery after stroke [7, 8], cerebral palsy [9], and SCI [10, 11]. VR makes use of advanced technologies (such as computers and multimedia peripherals) to provide an interactive and multidimensional simulated environment that users perceive as comparable with real-life experiences [11, 12]. The advantage of VR-based technologies over conventional rehabilitation therapies has been associated with increased motivation, engagement [13], and the wide range of possible tasks/exercises that might be implemented [10].

In fact, VR-based interventions in patients with SCI have been demonstrated to improve motor function [14–17], neuropathic pain [14, 18], balance [14, 19, 20], and aerobic function [21, 22]. Therefore, the use of VR-based rehabilitation in SCI clinical practice shows great promise; however, the evidence has not yet been formally reviewed or synthesized. To our knowledge, to date, there are no systematic reviews that integrate different results of the putative efficacy of VR in promoting sensorimotor recovery, as well as in reducing impairments and symptoms in patients after SCI. In order to provide a detailed and critical description of the effects of immersive or nonimmersive VR-based rehabilitation after SCI, we conducted a systematic review of published and unpublished studies up to May 2019.

2. Methods

This systematic review was performed in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [23, 24] and registered as a predefined review protocol in PROSPERO (CRD42016052629).

2.1. Search Strategy. An initial search was performed electronically in PubMed, BVS, Web of Science, Cochrane Central, and Scielo databases in order to identify studies published between January 1, 1980, and May 1, 2019. The grey literature was also searched in ClinicalTrials.gov and Health Services Research projects, as well as in generic Internet research engines, to avoid missing relevant unpublished studies. The identified keywords and Medical Subject Headings (MeSH) were combined by boolean logic using the following terms: "virtual reality" OR "virtual reality immersion therapy" OR "virtual reality therapy" OR "reality therapy" OR "game(s)" AND "spinal cord injury(ies)" OR "spinal cord trauma" OR "paraplegia" OR "tetraplegia." Additionally, the reference lists of all relevant literature were hand-searched to identify any additional suitable studies. Two reviewers performed the search independently.

2.2. Eligibility Criteria. Eligible studies included a sample with adults aged between 18 and 65 years (both genders) with traumatic or nontraumatic SCI who underwent immersive or nonimmersive VR-based rehabilitation. Only full scientific papers were included, regardless of the levels of lesion and the levels of disability (as assessed by American Spinal Injury Association (ASIA) Impairment Scale (AIS) classification) of the samples. Randomized controlled trials were included, along with nonrandomized controlled trials, quasiexperimental studies, and before and after studies. Studies reporting validity and/or development of VR games or devices as well as transversal comparisons designed to investigate physiological mechanisms rather than clinical efficacy assessments were excluded. Conference papers and abstracts, as well as papers written in languages other than English, Spanish, or Portuguese, were also excluded.

To increase confidence of the selection process, two reviewers (AA and JN) independently screened the title and abstract of each reference identified by the search strategy. The full-text article of all potentially relevant eligible references was subsequently retrieved and further examined independently. Discrepancies between reviewers were reconciled by discussion or a third independent reviewer (FM). All identified studies were stored in Mendeley®, and duplicates were removed.

2.3. Assessment of Risk of Bias. Two authors independently assessed the risk of bias and the methodological quality of the studies based on the PEDro scale, the most acceptable scale for rehabilitation research [25]. The scale assesses the presence or absence of randomization, allocation concealment, blinding of participants and/or researchers, homogeneity of the groups, intention-to-treat analysis, and presentation of statistical analysis. We considered the level of evidence as "excellent," "good," "fair," or "poor" for PEDro scores in the ranges of 9-10, 6–8, 4-5, and <4, respectively [25].

2.4. Data Extraction. Two independent reviewers (AA and JN) filled out a data collection form on a customized Excel® spreadsheet. Data included information on participant characteristics (sample size, age, sex, cause of SCI, level of injury, type of SCI, ASIA impairment level, and time after injury), descriptive studies' characteristics (time of publication, continent/country, type of VR, and rehabilitation objectives), methodological details (study design, dropout rate, type of therapy, VR characteristics, number and time of sessions, frequency by week, follow-up time, and outcome measurements), VR effects (statistically significant or nonstatistically significant results), risk of bias, size effects, statistical power, and limitations. The results of extraction were compared, and divergences were resolved by consensus.

Study design was analyzed by considering the following aspects: randomization, blinding, presence of the control group, bias, internal and external validity, and statistical power. The statistical power was low when $\beta - 1 < 80\%$ ($\alpha = 0.05$).

The participant characteristic data were grouped and expressed as mean or percentage for better visualization of the sample profile. To form the VR therapeutic guideline, we collected the following characteristics: type of VR (immersive or nonimmersive), type of the VR device (commercial or developed by authors), number and time of sessions, frequency of therapy by week, type of therapy (VR

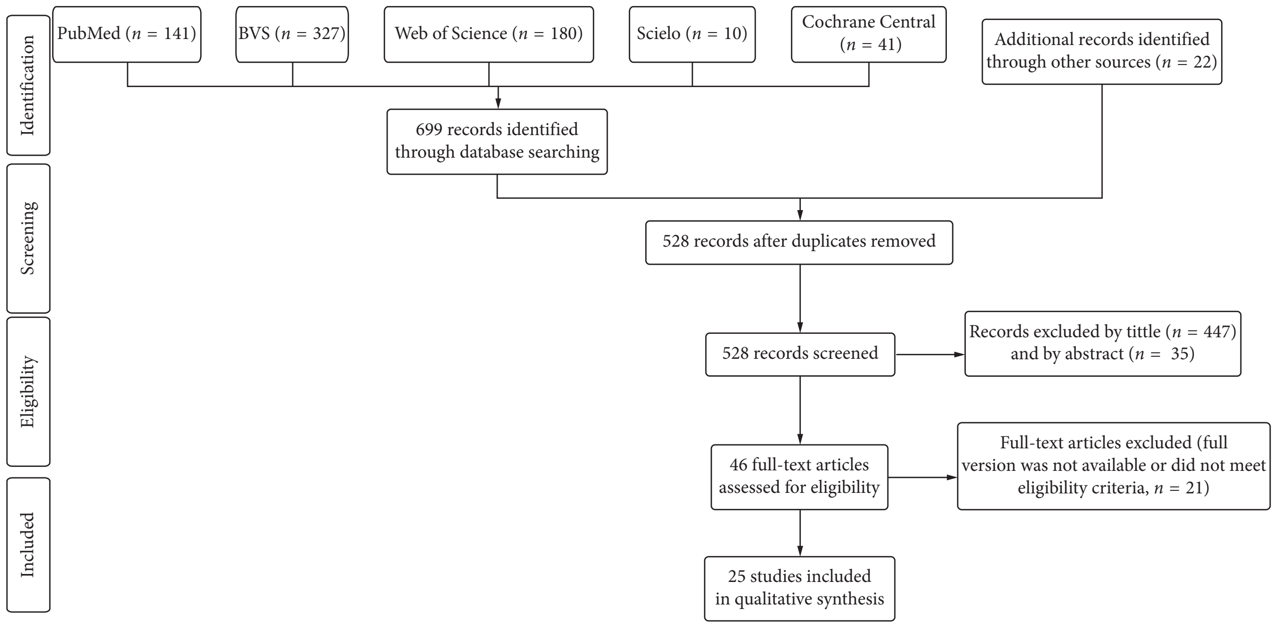

Figure 1: Flowchart of the search strategy of the published and unpublished literature and selection process (up to May 2019).

alone or combined with other interventions), motivational aspects, and adverse effects.

Finally, we observed the positive or negative effects of VR-based rehabilitation so as to perform considerations about the clinical practice based on statistical significance when $p < 0.05$.

3. Results

3.1. Search and Selection of Studies. We identified 721 titles from searches in all databases (i.e., published and unpublished) and coming from the screened list of references ($n = 2$) for VR-based rehabilitation studies in individuals with SCI. We also found 20 unpublished studies, but none of them met the eligibility criteria because full text was not available. One hundred ninety-three studies were excluded by duplicates, 447 by title, and 35 by abstract. After full-text screening, 21 studies were excluded. Figure 1 shows the selection process of studies identified and included, along with the reasons for exclusion. At the final stage, 25 studies were included in the qualitative analyses (Table 1).

3.2. Design of the Studies. From the 25 studies analyzed, 24 were prospective. Twelve of them used a pre-post design without control group. Thirteen were controlled in a parallel or crossover design (see Table 2). Only eleven studies used randomization to equally distribute the participants between groups of intervention. As to the blinding aspect, only two studies were double-blinded [10, 33], in which neither researchers nor participants knew how the sample was distributed within the groups. Three studies [18, 35, 39] were single-blinded, in which only researchers or participants knew group allocation (see Table 2). Another aspect that deserves attention is the sample size, which ranged from 6 to 54 participants. However, most of the studies had a small sample size and did not report statistical power associated with the observed effects.

The only nonprospective study was from Pozeg et al. [34], who used a 2-level factorial, randomized, repeated-measures design to investigate changes in perception of body ownership and neuropathic pain before and after experimental paradigms that combined virtual visual and tactile input.

3.3. VR Characteristics. The studies used either VR alone or VR paired with other therapy(ies). Fifteen applied treatment with only VR, while ten combined VR with occupational therapy and physiotherapy or conventional therapy. So, these studies show results about VR as an adjuvant treatment (see Table 2).

Despite different types of VR devices used in the studies (see Table 2), most of the protocols used the games to provide stimuli that encourage movements to improve motor function, balance, aerobic function, and pain. Some studies also used the walking control of an avatar in a virtual environment [17, 18], development of daily activities [10, 16], or training of driving skills [15, 29]. Both commercial and noncommercial VR devices were used in the studies.

The total number of VR rehabilitation sessions ranged from 1 to 36. The intervals between VR-based interventions also varied between studies, with a frequency ranging from 1 to 5 times a week (with sessions lasting from 1 to 90 minutes). However, some studies did not clearly report any of the following information: amount of sessions [15, 18, 21, 22, 26, 29, 39], duration [13, 15, 16, 20, 26, 29, 30], or frequency [15–18, 21, 26, 29] (see Table 2).

Finally, most of the studies reported results of the short-term effect of VR. Follow-up assessments to verify long-term effects were performed only in nine studies [13, 14, 16, 27, 31, 35–37, 39]. The follow-up time ranged

Table 1: General descriptive characteristics of included studies ($n = 25$).

	Time of publication
2000–2007	O'connor et al. [26]
2008–2012	Chen et al. [7]; Sayenko et al. [19]; Kowalczewski et al. [39]; Gil-Agudo et al. [28]; Sung et al. [29]
2013–2018	Villiger et al. [14]; Carlozzi et al. [15]; Gaffurini et al. [21]; Hasnan et al. [22]; Dimbwadyo-Terrer et al. [16]; D'Addio et al. [20]; Dimbwadyo-Terrer et al. [10]; Fizzotti et al. [30]; Villiger et al. [31]; Wall et al. [13]; Dimbwadyo-Terrer et al. [27]; Jordan et al. [18]; Roosink et al. [17]; An and Park [32]; Khurana et al. [33]; Pozeg et al. [34]; Prasad et al. [35]; van Dijsseldonk et al. [36]; Villiger et al. [37]
	Countries
Switzerland	Villiger et al. [14]; Villiger et al. [31]; Pozeg et al. [34]; Villiger et al. [37]
USA	Carlozzi et al. [15]; O'connor et al. [26]; Wall et al. [13]
Spain	Dimbwadyo-Terrer et al. [10]; Dimbwadyo-Terrer et al. [27]; Gil-Agudo et al. [28]; Jordan et al. [18]; Dimbwadyo-Terrer et al. [16]
Italy	Fizzotti et al. [30]; Gaffurini et al. [21]; D'Addio et al. [20]
Canada	Kowalczewski et al. [39]; Roosink et al. [17]
Japan	Sayenko et al. [19]
Sydney	Hasnan et al. [22]
Taiwan	Chen et al. [7]; Sung et al. [29]
Korea	An and Park [32]
India	Khurana et al. [33]; Prasad et al. [35]
Netherlands	van Dijsseldonk et al. [36]
	Type of VR
Immersive	Chen et al. [7]; Sayenko et al. [19]; Gil-Agudo et al. [28]; Carlozzi et al. [15]; Dimbwadyo-Terrer et al. [16]; Gaffurini et al. [21]; Hasnan et al. [22]; Villiger et al. [14]; D'Addio et al. [20]; Dimbwadyo-Terrer et al. [10]; Wall et al. [13]; Dimbwadyo-Terrer et al. [27]; Jordan et al. [18]; Roosink et al. [17]; Khurana et al. [33]; Pozeg et al. [34]; Prasad et al. [35]; van Dijsseldonk et al. [36]; Villiger et al. [37]
Nonimmersive	O'connor et al. [26]; Sung et al. [29]; Fizzotti et al. [30]; Villiger et al. [31]; Kowalczewski et al. [39]
Semi-immersive	An and Park [32]
	Objective of rehabilitation (domain)
Motor function	Kowalczewski et al. [39]; Gil-Agudo et al. [21]; Sung et al. [29]; Carlozzi et al. [15]; Dimbwadyo-Terrer et al. [16]; Villiger et al. [14]; Zimmerli et al. [38]; Dimbwadyo-Terrer et al. [10]; Fizzotti et al. [30]; Villiger et al. [31]; Wall et al. [13]; Dimbwadyo-Terrer et al. [27]; Roosink et al. [17]; An and Park [32]; Khurana et al. [33]; Prasad et al. [35]; Villiger et al. [37]; van Dijsseldonk et al. [36]
Aerobic function	O'connor et al. [26]; Gaffurini et al. [21]; Hasnan et al. [22]
Pain	Villiger et al. [14]; Jordan et al. [18]; Roosink et al. [17]; Pozeg et al. [34]
Balance	Sayenko et al. [19]; D'Addio et al. [20]; Wall et al. [13]; An and Park [32]; van Dijsseldonk et al. [36]; Villiger et al. [31]
Psychologic aspects	Chen et al. [7]; Pozeg et al. [34]; Villiger et al. [37]

between 4 and 30 weeks, and the pooled studies had a mean of 13.7 weeks of follow-up time (Table 2).

3.4. Outcome Measurements. Table 2 depicts all outcome measures used to assess the effects of the VR-based interventions. It is noteworthy that most of the studies used more than one instrument or scale. Moreover, many different scales were used to evaluate the motor function of lower or upper limbs, balance, and pain. Studies also quantified the independence and level of daily activities through the Spinal Cord Independence Measure Scale, Barthel Index, and Functional Independence Measure. On the other hand, all studies with quantification of the level of aerobic function in response to VR used similar measurements of the heart rate, oxygen consumption, and energy/metabolic expenditure. Five studies also used the quantitative variables such as the score or kinematic aspects of games or VR devices to evaluate the performance of SCI subjects in response to VR rehabilitation [15, 16, 28–30] (see Table 2).

Despite some studies have used the same outcome measurements, the variability in population characteristics, VR device aspects, and VR rehabilitation methods among the studies makes it very difficult and not relevant to perform a meta-analysis.

3.5. Participant Characteristics. The pooled sample of all studies included a total of 482 individuals with SCI. The dropout rate of participants was low, ranging from one to eight dropouts in nine studies. The majority of participants were men (73%), and the mean age was 47.6 ± 9.5 years.

The cervical level of injury was observed in 52% of the pooled sample, whereas 35% and 13% had thoracic and lumbar injuries, respectively. Incomplete lesions were more frequently observed (64.3% of the pooled sample). Regarding the ASIA impairment level, only 19 studies ($n = 227$ participants) presented complete data on this classification. In these studies, ASIA impairment level "A" was observed in 46% of the participants, whereas ASIA impairment levels "B," "C," and "D" were observed in 17%, 15%, and 22% of the participants, respectively. We highlight some studies did not present complete information about the cause of SCI (48%), level of injury (20%), type of SCI (16%), ASIA impairment level (24%), or time after injury (20%). In addition, two studies did not report most of the injury characteristics [20, 22].

Table 2: Methodological characteristics of included studies ($n = 25$).

Studies	Design	Sample/ dropout (n/n)	Type of therapy	VR characteristics	N/T of sessions	Sessions per week	Follow-up time (weeks)	Outcome measurements
Villiger et al. [14]	Prospective, before and after design, noncontrolled, nonrandomized, nonblinded	14/0	VR	VR-augmented therapy system (games)	16 or 20/ 45 min	4 or 5	12–16	Numeric Rating Scale, 10-Meter Walk Test, lower extremity motor score, Spinal Cord Independence Measure, Walking Index for Spinal Cord Injury II, Patients' Global Impression of Change, Berg Balance Scale
Carlozzi et al. [15]	Prospective, controlled, randomized, nonblinded	54/2	VR	Virtual reality driving simulator	—	—	—	Simulator Sickness Questionnaire and software driving simulator variables
Dimbwadyo-Terrer et al. [10]	Prospective, controlled, randomized, nonblinded	15/6	VR + occupational therapy and physiotherapy	CyberGlove® + 3D objects (reach and release)	10/30 min	2	—	Muscle Balance, Barthel Index scale for functional capacity, Spinal Cord Independence Measure, Nine-Hole Peg Test, Jebsen–Taylor Hand Function
Dimbwadyo-Terrer et al. [27]	Prospective, controlled, double-blinded, randomized	31/0	VR + occupational therapy and physiotherapy	VR system Toyra (games)	15/30 min	3	12	Functional Independence Measure, Spinal Cord Injury Independence Measure, Motricity Index, Manual Muscle Test, Quebec User Evaluation of Satisfaction 2.0
Fizzotti et al. [30]	Prospective, before and after design, noncontrolled, nonrandomized, nonblinded	15/0	VR + traditional neurologic exercises	Apple iPad 2 (games)	6–36*/—	2 or 3	—	Scores in the games and Trunk Recovery Scale
Gaffurini et al. [21]	Prospective, before and after design, noncontrolled, nonrandomized, nonblinded	10/0	VR	Wii Sports (games)	—/10 min	—	—	Oxygen consumption, pulmonary ventilation, heart rate, energy expenditure

Table 2: Continued.

Studies	Design	Sample/ dropout (n/n)	Type of therapy	VR characteristics	N/T of sessions	Sessions per week	Follow-up time (weeks)	Outcome measurements
Gil-Agudo et al. [21]	Prospective, controlled, randomized, nonblinded	10/0	VR + occupational therapy	Toyra system (games)	15/30 min	3	—	Variables of Toyra, Spinal Cord Injury Independence Measure, Nine-Hole Peg Test, Jebsen–Taylor Hand Function Test, Manual Muscle Test
Jordan et al. [18]	Prospective, controlled, single-blinded, randomized	35/0	VR	Visual illusory walking	—/20 min	—	—	Numeric Rating Scale and Quantitative Sensory Test
O'connor et al. [26]	Prospective, before and after design, noncontrolled, nonrandomized	10/0	VR	GAME^{Wheels} (games)	<3/ 3–12 min	—	—	Submaximal oxygen consumption, heart rate.
Roosink et al. [17]	Prospective, before and after design, noncontrolled, nonrandomized, nonblinded	9/0	VR	Visual illusory walking	2/90 min	NA	—	Motor imagery vividness, effort and speed, Basic Pain Data Set, Kinesthetic and Visual Imagery Questionnaire
Sayenko et al. [19]	Prospective, before and after design, noncontrolled, nonrandomized, nonblinded	6/0	VR	Game-based exercises	12/5 min	3	—	Force plate analysis system "Stabilan-01"
Villiger et al. [31]	Prospective, controlled, nonrandomized, nonblinded	9/0	VR	VR games	16 or 20/ 45 min	4 or 5	12–16	Longitudinal magnetic resonance
Wall et al. [13]	Prospective, before and after design, noncontrolled, nonrandomized	6/1	VR	Nintendo™ Wii Fit (games)	14/—	2	4	Timed Up and Go Test, 10-Meter Walk Test, 6-Minute Walk Test, Walking Index for Spinal Cord Injury II, Berg Balance Scale, Forward Functional Reach Test, Lateral Functional Reach Test, RAND SF-36
Hasnan et al. [22]	Prospective, before and after design, noncontrolled, nonrandomized, nonblinded	8/0	VR	Taxi Magic VR Trainer	—/32 or 48 min	2 or 3	—	Cardiorespiratory responses and power output

Table 2: Continued.

Studies	Design	Sample/ dropout (n/n)	Type of therapy	VR characteristics	N/T of sessions	Sessions per week	Follow-up time (weeks)	Outcome measurements
D'Addio et al. [20]	Prospective, controlled, randomized, nonblinded	30/0	VR + traditional physical therapy	Nintendo™ Wii Fit	36/—	3	—	Posturography (center of pressure data), Berg Balance Scale, Spinal Cord Independence Measure
Sung et al. [29]	Prospective, before and after design, noncontrolled, nonrandomized, nonblinded	12/0	VR	Driving simulator	—	—	—	Simulator performance measure
Dimbwadyo-Terrer et al. [16]	Prospective, controlled, nonrandomized, nonblinded	20/2	VR + occupational therapy and physiotherapy	Toyra system	12/—	4	12	Kinematic variables, Motor Index, Muscle Balance, Functional Independence Measure, Spinal Cord Independence Measure II, Barthel Index
Kowalczewski et al. [39]	Prospective, controlled, single-blinded, randomized	21/8	VR + conventional exercise therapy	ReJoyce Workstation	—/60 min	—	30	Action Research Arm Test and ReJoyce Automated Hand Function Test
Chen et al. [7]	Prospective, controlled, nonblinded, randomized	30/0	VR	EON Studio 4.0	—/—	—	—	Endurance, Borg's Rating-of-Perceived-Exertion Scale, Activation-Deactivation Adjective Check List, Simulator Sickness Questionnaire
An and Park [32]	Prospective, before and after design, noncontrolled, nonrandomized, nonblinded	10/0	VR	Interactive Rehabilitation and Exercise (IREX; GestureTek, Toronto, Canada)	18/30 min	3	—	Limit of stability, Berg Balance Scale, Timed Up and Go Test, Activities-Specific Balance Confidence Scale, Walking Index for Spinal Cord Injury II
Khurana et al. [33]	Prospective, before and after design, controlled, randomized, double-blinded	36/6	VR + conventional physiotherapy	Sony PlayStation 2 and EyeToy (Sony Computer Entertainment Inc., Beijing, China)	20/45 min	4	—	Modified Functional Reach Test, t-shirt test, self-care components of the Spinal Cord Independence Measure III

Table 2: Continued.

Studies	Design	Sample/ dropout (n/n)	Type of therapy	VR characteristics	N/T of sessions	Sessions per week	Follow-up time (weeks)	Outcome measurements
Pozeg et al. [34]	Single-session, cross-sectional, controlled, randomized, nonblinded	40/0	VR + tactile stimulation (synchronous and asynchronous)	Virtual leg illusion and full-body illusion	1/1 min	1	—	Sense of leg ownership (questionnaires) and perceived neuropathic pain (visual analogue scale pain ratings)
Prasad et al. [35]	Prospective, pilot, controlled, single-blinded, randomized	22/2	VR + conventional hand therapy and strength training	Wii Sports Resort game (Table Tennis, Swordplay Speed Slice, Bowling, and Cycling)	12/60 min	3	6	Capabilities of Upper Extremity Questionnaire, Box and Block Test for gross motor dexterity, Spinal Cord Independence Measure-Self Report, World Health Organization Quality of Life-BREF
van Dijsseldonk et al. [36]	Prospective, before and after design, noncontrolled, nonrandomized, nonblinded	17/2	VR	Gait Real-time Analysis Interactive Lab (GRAIL) training	12/60 min	2	20	Gait (spatiotemporal parameters and stability measures) and Activities-specific Balance Confidence (ABC) Scale
Villiger et al. [37]	Prospective, before and after design, noncontrolled, nonrandomized, nonblinded	12/1	VR	Mobile prototype of the YouKicker system (YouRehab AG, Schlieren, Switzerland) for the lower limbs	16–20/ 30–45 min	4-5	10–13	Muscle strength, balance, and mobility: lower extremity motor score, Berg Balance Scale, Timed Up and Go Test, 10-Meter Walk Test, 6-Minute Walk Test, Spinal Cord Independence Measure III, Walking Index for Spinal Cord Injury II, Motivational Scale and Global Impression of Change

Note. n or N, number; VR, virtual reality; T, time; NA, not applicable; —, information not available. *The number is not specified (ranges from min. to max.).

The mean time after injury was 5 years (pooled analysis), which corresponds to the chronic stage of SCI. Only three studies included participants in the subacute stage of SCI (from ~2 months to 1 year after injury) [29, 33, 35]. The detailed information and absolute numbers of each participant characteristic are shown in Table 3.

3.6. VR Effects. The main results concerning the effects of VR-based rehabilitation on individuals with SCI are summarized in Table 4. Overall, studies showed a statistically significant ($p < 0.05$) short-term improvement on motor function, aerobic performance, balance, pain, and psychological aspects. Only three studies reported effect sizes,

Table 3: Characteristics of patients with SCI included in the individual studies ($n = 25$).

Studies	Sample (n)	Age (years) (mean)	Sex		Cause of SCI		Level of SCI			Type of injury		AIS				Time after injury (years) (mean)
			F	M	T	NT	C	T	L	CO	IN	A	B	C	D	
Villiger et al. [14]	14	52.7	5	9	7	8	7	7	0	0	14	0	0	2	12	5.5
Carlozzi et al. [15]	52	37.9	7	45	42	10	—	—	—	—	—	—	—	—	—	8.9
Dimbwadyo-Terrer et al. [10]	9	49.5	2	7	6	3	1	8	0	8	1	8	0	0	1	5.41
Dimbwadyo-Terrer et al. [27]	31	37.4	9	22	29	2	31	0	0	21	10	21	10	0	0	4.9
Fizzotti et al. [30]	15	37	12	3	—	—	—	—	—	12	3	12	2	1	0	—
Gaffurini et al. [21]	10	40	0	10	—	—	2	8	0	10	0	10	0	0	0	—
Gil-Agudo et al. [21]	10	42.6	6	4	6	4	10	0	0	5	5	5	5	0	0	5
Jordan et al. [18]	15	47.5	2	6	7	1	4	4	0	5	3	5	2	1	0	16.1
O'connor et al. [26]	10	41.9	3	7	—	—	0	10	0	—	—	—	—	—	—	13.8
Roosink et al. [17]	9	53	2	7	9	0	3	5	1	6	3	6	1	2	0	6.7
Sayenko et al. [19]	6	41	1	5	—	—	2	4	0	0	6	0	0	4	2	9.16
Villiger et al. [31]	9	47.1	4	5	—	—	5	4	0	0	9	0	0	0	9	3.2
Wall et al. [13]	6	58.6	0	6	—	—	6	0	0	0	6	0	0	0	6	7.6
Hasnan et al. [22]	8	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
D'Addio et al. [20]	30	43	—	—	—	—	—	—	—	0	30	—	—	—	—	—
Sung et al. [29]	12	28.5	2	10	11	1	3	7	2	8	4	—	—	—	—	1.93
Dimbwadyo-Terrer et al. [16]	18	37.7	7	11	17	1	18	0	0	11	7	11	7	0	0	5.17
Kowalczewski et al. [39]	13	35.9	6	7	—	—	13	0	0	4	9	4	—	—	—	3.62
Chen et al. [7]	30	48.2	16	14	—	—	0	0	30	0	30	—	—	—	—	—
An and Park [32]	10	44.2	4	6	—	—	8	2	0	0	10	0	0	4	6	19.2
Khurana et al. [33]	30	29.6	2	28	30	0	0	30	0	—	—	—[*]	—	0	0	~0.25
Pozeg et al. [34]	20	47.3	2	18	18	2	0	—	—[**]	15	5	15	3	2	0	17.1
Prasad et al. [35]	20	28.3	1	21[#]	20	0	20	0	0	5	17[#]	5	9	4	4[#]	1.07[#]
van Dijsseldonk et al. [36]	15	59	4	11	—	—	—	—	—	0	15	0	0	13	2	3.5
Villiger et al. [37]	11	60	—	—	7	4	5	5	1	0	11	0	0	1	10	7.6

Note. n, number; SCI, spinal cord injury; AIS, American Spinal Injury Association (ASIA) Impairment Scale; —, information not available. [*]Participants were classified as A or B in AIS. [**]Lesions ranged from high thoracic (T2) to lumbar (L2). [#]Data prior to dropout of 2 participants.

which ranged from low to large treatment effects (Cohen's d values ranged from 0.41 to 1.95 and eta-squared values from 0.11 to 0.95) [33, 34, 39]. In addition, statistically significant long-term effects were observed on motor function [13, 14, 16, 31, 32, 35–37, 39], balance [14, 31, 35, 36], and pain [14, 34].

Interesting subjective results about positive VR motivational aspects such as better mood [14], high enjoyment [13, 14, 26], and improvements on satisfaction [27, 30] were reported in some studies.

3.7. VR Adverse Effects. Most of the studies did not directly report any adverse effect after VR therapy (88%). Only a reduced number of participants had a transient musculoskeletal pain ($n = 2$) [14, 17], physical fatigue ($n = 4$), and difficulties to maintain attention ($n = 2$) [17] because of the increased use of limbs during the sessions of therapy. Moreover, Carlozzi et al. [15] reported acute simulator sickness during the protocol in seven participants.

3.8. Risk of Bias. Risk of bias assessment showed that most of the analyzed studies involving the investigation of VR effects after SCI presented some level of potential bias. Only seven studies presented a low risk of bias associated with an excellent or good level of evidence (see Table 5).

3.9. Limitations of the Studies. All studies had design limitations (see Risk of Bias) and hence restriction on internal or external validity. Most of the studies did not perform randomization [13, 14, 16, 17, 19, 20, 22, 26, 29–32, 36, 37] or blinding [10, 13–17, 19, 22, 26, 28–32, 34, 36, 37].

The small and heterogeneous samples of SCI subjects with a wide range of injury levels, cause of injury, and time after injury were frequently observed in all studies. Therefore, the results of the studies included in this review cannot be generalized for the whole population with SCI, which represents an external validity limitation [40].

When accessible, the power of the statistical tests was low because of the small sample size used in most of the studies [41, 42]. In addition, only three studies included in this review reported effect sizes [33, 34, 39], an important estimator of clinical significance [43, 44].

Another limitation was the incomplete description of VR protocol characteristics (number of sessions, treatment frequency, duration, and training activities). Furthermore, a large variety of outcome measurements were

Table 4: Synthesis of the VR short-term effects by domain (motor function, aerobic function, pain, balance, or psychologic aspects) of statistically significant or nonsignificant results of individual studies ($n = 25$).

Studies	Statistically significant results ($p < 0.05$)					Statistically nonsignificant results				
	Motor function	Aerobic function	Pain	Balance	Psychologic aspects	Motor function	Aerobic function	Pain	Balance	Psychologic aspects
Villiger et al. [14]	✓		✓	✓						
Carlozzi et al. [15]	✓									
Dimbwadyo-Terrer et al. [10]						✓				
Dimbwadyo-Terrer et al. [27]						✓				
Fizzotti et al. [30]	✓									
Gaffurini et al. [21]		✓								
Gil-Agudo et al. [28]	✓								✓	
Jordan et al. [18]			✓							
O'connor et al. [26]		✓								
Roosink et al. [17]	✓							✓		
Sayenko et al. [19]				✓						
Villiger et al. [31]	✓			✓						
Wall et al. [13]	✓			✓						
Hasnan et al. [22]		✓								
D'Addio et al. [20]				✓						
Sung et al. [29]	✓									
Dimbwadyo-Terrer et al. [16]	✓*					✓			✓	
Kowalczewski et al. [39]	✓									
Chen et al. [7]					✓					
An and Park [32]	✓**			✓					✓	
Khurana et al. [33]	✓***					✓				
Pozeg et al. [34]			✓#		✓			✓		
Prasad et al. [35]	✓									
van Dijsseldonk et al. [36]	✓##			✓		✓				
Villiger et al. [37]	✓###			✓	✓	✓				

Note. *The study had statistically significant results only in one functional aspect measured. **Overall limits of stability significantly improved, but directional forward and backward limits of stability did not differ significantly after therapy. ***Modified Functional Reach Test (mFRT) and self-care components of the Spinal Cord Independence Measure III (SCIM III) significantly improved, but t-shirt test did not differ significantly after therapy. #Significant pain reduction when the lower back was stimulated synchronously with the virtual legs but no significant reductions for other conditions. ##Significant effects on 4 out of 9 spatiotemporal and stability measures of gait. ###Significant improvements on LEMS, BBS, and TUG, but no significant changes on 6minWT, SCIM III, and WISC-III.

reported among the studies, which preclude objective conclusions on specific aspects to be drawn.

4. Discussion

To the best of our knowledge, this systematic review is the first study aimed at investigating the effects of immersive or nonimmersive VR-based rehabilitation after SCI. Therefore, the present review provides a systematic overview and important guidelines for future research on VR-based rehabilitation for SCI individuals.

4.1. Summary of Main Results, Overall Completeness, and Applicability of Evidence. We included twenty-five studies involving a total sample of 482 subjects with SCI. The currently findings describe eighteen years of VR-based rehabilitation after SCI as an emerging research area. Based on the present results, reviewed studies applied VR therapy to (1) improve motor function or motor skills, (2) restore balance, (3) improve aerobic function, (4) reduce the pain level, or (5) provide better psychological/motivational aspects.

Seven of the studies presented an excellent or good level of evidence because they were controlled randomized clinical trials with satisfactory sample size [15, 18, 27, 28, 33, 35, 39] aimed to use immersive [15, 18, 27, 28, 33, 35] or nonimmersive VR [39] to improve upper limbs' motor function or reduce the pain level [18]. Six of these studies reported statistically significant positive effects of VR-based techniques associated with enhanced motor function [15, 28, 33, 35, 39] or reduction in pain levels [18].

Although high-quality evidence was limited, other statistically significant results were observed on aerobic function [21, 22, 26], balance [1, 13, 14, 19, 20, 31, 32, 37], and psychological aspects [7, 34, 37]. However, most of these studies presented important methodological limitations, and hence, the associated results should be interpreted with

Table 5: PEDro scale scores, assessment of the level of evidence, and risk of bias of individuals studies ($n = 25$).

Studies	PEDro scale score	Level of evidence	Risk of bias
Villiger et al. [14]	5	Fair	High
Carlozzi et al. [15]	6	Good	Low
Dimbwadyo-Terrer et al. [10]	5	Fair	High
Dimbwadyo-Terrer et al. [27]	10	Excellent	Low
Fizzotti et al. [30]	4	Fair	High
Gaffurini et al. [21]	5	Fair	High
Gil-Agudo et al. [28]	6	Good	Low
Jordan et al. [18]	7	Good	Low
O'connor et al. [26]	3	Poor	High
Roosink et al. [17]	5	Fair	High
Sayenko et al. [19]	4	Fair	High
Villiger et al. [31]	4	Fair	High
Wall et al. [13]	5	Fair	High
Hasnan et al. [22]	4	Fair	High
D'Addio et al. [20]	4	Fair	High
Sung et al. [29]	4	Fair	High
Dimbwadyo-Terrer et al. [16]	5	Fair	High
Kowalczewski et al. [39]	7	Good	Low
Chih-Hung et al. (2009)	5	Fair	High
An and Park [32]	4	Fair	High
Khurana et al. [33]	9	Excellent	Low
Pozeg et al. [34]	5	Fair	High
Prasad et al. [35]	6	Good	Low
van Dijsseldonk et al. [36]	4	Fair	High
Villiger et al. [37]	4	Fair	High

caution. Several studies also reported subjective positive results on motivational aspects of VR treatment [14, 27, 30, 39]. Indeed, previous studies have been considering VR as an interactive tool that provides a motivational environment associated with high engagement, which favors adherence to treatment [13, 45]. This is especially important when rehabilitation require repetitive movements or extensive protocols [46, 47].

Improved aerobic function and physical activity have been reported as beneficial effects of VR [21, 22, 26] on SCI. However, as few studies were aimed at assessing these aspects, the body of literature would certainly benefit from further investigations about the effects of VR-based protocols on aerobic performance, as VR protocols can be performed in safe and comfortable environments [48], besides allowing the trainers/therapists to set up the level of physical activity according to the physical fitness or functional limitation of the patient.

Most of the studies with adequate experimental design and positive effects on motor function investigated VR-based protocols paired with conventional rehabilitation [27, 28, 39]. Indeed, some ethical issues may arise regarding clinical trials designed to investigate isolated effects of a single (and sometimes novel) therapy. Such an investigation would require control groups to receive no treatment at all (even for conditions in which the current evidence points to effective treatments options), which might be considered not ethically appropriate [49]. Therefore, the present review suggests that VR might be an important adjunct tool for conventional therapy [50–54], considering benefits such as the wide variety of VR-based protocols that might be designed, the potential transferring of functional activities performed in the virtual environment to activities of daily living [55], the high adaptability of VR protocols according to the patient's limitations/preferences, and the positive effect of feedback during training on VR-based settings [10, 55, 56]. Additionally, some studies found positive effects of VR alone on motor function [13, 14, 17, 29, 31, 32, 36, 37], balance [13, 14, 19, 20, 31, 36, 37], aerobic function [21, 22, 26], and pain level [14, 34]. Thus, the present study cannot conclude whether VR-based rehabilitation is more effective than conventional therapy. Nevertheless, the positive effects reported provide the support to recommend the use of VR as an adjunct to conventional therapies in clinical practice.

Both commercial and noncommercial VR devices were used in the revised studies. The frequent use of noncommercial devices (i.e., customized and specifically built for the rehabilitation purposes at hand) is probably due to the requirement of contemplating the specific needs of the patients as a function of the level of their physical limitations after SCI [55]. Further studies are needed to determine whether there are different rehabilitation outcomes related to the use of specific types of VR devices.

Despite the large differences observed among the VR protocols used in the studies, both immersive and nonimmersive environments were able to induce the performance of a wide range of specific and global functional movements while promoting motivation to perform the activities [9, 50, 55, 57] and a safe rehabilitation setting with no adverse effects [9, 50, 55]. Taken together with the beneficial effects of the VR commented above, these aspects increase the potential use of VR as a rehabilitation tool after SCI.

4.2. Heterogeneity. The present review found a great level of heterogeneity, also reported in other VR systematic reviews in neurological disorders [9, 50, 54, 55]. Overall, the studies presented a wide range of VR characteristics and protocols. So, it remains unclear which device elements, VR type, number/frequency of sessions, and duration of VR-based rehabilitation are essential to induce optimal recovery after SCI. In addition, divergent outcome measurements were used in the studies reviewed. Similarly, heterogeneity in the injury level, lesion cause, injury type, and time after injury was commonly observed in the studies' samples. Indeed, SCI is a heterogeneous condition in nature, with nonlinear recovery [58, 59], which makes it difficult to run studies with homogeneous samples so as to establish the specific characteristics associated with better clinical outcomes. However, we observed that all studies applied VR-based rehabilitation in subjects with chronic SCI. So, the conclusion drawn in the present study can only be applied to individuals with chronic SCI, as none of the included studies assessed acute and subacute stages of SCI.

4.3. Quality of the Evidence. Despite the increased use of VR technology in neurorehabilitation study protocols [38, 54], it is not possible to draw strong conclusions about the efficacy of VR-based rehabilitation for patients with SCI because of the overall lack of methodological quality and statistical power observed in the current body of literature. Unfortunately, only seven studies included in the present systematic review had an excellent or good level of evidence (low risk of bias) (see Table 5). The same issue has been observed in other systematic reviews involving VR [9, 50, 54, 55].

The lack of adequate study design (randomized, controlled, and blinded studies), powered sample size, and absence of effect size report are the most important limitations of the studies reviewed here. Putative flaws in study design are associated with increased risk for selection, performance, or detection bias, thereby compromising internal validity [42, 60, 61]. Similarly, the lack of a control group in pre-post designs may have compromised the evidence of the treatment effect [62] and does not allow conclusions to be drawn about the nature of the observed effects [56]. In addition, studies with low statistical power and small samples might involve type II errors [41, 63] and hence low certainty of the detection of treatment effects.

Furthermore, some of the revised studies did not include information about the characteristics of VR rehabilitation protocols, reducing the possibility of replication by future studies. Future studies shall include appropriate description of training duration, frequency by week, and duration of sessions and detailed information about the virtual activities so as to allow putative associations between the observed effects and the specific training characteristics.

The limitations found in the revised studies preclude the detailed analysis of the effects of VR on SCI, as well as the grouping of results in a meta-analysis. Future studies should avoid methodological limitations and should use and report adequate statistic power so as to identify the effects of VR rehabilitation and ensure robustness for proper quantitative data analysis (meta-analysis).

4.4. Future Research. The present systematic review has important implications for future research. First, studies with participants in the acute and subacute stages of SCI are warranted. These phases are associated with greater potential for recovery and plasticity as compared to the chronic stage [2, 58] and hence might comprise an interesting scenario for VR-based rehabilitation. In this vein, future studies should be able to determine the VR applicability according to the injury level and comorbidities. Second, studies should explore the ideal VR characteristics related to success of rehabilitation and the effect duration (short-term and long-term effects). Third, studies should use the standardized outcome measurements. Fourth, statistical powered studies with adequate methods and design are warranted in order to reduce bias and provide reliable results. Finally, we highlighted the importance of the effect size report and detailed description of the VR protocol in future studies.

4.5. Potential Biases and Limitations in the Review Process. There are several limitations of this systematic review that must be pointed out: (1) although we conducted an extensive search in the published and unpublished literature, some relevant studies might not have been identified, (2) it is possible that publication biases exist in this field of research, (3) it was not possible to perform a meta-analysis because of heterogeneity of outcome measures and VR protocols, and (4) our findings are based on studies with a wide variety of methodological qualities and should therefore be interpreted with caution in terms of generalizability.

4.6. Agreements and Disagreements with Other Studies or Reviews. To our knowledge, no systematic review addressing the effectiveness of VR-based rehabilitation in subjects with SCI has been performed. However, we identified some current reviews on other neurologic disorders, such as stroke [50, 51, 54, 55], Parkinson's disease [55], and cerebral palsy [9].

Overall, these reviews reported positive effects of VR therapy on gait [50, 51, 54, 55], balance [50, 54], and motor function [9, 47, 52, 54]. The systematic review by Malloy and Milling [64] suggests beneficial effects of VR to reduce the pain level in a variety of pathological conditions. Therefore, VR emerges as a promising tool to improve the performance of daily activities and quality of life [55, 65].

Some of the studies report positive results when VR is used as an adjuvant therapy (i.e., VR paired with conventional therapy) [47, 50–52, 54], whereas other studies suggest that VR and conventional therapy may have similar effects [9, 55]. With the present review of the literature, it is not possible to conclude whether VR-based therapy in association with conventional therapy might provide more significant benefits for patients with SCI.

5. Conclusion

Overall, the studies that were included in the present systematic review reported a beneficial effect of VR therapy alone or VR associated with conventional rehabilitation. Initial evidence of VR to improve motor function, motor skills, balance, and aerobic function and to reduce the pain level was observed. Thus, our findings provide important implications for the VR-based rehabilitation research field. However, further studies should explore VR effects on SCI subjects considering the injury stage, level of lesion, and comorbidities. In addition, the related effects in response to VR characteristics and their specific applications should be studied. Similarly, evidence is required to provide information about VR long-term effects. Finally, high-quality studies are needed to provide robust guidelines and to draw conclusions about the potential benefits of VR before its integration into rehabilitation protocols for subjects with SCI.

Conflicts of Interest

The authors declare no conflicts of interest.

Authors' Contributions

All authors conceived and designed the systematic review. AA and JN collected and extracted data of the studies. All authors critically assessed the methodological quality and risk of bias and summarized the results. AA and JN drafted the initial version of the manuscript. FM and CM critically revised the manuscript. All authors read and approved the final version of the manuscript.

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Research Article

Wearable Technology for Detecting Significant Moments in Individuals with Dementia

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The detection of significant moments can support the care of individuals with dementia by making visible what is most meaningful to them and maintaining a sense of interpersonal connection. We present a novel intelligent assistive technology (IAT) for the detection of significant moments based on patterns of physiological signal changes in individuals with dementia and their caregivers. The parameters of the IAT are tailored to each individual's idiosyncratic physiological response patterns through an iterative process of incorporating subjective feedback on videos extracted from candidate significant moments identified through the IAT algorithm. The IAT was tested on three dyads (individual with dementia and their primary caregiver) during an eight-week movement program. Upon completion of the program, the IAT identified distinct, personal characteristics of physiological responsiveness in each participant. Tailored algorithms could detect moments of significance experienced by either member of the dyad with an agreement with subjective reports of 70%. These moments were constituted by both physical and emotional significances (e.g., experiences of pain or anxiety) and interpersonal significance (e.g., moments of heighted connection). We provide a freely available MATLAB toolbox with the IAT software in hopes that the assistive technology community can benefit from and contribute to these tools for understanding the subjective experiences of individuals with dementia.

1. Introduction

The prevalence of dementia is expected to dramatically increase in the coming decades: in Canada, it is anticipated that the number of individuals over the age of 65 living with dementia will double within the next 20 years [1]. Dementia is a set of symptoms caused by disorders and diseases affecting the brain, including Alzheimer's disease and vascular dementia. Individuals with dementia typically experience memory loss, difficulties with problem-solving, language and orientation, and altered mood and behavior. These symptoms diminish the individual's ability to perform activities of daily living and disrupt their relationships, often reducing their ability to participate in society and requiring significant support in their daily lives. At present, hospitals in Canada already provide full-time care to approximately 51,000 individuals with dementia [1], and almost half a million more are cared for by family and informal caregivers. The indirect annual cost of caring for those with dementia is conservatively estimated at $1.2 billion; this estimate is projected to double by 2031 [1].

In response to the escalating demands of caring for persons with dementia, intelligent assistive technologies (IATs) for this population have proliferated. IATs have been developed for nearly every aspect of daily living and range from distributed systems (e.g., smart homes and integrated sensor systems), personal robots (e.g., socially/physically assistive), mobility and rehabilitation aids (e.g., powered wheelchairs and electronic canes), handheld/multimedia devices (e.g., smart phones, personal digital assistants (PDAs), and tablets), software applications (mobile or web-based apps), voice-prompting systems [2], wearable devices (e.g., smartwatches and e-textiles), and human-machine interfaces (HMIs) [3]. Of particular note is the growth in wearable technologies for this population, which are primarily used to monitor the well-being and safety of individuals with dementia. Wearables have been employed to track sleep and toileting patterns [4], to aid memory retrieval [5], and to aid way finding and navigation [6–9].

While the majority of IATs for individuals with dementia have focused on maintaining and improving their functional and cognitive abilities, there has been minimal focus on tracking the subjective experience of individuals with dementia. Understanding the subjective emotional and mental experience of an individual with dementia has important implications for the quality of life of these individuals and their caregivers (familial and professional). Insight into the significant events for individuals with dementia can make visible what is meaningful to them [10] and can, thus, empower caregivers to understand and ameliorate care decisions based on what matters to them [11], as well as intervene before a minor annoyance or frustration can build into an outburst or an aggressive behavior. Moreover, the communication of meaning and important moments is critical to maintaining a sense of connection and thus to preserving relationships between individuals with dementia and their caregivers [12]. In this paper, we describe a novel, wearable IAT that can track and detect moments of significance for individuals with dementia. As dementia is associated with progressively declining cognitive and motor abilities, this IAT focuses upon detecting significant moments from their physiological signals.

The feasibility of detecting significant mental and emotional reactions from changes in physiological signals has long been established [13]. Physiological signals have been used to provide insight into an individual's significant reactions in fields such as polygraphy [14] and biofeedback [15] for decades. Additionally, physiological signals such as electrodermal activity (EDA), heart rate, and skin temperature are amenable to being recorded from noninvasive, wearable sensors. The IAT presented in this paper records physiological signals from a device worn on the hand and uses a custom software to detect individual-specific moments of significance from changes in their physiological patterns. We demonstrate that this IAT is able to accurately detect moments of physiological significance and moments experienced as significant interpersonal interactions in individuals with dementia and their caregivers. Furthermore, we make the algorithms and software freely available through a Matlab toolbox, which can be effectively used to detect moments of significance from patterns of physiological signals recorded from wearable sensors.

2. Materials and Methods

2.1. Description of Assistive Technology

2.1.1. Hardware. Autonomic nervous system (ANS) signal data were collected from a wearable device called the Triple Point Sensor (TPS) (Thought Technology Ltd. ©). The TPS was designed to be worn on the fingertip by securing it with a loose elastic or Velcro strap. Three physiological signals were recorded at a sampling frequency of 15 Hz: (1) electrodermal activity (EDA); (2) skin temperature; and (3) heart rate (HR). Signals were transmitted via Bluetooth to a paired Android phone, which stored the data in a custom database.

2.1.2. Software. Custom software, called *Events Finder*, a freely available MATLAB toolbox (https://github.com/BIAPT/Events-Finder), was designed to detect salient moments from individual-specific physiological signatures. Broadly, the software detected characteristics from the ANS signals that are known a priori to be associated with changes in emotional state. Analysis of the EDA signal focused on the detection of electrodermal reactions (EDRs)—transient increases of 0.05 μs or more within 10 seconds, which have been associated with heightened emotional arousal [16, 17]. Skin temperature analysis focused on detecting changes between vasoconstrictor and vasodilatory responses [18], and the heart rate was monitored for unusual patterns of acceleration and deceleration [19]. The software consists of three components: (a) preprocessing; (b) signal quality assessment; (c) event detection, which are detailed in the sections below.

(1) Preprocessing. Each of the three ANS signals was preprocessed to remove nonphysiological artifacts. Filters were chosen to be compatible with real-time processing, to ensure that the final software had translational potential for real-world use. First, missing datapoints or datapoints that resulted from hardware error were identified by flagging samples with (1) a value of 0 and (2) whose value was greater or less than three standard deviations from the average of the preceding second of data. These datapoints were replaced by interpolation using a 1-D median filter (EDA filter order $n = 75$; skin temperature filter order $n = 1$). Second, all signals were sent to a moving average filter with a non-overlapping, 0.5-second window; the resulting smoothed data had a sampling frequency of 2 Hz. Third, the signals were sent to a modality-specific filter that enhanced particular features associated with a salient reaction. To minimize jitter and lag in the EDA signal, a *one Euro* filter was applied with parameters mincutoff = 50 and beta = 4 [20]. An exponential decay filter was applied to the skin temperature signal to remove the high-frequency noise inherent in the signal (smoothing parameter $p = 0.95$). Finally, the cubic smoothing spline function from MATLAB was applied to the heart rate data (smoothing parameter $p = 0.001$). The effects of these modality-specific filters on their respective physiological signals are illustrated in Figure 1.

(2) Signal Quality Assessment. After preprocessing, a signal quality index (SQI) algorithm was applied on a sliding window of 0.5 seconds across all three physiological signals. The index ranged from $\mathrm{SQI}_x = 1$, when data from physiological signal x was physiologically valid, to $\mathrm{SQI}_x = 0$, when data from physiological signal x was wholly contaminated by noise resulting from the actions of the user, such as shifting the sensor's position on the hand, scratching around the

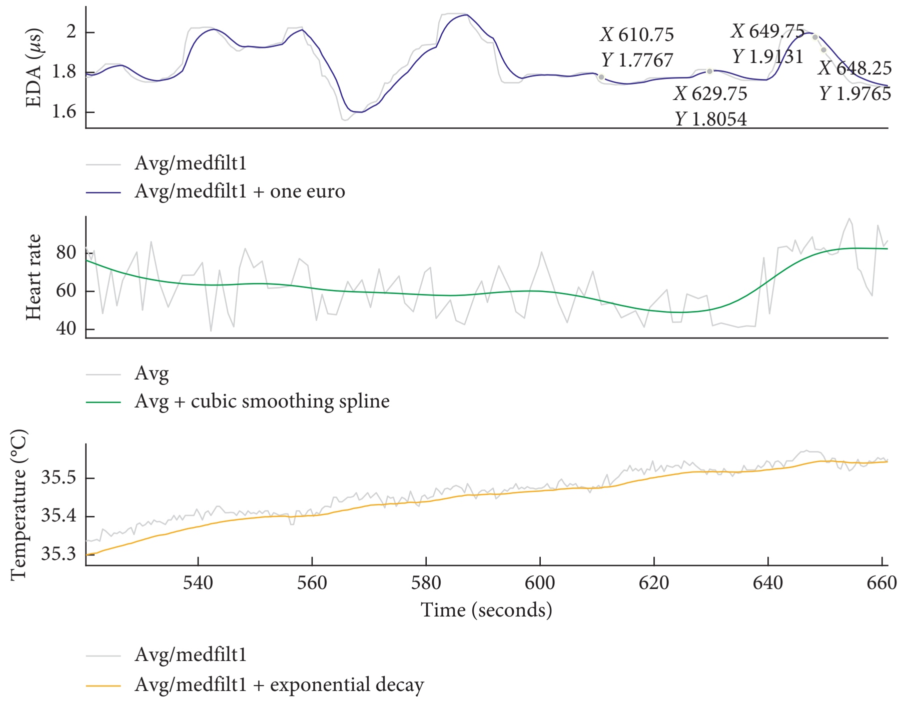

Figure 1: Preprocessing of autonomic nervous system signals. Modality-specific filters were applied to each physiological signal to enhance salient features.

sensor, and applying pressure to the sensor. EDA signals were assigned a lower SQI_{EDA} when the rate of change exceeded physiological possibility, when it registered no signal for 25 seconds or longer, or when the absolute value exceeded the bounds of a normal physiological range. Skin temperature signals were assigned a lower SQI_{temp} when it registered no signal for 25 seconds or longer, or when values were less than 15 degrees Celsius (e.g., below normal physiological range). The specific parameters used to generate SQI_x are reported in Table 1. Upon completion of a data recording session, the mean (μ) and standard deviation (σ) of the SQI_x for each individual physiological signal were calculated. Subsequently, a binary time series (SQI_{all}) of non-overlapping 0.5 second steps was created, where $SQI\ (t)_{all} = 0$ if $SQI\ (t)_{EDA} < \mu\ (SQI_{EDA}) - \sigma\ (SQI_{EDA})$ or $SQI\ (t)_{temp} < \mu\ (SQI_{temp}) - \sigma\ (SQI_{temp})$, and $SQI\ (t)_{all} = 1$ otherwise. Any datapoint where $SQI\ (t)_{all} = 0$ was not considered in the subsequent event detection algorithm.

(c) Physiological Event Detection. The objective of this subcomponent was to detect events in the cleaned, high-quality data that corresponded to a salient moment for the user. The dominant physiological modality that manifests emotional processing varies from individual to individual [21, 22], and the characteristics of the changes within this dominant modality also vary according to multiple factors, including sex, age, and time of day [23]. Thus, in broad terms, event detection required (1) tuning the parameters for detecting specific features within each signal and (2) varying the relative weight of contribution of each of the three physiological signals.

Signal-specific feature detection consisted of a set of adjustable parameters for each physiological modality. Within the EDA signal, electrodermal reactions (EDRs) are associated with an orientation response and heightened emotional arousal [16, 17]. Canonically, an EDR consists of an increase greater or equal to 0.05 μS within a 10-second interval [16]. Tuning the event detector to capture EDRs for each individual required varying (1) t_{EDR}, defined as the time interval within which to search for an EDR and (2) A_{EDR}, defined as the minimum amplitude (μs) increase across t_{EDR} that was considered to be an EDR. Heart rate has natural patterns of acceleration and deceleration, driven by factors such as respiratory sinus arrhythmia [19, 24]. Salient events were detected at time points where heart rate acceleration and deceleration varied outside of these baseline patterns. Acceleration and deceleration patterns were tracked using the *find_peaks* algorithm in MATLAB. Tuning the event detector to capture significant changes from these patterns required varying *minPeakProminence*, the threshold for which one peak must deviate with respect to height and location from the other peaks in the heart rate time series to be flagged as an event. Fingertip temperature changes associated with salient responses are driven by transient changes in the cutaneous microcirculation [18, 25]. Vasoconstriction and vasodilatory responses manifest as changes between the rate of cooling and heating in the fingertip. The event detector for fingertip temperature was tuned by varying (1) t_{temp}, defined as the time interval within which to consider trends in temperature and (2) $T_{max} - T_{min}$, defined as the difference between the maximum and minimum temperature (°C) within the interval t_{temp}.

Table 1: Creating an artifact-detection algorithm to score the signal quality of physiological data.

ANS signal	Feature extracted	Threshold	SQI
Electrodermal activity	First derivative of signal over 15 s sliding window, incremented in 0.5 s intervals	Positive or negative change >3 μs	0.4
	Flatness over 25 s sliding window, incremented in 0.5 s intervals	Difference between two consecutive points ≤0.001 μs	0.1
	Out of normal physiological range	≤0.02 μs	0
		>20 μs	0.65
		>30 μs	0
Skin temperature	Flatness over 25 s sliding window, incremented in 0.5 s intervals	Difference between two consecutive points ≤0.0001°C	0.5
	Out of normal physiological range	<15°C	0.5

Applying the above rules for detecting features in each physiological modality yielded three time series, with a step size of 0.5 seconds, and values corresponding to the strength of each feature extracted from the physiological data: EDR (t), Δtemp (t), and $\mathrm{HR}_{\mathrm{var}}$ (t). Subsequently, the three physiological modalities were assigned a weighting factor to scale the relative contribution of each signal to the overall score S, indicating the magnitude of change in the weighted physiological features.

$$S = a\mathrm{EDR}(t) + b\Delta\mathrm{temp}(t) + c\mathrm{HR}_{\mathrm{var}}(t), \qquad (1)$$

where $0 \leq a, b, c \leq 1$. All three weighting factors (a, b, and c) where initialized to 1 and adjusted in an iterative fashion as described in Section 2.3.

2.2. Study Design

2.2.1. Participants. Participants were recruited from a nonprofit organization that provided a variety of services to the community for individuals with dementia and their caregivers. The assistive technology was calibrated and tested on three dyads, each dyad consisting of an individual with dementia and his/her primary caregiver. Pseudonyms and the relationship between members of the dyad are listed in Table 2. Written consent was obtained from all caregivers for themselves and for the individual with dementia—who also provided written assent—after a careful discussion of risks and benefits. This study was approved by the Institutional Review Board of McGill University (A06-B25-17B).

2.2.2. Data Collection. Participants engaged in an 8-week movement-based program and ran over the course of 15 weeks. The program was held at the nonprofit organization—a familiar environment that was chosen to support the engagement and self-expression of the individuals with dementia [26]. Prior to the beginning of each session, each member of the dyad was outfitted with the assistive technology. Participants were given the choice of securing the sensor onto their fingertip or onto the palm of their hand based on comfort and ease of movement. Sensors were secured with a Velcro band. Collection of ANS data from the sensors was initiated from a paired Android smartphone prior to the movement session by a research assistant. Sessions were also video and audio recorded by using a video camera mounted near the ceiling; audiovisual data were timestamped and synchronized with the ANS data from each participant.

Table 2: Participant description.

Participant with dementia	Caregiver	Dyad
Mary	Liam, spouse	1
Elisa	Giselle, daughter	2
Irene	Sophie, daughter	3

Following each 45-minute movement session, ANS data from each participant were run through the *Events Finder* software described above. Events with the highest S score were selected, and the video recording was spliced 10 seconds prior to and 10 seconds following each event, resulting in 10-second–20-second clips of physiologically triggered salient moments for each dyad.

After selected sessions, these 20-second video clips were presented to the respective dyad on a laptop computer. Dyads were interviewed to assess whether or not the salient moments detected by the algorithm corresponded to a subjective recollection of a significant experience. Significant experiences were defined as events [10] or heightened moments that stood out and/or were memorable (e.g., see also [27]). A research assistant guided their reflection about the moments captured in the video using the following questions:

(i) What was happening at this point during the session? Was this in relation to your partner?

(ii) Did this moment stand out to you from the ordinary flow of the session? If yes/no, why?

(iii) Are there moments we did not go over where you felt an especially strong sense of connection or disconnection to your partner?

Participant responses were audio recorded and used to adjust the parameters of the event detection algorithm.

2.3. Personalization of the Assistive Technology.

Prior to the first movement session, all parameters of the *Event Finder* algorithm were set to default values. All physiological modalities were equally weighted (i.e., $a = b = c = 1$). Default parameters for feature detection within each physiological signal were empirically derived from preliminary data: electrodermal reactions were initiated as increased in 0.05 μs across 10 seconds (i.e., $t_{EDR} = 10$; $A_{EDR} = 0.05$); heart rate acceleration and deceleration were flagged at *minPeakProminence* = 10 bpm; skin temperature trends were considered to change if there was a change of 0.01°C across 10 seconds (i.e., $T_{max} - T_{min} = 0.01$; $t_{temp} = 10$).

After each of the first four sessions, a research assistant reviewed the physiological data of each participant to individually tailor each of the parameters to match the particular idiosyncratic patterns of his/her physiological responsiveness. First, the audiovisual recording was observed in full for any moments that stood out from the ordinary flow of the session. Time points associated with these moments were flagged on the synchronized physiological signal recording. For each of these time points, a 10-second epoch surrounding each event was segmented, and EDR (t), Δtemp (t), and HR_{var} (t) were calculated. The parameter value (Table 1) associated with each feature was calculated and used to replace the default parameters. Subsequently, the *Event Finder* algorithm was re-run, and the accuracy of detection of significant moments was calculated. The parameter set that produced the highest accuracy was retained for the next movement session.

At the end of some of the last four sessions, the algorithm parameters were iteratively adjusted to align with participants' subjective report of the experience associated with detected physiological responses. Participants were presented with 20-second video clips containing salient moments detected by the personalized *Event Finder* algorithm. Their responses of whether or not the video detected a significant event were used to iterate on the parameters to decrease the overall score *S* of the nonsignificant moments. If participants reported significant moments that were not detected by the algorithm, parameters were adjusted to increase the overall score *S* of these moments. The algorithm with the adjusted parameters was used to detect significant moments in the participant's next movement session.

2.4. Data Analysis. For all sessions where participants provided feedback about the salience of the moments identified by *Event Finder*, two research assistants independently reviewed the video and interview data to assess the performance of the assistive technology. True positives (TPs) consisted of events identified by the algorithm that corresponded to a salient moment for the user. These moments were recognized by the participant's ability to vividly recall their subjective experience in the video clip associated with the event. False positives (FPs) consisted of events identified by the algorithm that did not correspond to a salient moment for the user. FPs occurred when (1) the event was flagged as a result of a signal artifact (e.g., the video showed the user adjusting the sensor) or (2) the participant could not recall what happened at the moment depicted in the video, or described only what he/she was observing in the video. All true-positive events were further coded to assess whether they corresponded to a moment of physiological significance (TP_{phys}) or a moment of interpersonal significance (TP_{pers}). TP_{phys} included vivid recollections of subjective feelings of discomfort, effort, pain, surprise, relaxation, or stress in relation to the event. TP_{pers} were defined as events where participants described positive or negative feelings induced by interactions with another individual. These events were typically accompanied by an underlying explanation or story.

3. Results

Each dyad participated in 2-3 sessions where they provided oral feedback that was used to calibrate *Event Finder* and to assess the performance of the algorithm. The total number of events per session presented to the dyads for feedback varied according to Table 3, with fewer events in the earlier sessions to help dyads become accustomed to the interview process. The session ID reflected the state of the internal parameters of the algorithm (e.g., default or customized).

3.1. Persons with Dementia Have Distinct, Personal Characteristics of Physiological Responsiveness. While the *Events Finder* software was initialized with the same default parameters across all participants, individual-specific patterns were identified by the end of the fourth session. The tailored parameters used in *Events Finder* at the end of the final session are presented in Table 4 for all participants with dementia. Mary's salient reactions were characterized by EDRs, which morphologically increased sharply in amplitude (i.e., 0.24 μs in 10 seconds) (Figure 2(a)). Elisa's salient reactions were manifest in heart rate accelerations and decelerations (i.e., peak prominence >25 bpm) (Figure 2(b)). Irene's reactions were primarily reflected in changes in the rate of change of her peripheral skin temperature (Figure 2(c)).

Examples of the physiological responses that triggered the detection of an event for each person with dementia are presented in Figure 2 and for each caregiver in Figure 3.

3.2. Assistive Technology Can Identify Salient Events from Physiological Reactions. The performance of the assistive technology in identifying salient events was assessed through classifying each flagged event as either TP or FP, based upon video observation and participant feedback. Two research assistants independently classified each event; the interrater reliability was 96.6%.

Across all participants, 70% of significant moments detected by the best tailored *Event Finder* algorithm were true positives. The performance of the algorithm improved upon individual tailoring for both persons with dementia (Figure 4(a)) and their caregivers (Figure 4(b)).

3.3. Events Identified through Physiological Reactions Include Interpersonal Moments. Within the TP events identified by *Event Finder*, TP_{pers} ranged from 40 to 89%. While the software predominant caught moments of TP_{phys} such as anxiety or pain over performing a specific movement, a significant portion was related to moments of interpersonal

Table 3: List of sessions with marker feedback from dyad interviews.

Dyad	Session no.	Session ID	Max. no. of markers generated per individual
1	4	Default	5
	5	Customized (1)	5
	6	Customized (2)	7
2	6	Default	7
	8	Customized	10
3	4	Default	5
	8	Customized	10

Table 4: Creating customized algorithms for dementia participants from ANS signals.

ANS signal	Feature extracted	Thresholds	Scaling factor
(A) Dyad 1 dementia participant Mary			
Electrodermal activity	First derivative of signal over 10 s sliding window, incremented in 0.5 s intervals	Positive EDA change of 0.24 μs	5
Heart rate	Local maxima and minima	Peak prominence of 20 bpm	0.05
Skin temperature	First derivative of signal over 15 s sliding window, incremented in 0.5 s intervals	Positive or negative temperature change of 0.05°C	1
(B) Dyad 2 dementia participant Elisa			
Electrodermal activity	First derivative of signal over 20 s sliding window, incremented in 0.5 s intervals	Positive EDA change of 0.25 μs	4
Heart rate	Local maxima and minima	Peak prominence of 25 bpm	0.96
Skin temperature	First derivative of signal over 15 s sliding window, incremented in 0.5 s intervals	Positive or negative temperature change of 0.11°C	8.4
(C) Dyad 3 dementia participant Irene			
Electrodermal activity	First derivative of signal over 10 s sliding window, incremented in 0.5 s intervals	Positive EDA change of 0.25 μs	4
Heart rate	Local maxima and minima	Peak prominence of 35 bpm	0.06
Skin temperature	First derivative of signal over 25 s sliding window, incremented in 0.5 s intervals	Positive or negative temperature change of 0.02°C	9

interaction. The physiological characteristics of three such events are presented in Figure 5, and the context of these events are described below. In contrast to Figure 4, where data were presented over the course of a long session (e.g., more than 10 minutes), Figure 5 illustrates a signal event detected in 30 seconds of physiological data.

The first event was triggered by a sharp decrease in temperature, identified by the algorithm as a negative 0.01°C change within 10 seconds ($T_{\max} = 35.8367$°C and $T_{\min} = 35.8267$; $t_{\text{temp}} = 10$) measured (Figure 5(a)). Prior to this moment, Mary was disengaged from the movement activity. Liam described the change in their interpersonal interaction that accompanied this event:

> "I pretend to be pulled away from Mary. Then she gave me a light headbutt on my back. And that's when I touched her forehead with mine (forehead) back. She was playing!"

The second event was from dyad 1, triggered by Mary's EDR and shift from increasing to decreasing fingertip temperature (Figure 5(b)). Prior to this event, Mary had made eye contact with a staff member, Meredith, from the nonprofit organization, who she had known for several years but had recently forgotten. Liam describes the moment accompanying the physiological change:

> "Oh, it was you! Meredith! You got a response. It was Meredith's engagement. Do you remember dear [to Mary] when Meredith was looking at you? You can see you and Meredith in the picture over there. And... when you saw her, you wanted to move with her."

While Mary could not self-report about her experience of the moment, the significance of this event was described by several other participants. Meredith reported experiencing a significant connection with Mary during this moment:

> "She looked at me and her face lightened up... something changed in her eyes and she smiled at me. I do not know how to say it... it's something you feel... I think it was recognition! Recognition! She recognized me... she remembered who I was."

Sophie (caregiver in dyad 3) also reported that she noticed the significance of this moment. She began to cry as she explained what she witnessed: "I was so happy to see [Mary] happy, so that made me happy too. Because she was really smiling and she was really happy, and I thought, "Oh good for her!" Meredith got [Mary] up dancing... and [Mary] was enjoying it."

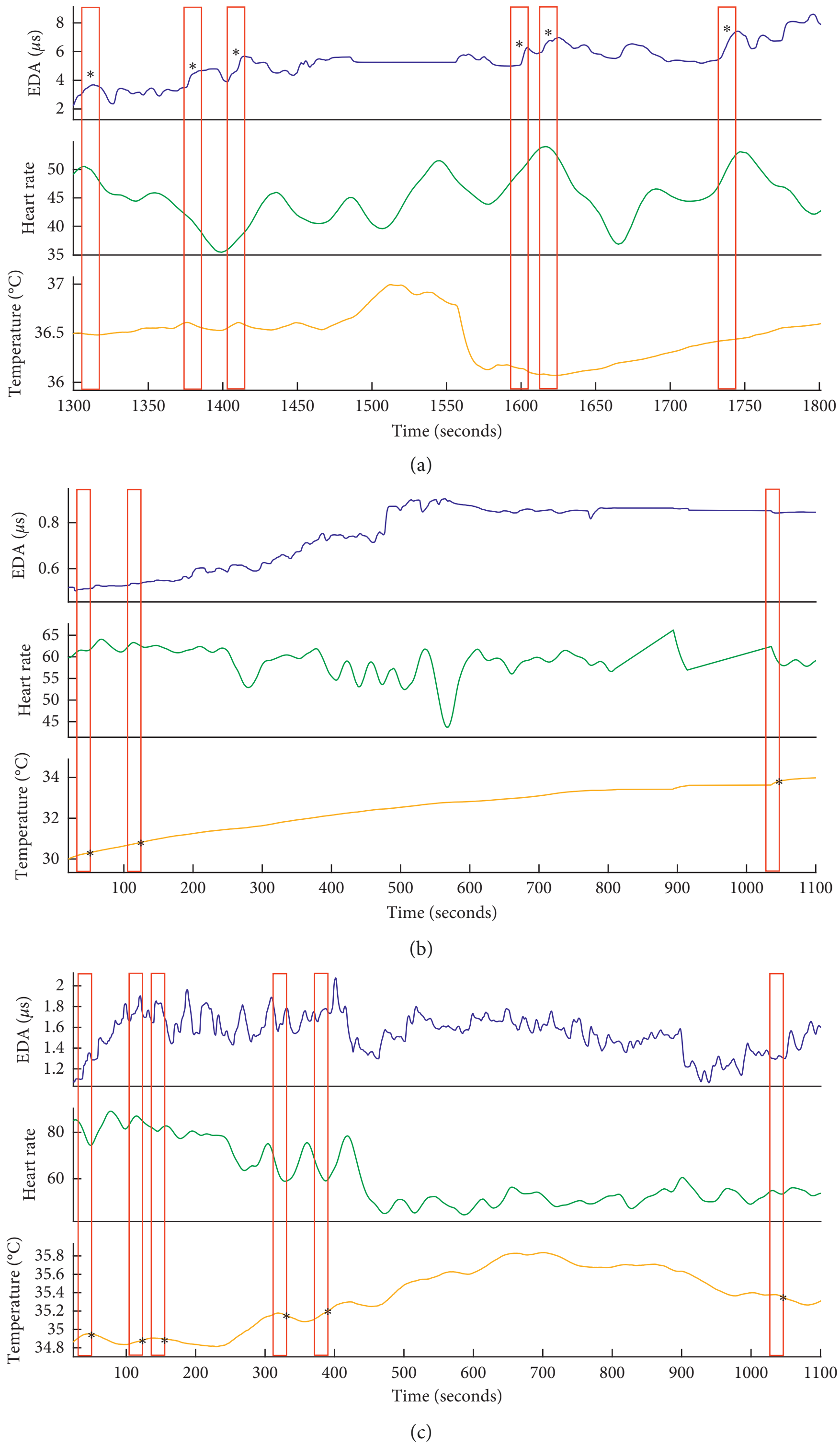

Figure 2: True positive events detected for participants with dementia in their final movement session. Preprocessed and quality-checked signals for electrodermal activity (blue), heart rate (green), and skin temperature (yellow) are presented for Mary (a), Elisa (b), and Irene (c). Red boxes indicate the 30-second "event" that was detected by the final tailored algorithm using parameters presented in Table 4. For each detected event, * represents the physiological modality dominating each change. Each participant presents varying patterns of physiological responsiveness, and their event-detection algorithm is dominated by different physiological modalities, illustrating the need for personalizing the software for each individual.

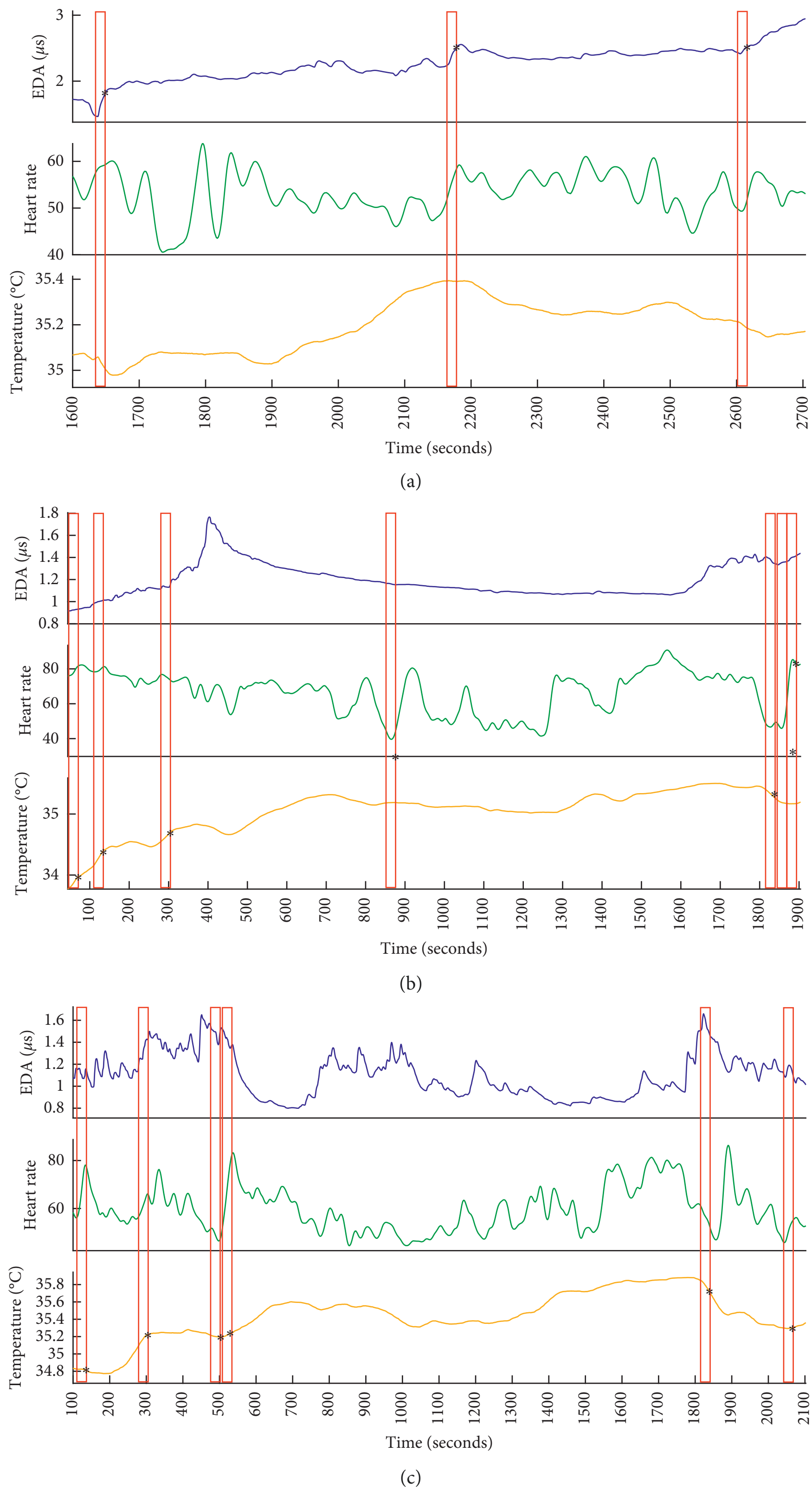

Figure 3: True-positive events detected for caregivers in their final movement session. Preprocessed and quality-checked electrodermal activity (blue), heart rate (green), and skin temperature (yellow) signals are presented for Liam (a), Giselle (b), and Sophie (c). Liam's significant events are triggered by electrodermal reactions; Sophie's by changes in vasodilatory and vasoconstriction responses in skin temperature. Giselle's significant events are triggered by a combination of both skin temperature and heart rate responses. The specific parameters for each individual's algorithm are presented in Supplementary Data, Table 1. The unique patterns of responsiveness illustrate the need to tailor the event detection algorithm for caregivers.

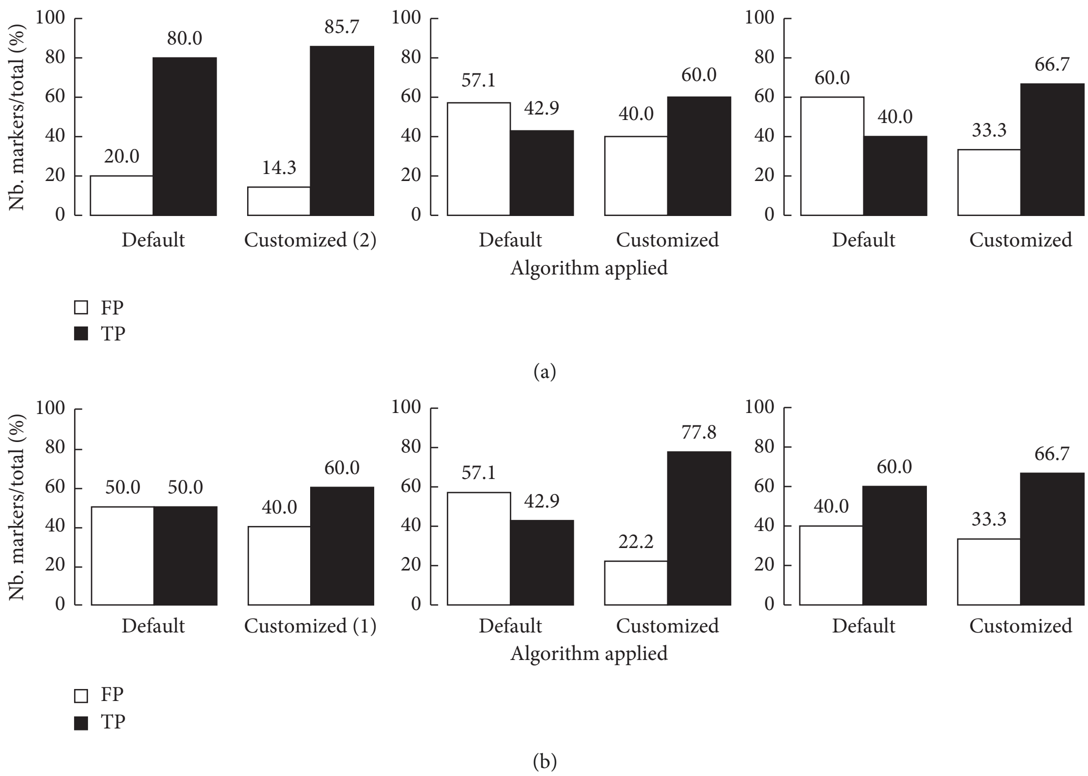

Figure 4: False-positive (FP) vs. true-positive (TP) markers identified by the default algorithm and the customized algorithm across chronological sessions. (a) A. Dyad 1 dementia participant Mary. B. Dyad 2 dementia participant Elisa. C. Dyad 3 dementia participant Irene. (b) A. Dyad 1 caregiver Liam. B. Dyad 2 caregiver Giselle. C. Dyad 3 caregiver Sophie.

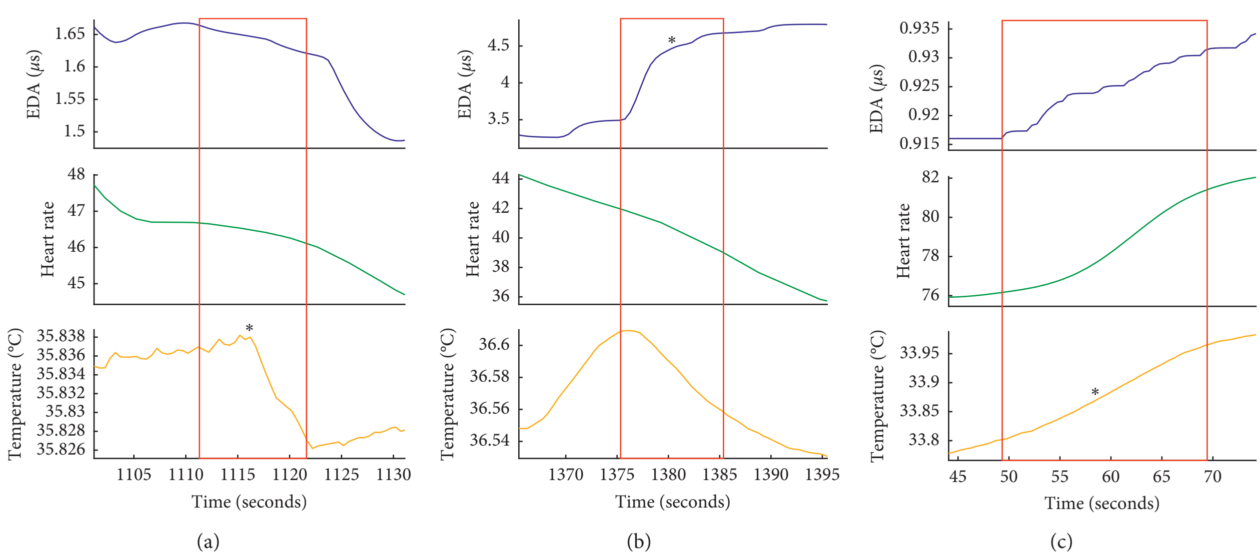

Figure 5: Examples of physiological signals associated with experiences of interpersonal significance. Red boxes highlight the detected event for (a) a moment of connection experience by an individual with dementia with her spouse; (b) a moment of recognition between an individual with dementia and a staff member; (c) a moment of connection experienced by a caregiver with her mother. *The physiological modality dominating the event-detection. However, the patterns of physiological changes triggering events differ within (a) and (b) and between (b) and (c) participants; all are associated with subjective experiences of interpersonal connection.

The third event was from dyad 2, triggered by Giselle's increase of 0.17°C in skin temperature over 20 seconds ($T_{max} = 33.96$°C and $T_{min} = 33.79$; $t_{temp} = 20$) (Figure 5(c)). Giselle described the excitement that triggered this event: "I was watching [Elisa] move and realizing she's doing it more than usual. Sometimes she only gets into it later. I didn't realize she was still moving. I think she moved today more than she ever did!"

These examples demonstrate that the assistive technology is not only able to capture moments of physiological relevance but also able to capture moments of emotional and interpersonal significance.

4. Discussion

Intelligent assistive technologies (IATs) have emerged as promising tools to meet the escalating demands of caring for persons with dementia. While many wearable IATs have been developed for the purposes of tracking activity and maintaining functional and cognitive abilities, few technologies have focused on accessing the subjective experiences of individuals with dementia. In this study, we present a novel IAT that detects moments of significance for individuals with dementia through patterns of their physiological signals. This IAT is tailored to the individual's idiosyncratic response profile and is trained using the domain expertise of the caregiver with respect to the emotional state of the individual with dementia. We demonstrate that this wearable technology is able to accurately track significant moments associated with both physical and emotional events. Such a technology has the potential to accompany frameworks such as deep assessment [11] to improve care for people with advance dementia and to support the quality of life and care decisions of professional and more distal carers. Physiological markers of "significance" or meaning can support the understanding of what matters to persons with dementia, which is now core to health policy [28]. To accompany this article, we developed a freely available open-source toolbox for detecting significant events from physiological signals (http://www.github.com/BIAPT/Events-Finder). Our toolbox enables nonexperts to flag segments of a video recording with a high probability of physical or emotional salience, facilitating discussion and feedback of the event from the individual with dementia and their caregiver. The open-source nature of our toolbox allows researchers to customize individual functions for their needs and to incorporate individual sections into their respective analysis protocols.

Every individual has a distinct pattern of physiological responsiveness to salient stimuli. Thus, the performance of the IAT is dependent on the process of tailoring the parameters of the algorithm to an individual's idiosyncratic physiological characteristics. Tailoring the algorithm resulted in an increase in true-positive events and a decrease in false-positive events for both individuals with dementia and their caregivers (Figures 2(a) and 2(b)). The initial steps of this tailoring are time-consuming, as they involve reviewing video recordings synchronized with the physiological signals for visual moments of significance. However, this customizes the *Event Finder* algorithm so that it is sufficiently tuned to an individual's particular patterns of responsiveness to capture events with a high probability of salience (Figures 3 and 4). These events include both moments of physical significance and experiences of interpersonal significance (Figure 5). The latter steps of tailoring the algorithm parameters involved incorporating feedback from both the individual with dementia and their caregiver about the identified events. This combination of subjective self-report and third-person observation enabled us to incorporate the perspectives of individuals with dementia into the tailoring process and has been shown to be an effective strategy in the previous research with this population [26]. As symptoms of dementia include difficulties with abstract reasoning, such as remembering events and reflecting on their meaning [29], supporting the feedback process with video recordings and caregiver reflections was key to the latter stages of tailoring the algorithm parameters. Feedback from the participants was also key to identifying the valence of the event, which was less evident from the physiological data alone [30]. It was evident in the feedback process that caregivers were extremely attuned to the nonverbal behavior of the individual with dementia, which was an evocative means of self-communication and interpersonal communication [31]. Integrating their expertise into the behavior of the algorithm was a critical process in achieving high-performance accuracy in the detection of significant events. Furthermore, this integration may also facilitate the eventual acceptance of the IAT for everyday use, as low levels of user involvement in technology design is a codeterminant of low IAT adoption rates by individuals with dementia [3].

The IAT presented in this paper is one of a small handful IATs that use physiological signals to gather information about an individual with dementia. Smartwatches have been developed for this target population to use a combination of ANS and accelerometry signals to track physical activity [4, 32] as well as to detect changes in mental and emotional states. The technologies developed to-date use EDA alone [33] or in combination with heart rate, temperature and accelerometry signals to recognize stress and agitation in individuals with dementia [34, 35]. The IAT presented in this paper advances the capabilities of those developed to-date in two significant ways. First, existing IATs focus on tracking states of negative valence (e.g., stress and agitation) in individuals with dementia; we have demonstrated that our IAT can also detect moments of positive valence, including meaningful interpersonal connection, in individuals with dementia and their caregivers. Second, existing technologies focus on changes in overall state, such as activity and mood, and ignore transient, short-term changes. In contrast, our IAT is specifically tailored to detect "moments" of significance, which are transient by nature, in an effort to make visible what is meaningful to individuals with dementia [10]. By synchronizing the moments detected by physiological changes with 30-second video clips, our IAT enables individuals with dementia and their caregiver to focus on the transient events that are meaningful during an activity or an interaction, as opposed to their general baseline state. As such, our IAT advances the capabilities of existing technologies by highlighting events that signify what matters to an individual with dementia [11].

While the number of IATs designed for individuals with dementia double approximately every five years, less than 2% are intended to assist with the social and relational challenges associated with this condition [3]. Technologies that address interpersonal interactions are significantly more popular in other conditions, such as autism spectrum disorder [36, 37]. Moreover, IATs designed to detect emotions from physiological signals have been developed for decades in the field of affective computing [13, 38]. These technologies use advanced features calculated from ANS signals to train feature-based machine learning algorithms to detect discrete states of emotion [39, 40] or deploy an end-to-end deep learning approach for the dimensional recognition of emotions [41]. Drawing from the techniques and knowledge of these established fields will significantly accelerate the development of IATs that support the social and interrelation fabric of individuals with dementia.

This study has several limitations. First, the algorithm parameters were only tailored across the last four movement sessions. As some participants were absent during one or more sessions, this only allowed for two to three meaningful iterations of the algorithm parameters per participant. While each iteration improved Event Finder performance, we believe that the algorithm's performance would continue to improve with more sessions for tailoring the parameters and that the results reported herein do not represent the full capabilities of the Event Finder software. Second, the process we present for customizing the algorithm runs the risk of overfitting the parameter set to an individual's quotidian physiological characteristics. As the progression of dementia has been associated with changes in autonomic functions [42–44], it is possible that the algorithm would need to be retrained periodically on an individual with dementia as their physiological characteristics changed over time. Third, while signals from the autonomic nervous system are being recorded, it is important to not exclusively link the detected events with physiological responses. For example, clenching of the fists reflexively during significant moments has been associated with increases in electrodermal activity [16] and would have triggered an event detection by the *Event Finder* algorithm. Fourth, each physiological signal was processed independently, though it is known that interactions between the physiological modalities can discriminate between different mental and emotional states [45–47]. A multivariate approach to detecting significant changes in physiological state may result in better algorithm performance [48]. Finally, a limited number of features were extracted from each physiological modality; future improvements to the algorithm could involve the addition of features such as heart rate variability, which have shown strong correlation with an individual's emotional state [39].

5. Conclusions

We present a novel intelligent assistive technology (IAT) that detects salient physical and emotional events in individuals with dementia through patterns of their physiological signals. Our IAT consists of software that displays video recordings of events that are synchronized with potential moments of significance detected from physiological changes. Gathering feedback from individuals with dementia and their caregiver on their subjective experience of these moments enabled us to tailor algorithm parameters and improve algorithm performance. The algorithm was able to accurately detect moments of both emotional significance and moments of significant interpersonal connection in individuals with dementia. We provide our software as an open-source toolbox for the detection of significant physiological events from individually-tailored parameters in hopes that the assistive technology community will be able to benefit from and contribute to these tools.

Data Availability

The physiological data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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Supplementary Materials

Supplemental Table 1: creating customized algorithms for caregivers from ANS signals. (*Supplementary Materials*)

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Research Article

Factors Affecting Consumer Food Preferences: Food Taste and Depression-Based Evoked Emotional Expressions with the Use of Face Reading Technology

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In this study, several factors (social status, age, gender, education, knowledge about healthy eating, and attitude to food) affecting consumer food choices (FC), including the relationship between the taste of food, FC, and depression, were analysed by using sensory traits and face reading technology. The first stage of the experimental scheme was the analysis of factors affecting consumer food preferences by using a questionnaire, while the second stage was evaluation of emotional expressions evoked by different food tastes in individuals with and without depressive disorders (DD), using the FaceReader 6 software. We show that gender is a significant factor for most emotional motivations, with a higher effect in females where there was an indication of increased cravings for sweets when feeling depressed. Age was a significant factor in the motivation to eat for positive feelings, while education had a significant influence on perceptions regarding healthy eating. Face reading technology was found to be sufficiently accurate to detect differences in facial expressions induced by different tastes of food, for groups with and without DD. In conclusion, many factors are of high importance in the analysis of food choices, and the results obtained using the FaceReader 6 technique are very promising for food-mood relation analysis. We suggest that mood has a strong link with the choice of food.

1. Introduction

The appropriate intake of nutrients has a major influence on public health [1] and is a major challenge for nutrition professionals when recommending balanced and/or healthy diets and affecting dietary change when necessary. It also affects the food choice of consumers. Many factors have an influence on food choice, which has led to the development of new food product technologies, as well as foods with new textures, tastes, and aroma characteristics to improve available food choices. Many people find it hard to change their dietary choices, which often occur impulsively and without deliberation; it is however unclear whether impulsive food choices can be experimentally created [2]. The major determinant of food choice is hunger, but if we have options what we choose to eat is not determined solely by physiological or nutritional needs. The consumers' gender, age, and education level, along with perception, emotional motivations, and selection of information sources about healthy eating should also be taken into account. According to the European Food Information Council (EUFIC), food induced emotions are very important, as food choice can also depend on our mood (EUFIC 2018). Mood is a complex human mental situation which fluctuates depending on several central and peripheral biological factors and other extraneous factors, including food. Essentially, good or bad moods are the result of certain chemicals influencing a neural response, and some foods have proved to be mood enhancers by affecting the release of desired neurotransmitters in the brain and also by relieving stress [3]. In humans, eating behaviour is complex

Table 1: Sociodemographic characterisation.

Sociodemographic data		Frequency (N)	Percentage (%)
Gender	Female	380	75.3
	Male	125	24.7
Highest Level of Education	Primary School	63	12.5
	Secondary School	168	33.3
	University Degree	274	54.2
Total Number of Participants		505	

and is affected by both moods and emotions; in addition, food consumption is important for mood-regulating behaviours. The interaction between mood, emotional state, and eating behaviours is varied, and it is hypothesised that individuals can regulate their emotions and moods by changing both food choices and quantities. A bidirectional link was suggested between good nutrition and psychological health, with evidence that individuals with a healthy diet are less likely to be depressed or develop depression [4]. On the other hand, depression can influence food choices via physiological processes that influence appetite or other behaviours that constrain or alter food availability [5].

The aim of this study was to evaluate the association between consumers' gender, age, and education level with their perception, emotional motivations, and knowledge about healthy eating. In addition, to evaluate a possible relationship between food choice and a person's mood, a study of emotions induced by different tastes of food in people with and without depressive disorder (DD) was performed.

2. Materials and Methods

2.1. Questionnaire Data Collection. This study involved 505 participants aged between 18 and 85 years, with 75.3% women and 24.7% men. Most participants (54.2%) had a university degree, 33.3% completed secondary school, and 12.5% finished primary school only. Demographic data of the sample studied is given in Table 1. To evaluate perceptions of healthy eating, sources of information about healthy diets, and emotional motivations associated with food choices and eating practices, a questionnaire was used [6].

2.2. Evaluation of Emotions Induced by the Different Tastes of Food in People with and without DD. To evaluate possible differences in food induced emotions in people with and without DD, the FaceReader technique (ver. 6; Noldus Information Technology, Wageningen, The Netherlands) was used. The principal scheme of the experiment is shown in Figure 1.

Two groups of subjects were invited to participate in the study: (I) patients diagnosed with DD and (II) a control group of subjects, not diagnosed with a mental disorder for at least a 1-year period. Their age varied between 18 and 55 years old. The severity of DD symptoms among patients was evaluated using a standard instrument, the Montgomery and Asberg Depression Rating Scale (MADRS) [7], at the Psychiatry Clinic of the Lithuanian University of Health Sciences (Kaunas, Lithuania).

The capture and analysis of the facial emotional expressions of patient and control group subjects, as well as emotional responses to different tastes of food, were carried out using FaceReader software in the morning (after 8 hours of fasting, but with no limit to water intake). In parallel, the acceptability of different food tastes was evaluated using a 10-point Likert scale from 0 (dislike extremely) to 10 (like extremely). Different food tastes ("sweet", "salty", "bitter", "sour", "neutral") were presented by displaying cards showing the name of the particular food taste, and the tested individual was then asked to explain with which food product the presented taste is associated. The person was then asked to grade using the scale from 0 (dislike extremely) to 10 (like extremely) how much they liked the taste and/or product associated with the taste. No timer was used, to allow natural facial expressions. The whole procedure was filmed using a Microsoft LifeCam Studio webcam mounted on a laptop facing the participants, and Media Recorder (Noldus Information Technology, Wageningen, The Netherlands) software. Special care was taken to ensure good illumination of participant faces. The recordings, using a resolution of 1280×720 at 30 frames per second, were saved as AVI files and analysed frame by frame with FaceReader 6 software, scaling the 8 basic emotion patterns (neutral, happy, sad, angry, surprised, scared, disgusted, and contempt) to 1 (maximum intensity of the fitted model). In addition, the FaceReader also analysed the valence, which indicates whether the person's emotional status is positive or negative. 'Happy' is the only positive emotion, while 'Sad', 'Angry', 'Scared', and 'Disgusted' are considered to be negative emotions. 'Surprised' can be either positive or negative. The valence is calculated as the intensity of 'Happy' minus the intensity of the negative emotion with the highest intensity. Valence scores ranged from -1 to 1.

For each food taste sample, the section of intentional facial expression (from the exact point at which the subject had finished raising their hand to give the signal until the subject started lowering their hand again) was extracted and used for statistical analysis. The FaceReader contains an image quality bar, which gives a good indication of how well the program is able to model the face depicted in the image. For the best image quality, the main attention was focused on camera position and illumination. For this reason, participants were asked to sit and look directly into the camera. For statistical analysis, the maximum values of facial expression patterns of the respective sections were used.

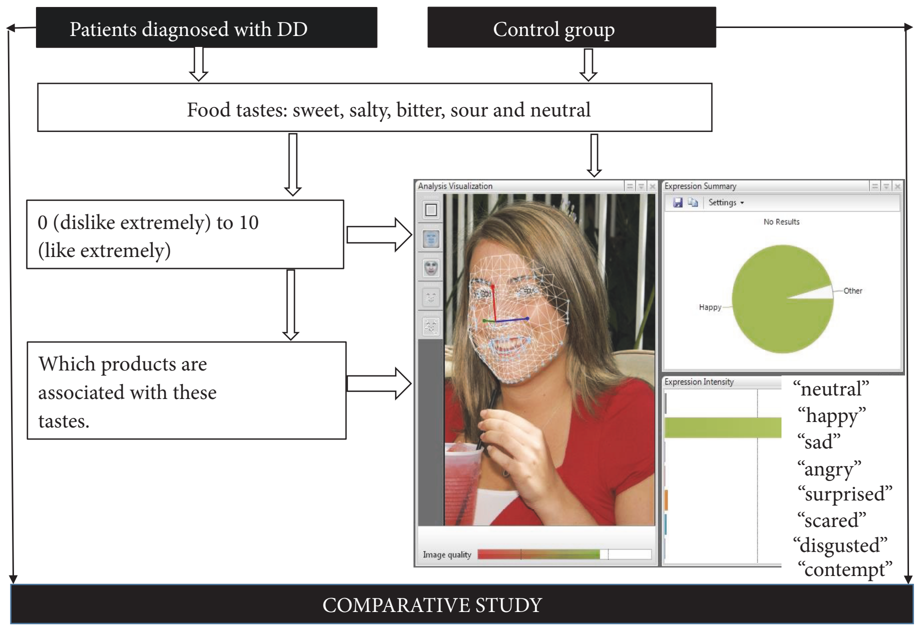

Figure 1: Principal scheme of the primary pilot comparative study of the food induced emotions of people with and without depressive disorder (DD).

2.3. Statistical Analysis. Data analysis was performed using SPSS software from IBM, Inc. (version 24). The relationship between consumer gender, age, and education level with their perception, emotional motivations, and selection of information sources about healthy eating was evaluated using a descriptive statistics crosstabs test. The influence of the analysed factors was considered to be statistically significant when $p \leq 0.05$. For the study of different tastes in food induced emotions in people with and without DD, 40 subjects suffering from DD and 40 control subjects were tested.

2.4. Ethical Approval. All ethical issues were verified when formulating and applying the questionnaire, which was approved by the Ethical Committee with reference no. BEC-MF-147. For the study of different tastes in food induced emotions in people with and without DD, approval to conduct the study was received from the Bioethics Committee (No. 04/2017). All subjects were informed about the study using a "personal information form". Subjects were included in the study if they agreed to participate and signed an "informed consent form". The study was conducted in accordance with the guidelines of Good Clinical Practice and the principles of the Declaration of Helsinki.

3. Results and Discussion

3.1. Relationship between Consumer Gender, Age, and Education Level and Their Perceptions, Emotional Motivations, and Selection of Information Sources Regarding Healthy Eating. Perceptions of healthy eating can be considered to be one of the many factors influencing people's eating habits and choice of food. Scientists, dietitians, and the public agree that an optimal diet should be a primary focus of a healthy lifestyle [8, 9]. More data are needed on perceptions of healthy eating in general, on the influence of information from diverse sources such as food companies, and most importantly on the role of perceptions of healthy eating as a determinant of food choice [10]. Results regarding the influence of different factors (gender, age education level) on consumer perceptions, emotional motivations, and the selection of information sources about healthy eating are presented in Figures 3.1–4.

Evaluation of consumer perceptions about healthy eating showed that gender is not a significant factor; however, a significant influence was observed for gender on emotional motivations such as 'food helps me cope with stress', 'food serves as emotional consolation' and 'I have more cravings for sweets when depressed' ($p = 0.04$, $p = 0.08$, $p = 0.06$, respectively) (Figure 2(a)).

When comparing female and male participants for the perception 'food helps me cope with stress', 8.7% of females and 6.4% of males 'strongly agree', while 39.7% of females and 29.6% of males state that they 'agree'. Greater differences were found between female and male respondents when analysing the perceptions 'food serves as emotional consolation' and 'more craving for sweets when depressed', with 'strongly agree' indicating for 9.2% and 13.2% of females, and 4.8% and 5.6% of males, respectively. Also, gender has a significant influence on the selection of sources of information about a healthy diet: according to questionnaire data, information 'sporadically' obtained information from television ($p = 0.015$) and books ($p \leq 0.0001$) was higher in males (16.0% and 28,8%) than in females (10.8 % and 18,9 %)); in contrast, females obtained information from books and television more 'frequently' (39.2% and 28,2%) than males (26.4% and 20,0%) (Figure 2(b)).

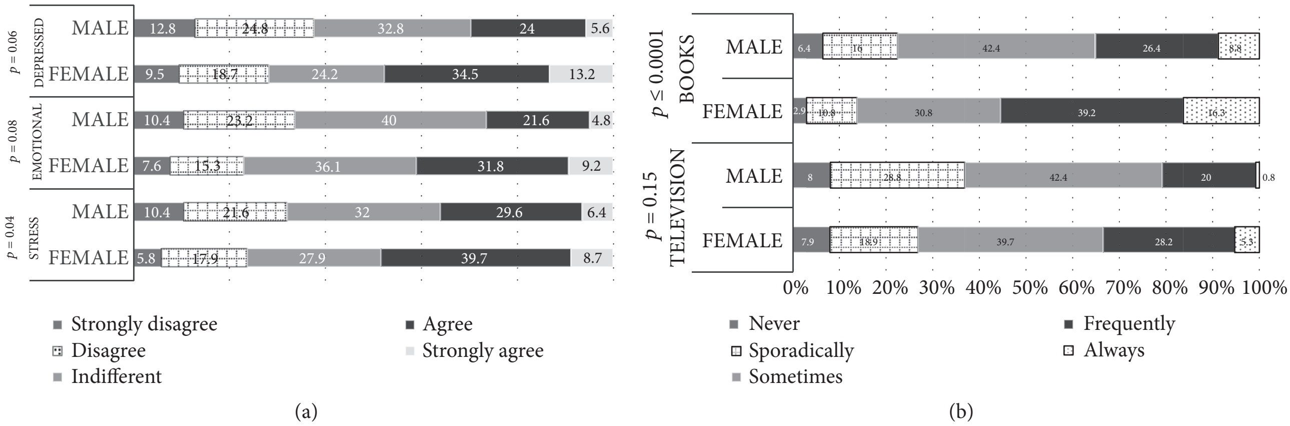

Figure 2: Influence of consumer gender on their (a) emotional motivations and (b) selection of information sources about healthy eating.

There were a number of important relationships observed between stress, coping mechanisms, and lifestyle. Relationships between job stress and maladaptive or unhealthy coping behaviours were more clearly demonstrated in men than in women, particularly with respect to excessive consumption behaviour (food, cigarettes, and alcohol) and denial of feeling stress. Men reported significant associations between job stress, drinking status, and unhealthy eating patterns [11]. Some studies have shown that, compared to men, women are more aware of and attentive to their emotions and more likely to engage in concerted efforts to change them. Women show more awareness of their own emotions, and those of others, and pay more attention to them compared to men, on both self-report and performance-based measures [12]. Data from a representative survey of the Norwegian population showed that women considered health aspects and accordingly chose foods they consider to be healthy more often than men, when selecting foods for an everyday dinner [13].

In our study, the age of respondents had a significant influence on the emotional motivation ‘food makes me feel good’ ($p = 0.037$); however, other analysed emotional motivations such as ‘food helps to control weight’ or ‘eating when feeling lonely’ and ‘I eat more when there is nothing to do’ were not influenced by age (Figure 3(b)). It has previously been shown that people usually change their eating behaviours when they perceive themselves to be stressed or are under persistent external interpersonal, financial, or other strains [14, 15].

Although approximately 20% of people do not change their eating behaviours during stressful periods, the majority do; approximately 40% or more increase and 40% or less decrease their caloric intake when stressed [16, 17]. The age of respondents was a significant factor in perceptions of healthy eating (from $p \leq 0.0001$ to $p = 0.048$, Figure 3(a)), as well as in perceptions of some of the sources of information for selection of a healthy diet, such as school and the press ($p \leq 0.0001$; Figure 3(c)). Generally, previous tests have shown that TV or Internet sources can influence food choices and even food intake and that food preferences in young people are acquired through learning processes, with these preferences having long-lasting effects (18-40) (Figure 3(c)).

Different foods induce different emotions, and consumers choose foods depending on their mood. Age was found to be a significant factor for the ‘food–mood’ association of participants in this study. It is suggested that ‘comfort foods’ have a high calorie content and tend to be associated with childhood and/or home cooking, often prepared in a simple or traditional style. They may have nostalgic or sentimental appeal, perhaps reminding us of home, family, and friends [18]. Older people are more likely to report positive emotions after having eaten their favourite comfort food, and people tend to focus more on positive emotions/situations as they age [19, 20]. Our obtained results are in agreement with this finding, as 90% of the participants in the age group of 71–85 years old indicated ‘agree’ and ‘strongly agree’ when ‘food–mood’ relationships were analysed.

There may also be a neuropsychopharmacological aspect to ‘comfort foods’, as eating palatable foods can lead to the release of trace amounts of mood-enhancing opiates. However, in the younger age groups, the ‘food–mood’ relationship was indicated by a lower number of participants (in the group of 25–40 year olds, it was 21% lower, while in the other groups it was an average of 11% lower) (Figure 3(a)).

Education has a significant influence on three out of the seven information sources (radio, press, and Internet (from $p = 0.03 \leq 0.0001$, Figure 4(c)). 44.4% of participants with a primary school education level sometimes chose a radio as an information source. However, with increasing education level, the popularity of radio as information source was reduced, with only 37.5% and 38.3% of participants with an education level of secondary school and university indicating that they ‘choose sporadically’ radio as a source, respectively. Books or magazines as an information source were “used sometimes” by 55.6% of participants with an education level of primary school, while this source was more popular in the participant group with higher education levels. In addition, only 10% of participants with a primary school education level indicated ‘always use Internet’ as information source, while for respondents with an education level of secondary school and university this corresponded to 21% and 24%, respectively (Figure 4(c)).

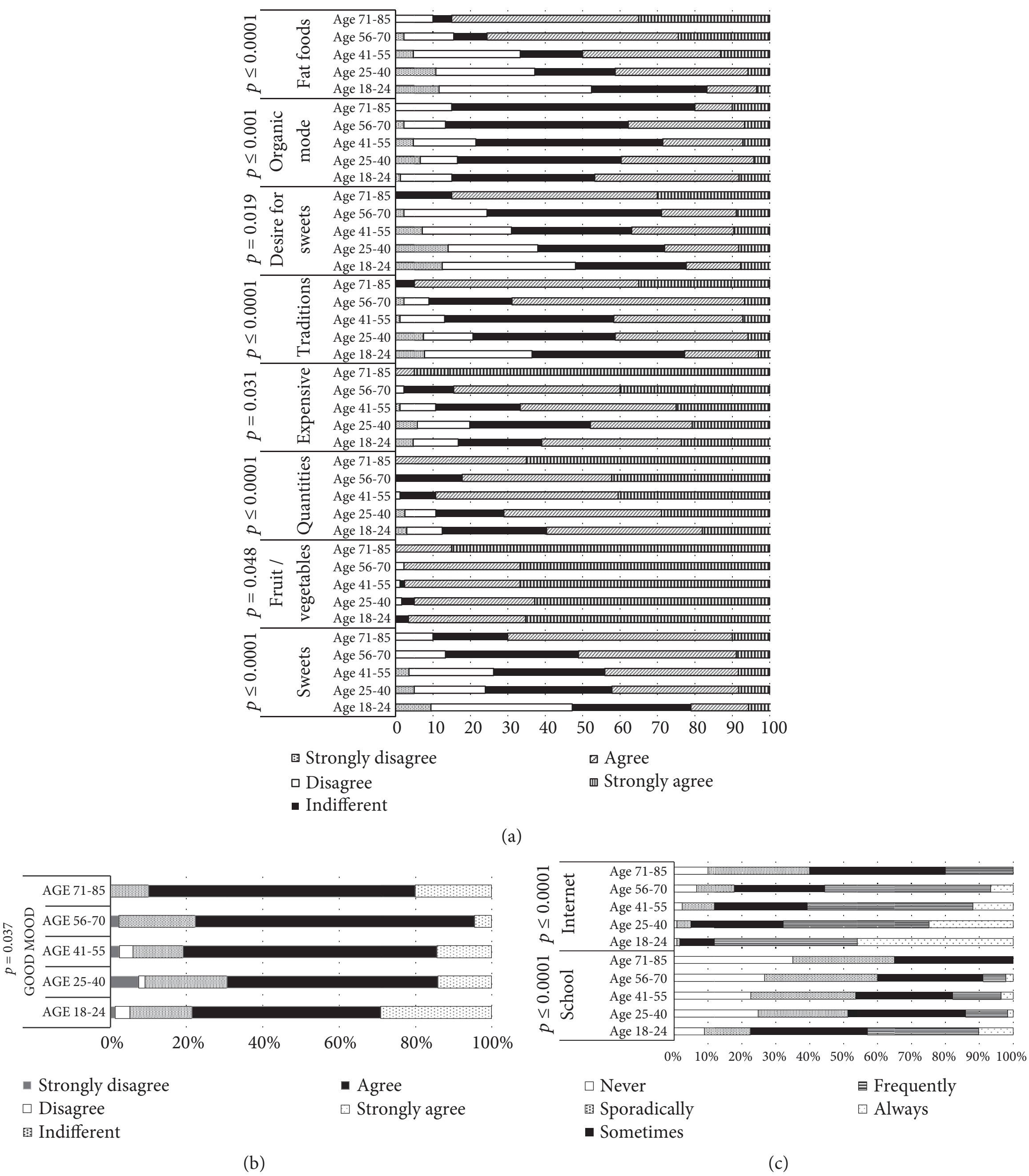

Figure 3: Influence of consumer age on their (a) perception, (b) emotional motivations, and (c) selection of information sources regarding healthy eating.

Education was a significant factor ($p = 0.012 \leq 0.0001$) on perceptions of healthy eating (Figure 4(b)). A high number of participants with an education level of primary school (38.1%) agreed that sweets are not a healthy food; however, most participants with a higher education level were indifferent on this point (on average 31.3%). In addition, about half of participants (46–51%) with an education level of primary school strongly agreed with 'can eat everything in small quantities' and 'healthy diet is not cheap', and 40–48% of these respondents agreed with the perceptions 'tradition is very important to a healthy diet' or 'never consume fat products' (Figure 4(b)). Compared with the higher education groups, it could be stated that people who have a lower education level have a lower tolerance of perceptions and believe popular healthy diet/eating claims more strongly.

For most of the analysed emotional motivations, participants' education level had a significant influence ($p \leq 0.05$) (Figure 4(a)). However, 32–34% of participants with university education level agreed with the emotional motivation 'usually eat foods that help control my weight', as well as with

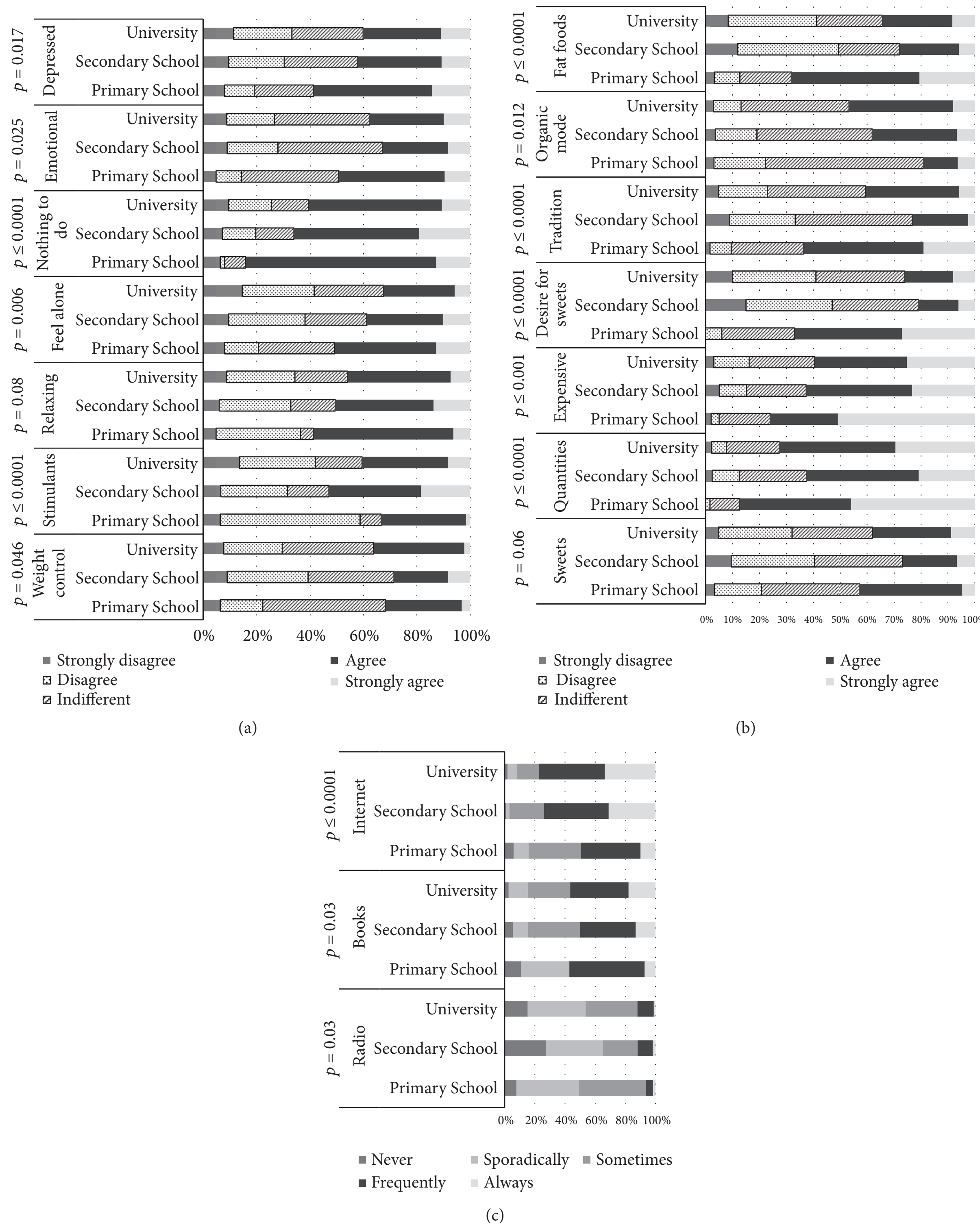

Figure 4: Influence of consumer education level on their (a) emotional motivations, (b) perception, and (c) selection of information sources about healthy eating.

the perception 'often consume foods that keep me awake'. Up to 52.4% of participants with an education level of primary school agreed with the emotional motivation 'often consume food that helps'; this point was very popular with higher education groups (36.9% for secondary school and 38.7% for university). A high number of participants (38.1% and 71.4%) with an education level of primary school agreed that emotional motivations have an influence on eating habits.

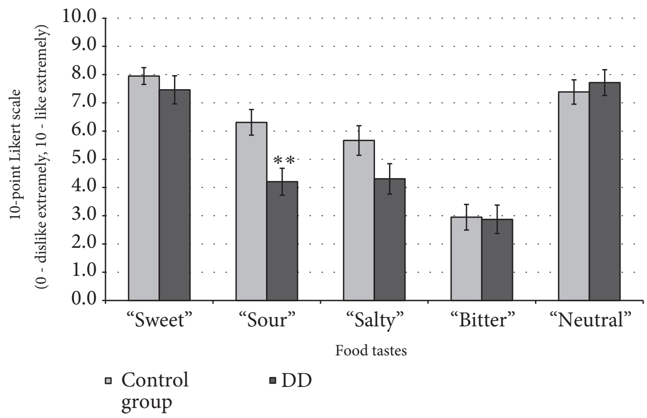

Figure 5: Different food tastes (sweet, salty, bitter, sour, and neutral) evaluated using a 10-point Likert scale (from 0: dislike extremely to 10: like extremely) in people with and without depressive disorder (DD). ∗∗: significant differences compared with control group ($p \leq 0.001$).

Most of the participants with a higher education level also agreed with the emotional motivation 'eat more when I have nothing to do' (47.0% for secondary school and 50.0% for university). Also, higher numbers of primary school education participants (44.4%) were strongly influenced by the emotional motivation 'have more cravings for sweets when I feel depressed', compared to participants with higher education levels (31.5% for secondary school and 29.2% for university). Previous studies have concluded that individuals with lower income were more likely to have lower levels of nutrition knowledge [21, 22], which is associated with lack of use of nutritional labels [23]. Similar effects have been observed for education levels: individuals with more education have reported a greater use of nutrition labels [24]. Several studies have shown that dietary quality seems to depend on socioeconomic variables such as occupation, income, and education [25]. Indeed, there is plenty of literature suggesting that, in developed countries, lower socioeconomic levels are traditionally characterized by unhealthier dietary habits as compared to upper socioeconomic levels [26].

3.2. Food Induced Emotions in People with and without Depressive Disorder. Food induced emotion results, presented as the mean values of analysed emotions and valence in the persons with DD (n=40) and in the control group (n=40), are shown in Figures 5 and 6.

Hedonic Scale. In persons with DD, "sour" taste showed 29.3% lower acceptability in the hedonic scale as compared to control group ($p \leq 0.001$) (Figure 5). However, there was no other relationship between food taste and emotions when comparing the control group to people with DD.

Sweet Taste. Persons with DD expressed lower "happy" emotions for "sweet" taste compared to the healthy group (77.9% lower, $p \leq 0.001$) (Figure 6(a)).

Sour Taste. Similar tendencies in the evaluation of "sour" tastes were obtained, with persons suffering from DD expressing 56.6% lower "happy" emotions compared to the healthy group ($p \leq 0.05$) (Figure 6(b)).

Salty Taste. Similar to tendencies in "sweet" and "sour" tastes, in evaluation of "salty" tastes persons suffering from DD expressed 71.5 % lower "happy" emotions as compared to the healthy group ($p \leq 0.05$). Furthermore, we found a statistically significant difference between people with DD and the control group in terms of the "neutral" emotion (18.1% lower, $p \leq 0.05$). Opposite results in terms of the emotions "sad" and "scared" were obtained, as in all cases they were higher in persons with DD (64.0% and 57.1% higher, respectively, $p \leq 0.05$) as compared to the healthy group (Figure 6(c)).

Bitter Taste. Lower "neutral" and "contempt" emotions were observed in persons with DD for "bitter" taste (20.2% and 64.6% lower, respectively, $p \leq 0.05$) (Figure 6(d)).

Neutral Taste. Higher "sad" and lower "contempt" emotions were observed in persons with DD for "neutral" taste (62.3% higher and 61.3% lower, respectively, $p \leq 0.05$) (Figure 6(e)).

In addition, valence results showed that the valence mean significantly correlated with the emotional state of persons with DD. People with DD showed an average decrease in valence mean for sweet, sour, salty, bitter, and neutral tastes of 91.9, 55.6, 67.4, 58.3, and 52.3%, respectively ($p \leq 0.05$) compared to control group (Figure 6). This can be explained by the fact that people with DD are characterized by a low mood, accompanied by lowered self-esteem, and a loss of interest or pleasure in normally enjoyable activities (American Psychiatric Association, 2000). Our data are partly consistent with that of Ille et al. [27], who reported a response bias in patients with depressive disorder, who judged happy faces as less happy compared to healthy people.

According to the literature, food choice and emotions, stress-related eating, eating comfort foods, and emotional eating have a direct relationship with negative mood states such as sadness, loneliness, and concern [28–30]. Beyond stress, which affects most of the population at some time, about 7% of the European population suffers from DD every year [31]. Only one investigation has directly tested the relationship between DD and food reward using behavioural paradigms [32]. Using a modified probabilistic incentive-learning task in which children were rewarded with candy (Skittles or M&Ms), depressive symptoms were found to

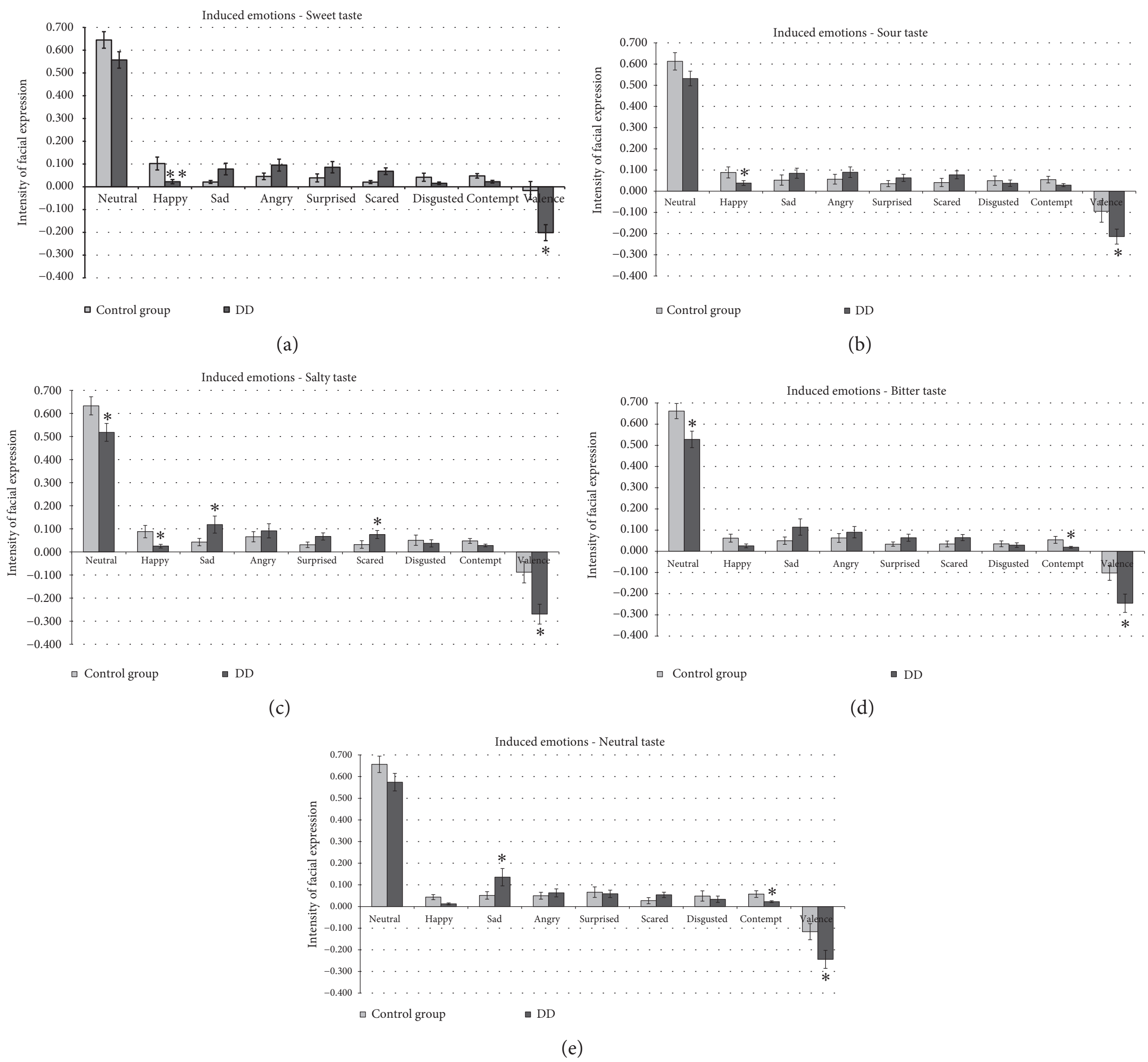

Figure 6: Emotions induced by different food tastes (sweet, salty, bitter, sour, and neutral) in people with and without depressive disorder (DD). ∗: significant differences compared to control group ($p \leq 0.05$), ∗∗: significant differences compared to control group ($p \leq 0.001$).

be unrelated to response bias in food reward [33]. These findings complement results from sugar taste tests in which depressed and nondepressed adults responded similarly in terms of pleasure ratings for increasingly sweeter sucrose solutions [34–36]. These limited behavioural results do not suggest that depressive symptoms are associated with reduced reward functioning per se; however, in a sample of adolescents at risk for depression, high-risk youth demonstrated a reduced neural response to chocolate relative to low risk youth [37]. Overall, studies testing the relationship between depressive symptoms and food reward yield mixed findings, with behavioural results suggesting no relationship between depression and food reward and neuroimaging studies suggesting a decreased neural response to food in depression [38]. However, our results, obtained using *FaceReader* technique, are very promising and showed that emotions induced by different food tastes have a differing tendency when comparing healthy people to people suffering from DD. Our results also showed higher sensitivity as compared with evaluation using the hedonic scale, which can be influenced by previous emotions induced by a participant's past food use. These results are consistent with the concept that emotions have a uniquely important role in food consumption and affect eating responses along the entire process of ingestion [39]. Finally, we suggest that mood also has a relationship with the choice of food and that further studies are needed with a higher number of participants for evaluation of this process.

4. Conclusions

There are many relationships between consumer social status and perceptions of food. Gender is a significant factor in the emotional motivations of "food helps me cope with stress", "for me, food serves as an emotional consolation", and "I have more cravings for sweets when I am depressed". Significant differences between female and male participants were observed as regards selection of the perception "for me, food serves as an emotional consolation" and "I have more cravings for sweets when I am depressed". Participant age has a significant influence on the emotional motivation "food makes me feel good", and education has a significant influence on perceptions regarding healthy eating. Overall, many factors are very important when food choices are being analysed, and personalised nutrition has become an important concept used to balance the diet of a population with different social statuses. Also, results obtained using face reading technology showed higher sensitivity than evaluations using a hedonic scale, which can be influenced by previous emotions of participants induced by past memories of foods. We suggest that mood also has a link to the choice of food. Finally, the Noldus *FaceReader* 6 software is very promising and sufficiently accurate to detect differences in facial emotion expressions induced by different tastes of food for different mood groups (with and without DD). However, more research is needed to determine how this technology performs in more complex testing procedures, in both simulated and "real life" environments.

Data Availability

The data of patients information used to support the findings of this study are restricted by the Bioethics Committee (No. 04/2017) in order to protect patient's privacy.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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Review Article

Acceptance and Use of Innovative Assistive Technologies among People with Cognitive Impairment and Their Caregivers: A Systematic Review

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Cognitive impairments (CI), associated with the consequences of Alzheimer's disease and other dementias, are increasingly prevalent among older adults, leading to deterioration in self-care, mobility, and interpersonal relationships among them. Innovative Assistive Technologies (IAT) such as electronic reminders and surveillance systems are considered as increasingly important tools to facilitate independence among this population and their caregivers. The aim of this study is to synthesise knowledge on facilitators and barriers related to acceptance of and use of IAT among people with CI and their caregivers. This systematic review includes original papers with quantitative, qualitative, or mixed methods design. Relevant peer-reviewed articles published in English between 2007 and 2017 were retrieved in the following databases: CINAHL; PubMed; Inspec; and PsycINFO. The Mixed Method Appraisal Tool (MMAT) was used for quality assessment. We retrieved thirty studies, including in total 1655 participants from Europe, USA/Canada, Australia, and Asia, enrolled in their homes, care-residences, day-care centres, or Living Labs. Two-thirds of the studies tested technologies integrating home sensors and wearable devices for care and monitoring CI symptoms. Main facilitators for acceptance and adherence to IAT were familiarity with and motivation to use technologies, immediate perception of effectiveness (e.g., increase in safety perceptions), and low technical demands. Barriers identified included older age, low maturity of the IAT, little experience with technologies in general, lack of personalization, and support. More than 2/3 of the studies met 80% of the quality criteria of the MMAT. Low acceptance and use of IAT both independently and with caregivers remains a significant concern. More knowledge on facilitators and barriers to use of IAT among clients of health care and social services is crucial for the successful implementation of innovative programmes aiming to leverage innovative technologies for the independence of older people with CI.

1. Introduction

Age-related changes in mental and physical abilities can make independent living at home challenging. Deterioration in mobility, self-care, and interpersonal interaction and relationships has serious implications for independent living among older people [1], especially when a person has problems to remember, learn new things, concentrate, or make decisions that affect their everyday life. Cognitive impairments (CI) are increasingly prevalent in the ageing population [2] and are strongly associated with decline in activities of daily living (ADL) [3]. As the CI progresses, people become increasingly dependent on others to manage their everyday life and consequently their families and relatives (informal caregivers) are at risk of burden and stress [4]. Thus, the cost and burden of caring for older people with CI are considerable, for both informal caregivers and health care and social service (care and service) systems [5]. Efforts to reduce the societal impact of CI are needed, as well as alternative solutions to maintain independence, participation, active citizenship, and quality of the life.

Innovative Assistive Technology (IAT) is currently being developed, tested, and introduced worldwide, as an important tool to maintain independence and quality of life among community living older people with CI. This is very much in line with the European Union (EU) strategy for long-term care, which identified technologies as a key enabler for ageing in place policies and the sustainability of welfare states [5, 6]. IAT includes, e.g., sensor based surveillance and monitoring systems, mobile technology such as wearable fall detectors, and activity bracelets as well as tablets with health information or alarm functions. Indeed, the application of IAT in care and services is a rapidly changing area, in which new products and services are constantly developed and introduced at a high pace. Ambient Assisted Living (AAL) technologies, among the most promising and fast-changing types of IAT, have been categorized by Blackman and colleague [7] into different "generations," according to how they have evolved over time. This categorization differentiates low-tech devices such as wearable alarms that only need user initiation (1st generation); from systems for automatic detection of hazards (2nd generation) to more complex "smart" systems integrating home sensors and wearable devices (3rd generation). By now, even additional IAT not under scope of the categorization suggested by Blackman et al. [7] are emerging, e.g., social and service robots [8], in this study referred to as the "4th generation."

The use of IAT in care and services implies new lived experiences and in most cases new challenges for older people and their informal caregivers. This applies especially for older people with CI and their informal caregivers that are often old and frail themselves.

According to the literature, positive experiences of technology are prerequisites for the acceptance of any new device in general, and this may apply especially in the case of older people [9–11]. However, specific factors seem to apply to the case of older people with CI. Their ability to use technological devices in general could affect their likelihood to use IAT; however, even when older people are proficient in using a technological device such as a mobile phone [9], they may not benefit as much from other forms of more complex IAT, integrating additional components such as alarms and sensors. This could happen for example because of privacy concerns, lack of familiarity or training, and cognitive or visual impairments [10, 11].

Nonetheless, novel IAT in care could play a key role in supporting independent living of older people and could even be more important for the people with CI as it may potentially reduce their dependence on others and promote their autonomy and independence [12]. The implementation of IAT-based is, however, a multifaceted process that affects both older people themselves and their informal and formal caregivers, and the outcome is not always predictable. In this process, acceptance (the intention to use technology [13]) and adherence (the actual use after acceptance [14]) are two important dimensions to be addressed if a successful outcome is to be secured.

A recent review focusing on usability and acceptability of technology among people with mild cognitive impairment and dementia shows that a wide range of IAT is already available for this target group, e.g., digital calendars and Global Positioning System (GPS) [15], but that studies in this area remain contradictory. Updated and systematized knowledge on facilitators and barriers for the implementation of IAT in the homes of people with CI could be highly relevant for the design of future home-based support strategies involving IAT. Such efforts could optimize care effectiveness and cost-efficiency [16] as well the independence, autonomy, and active citizenship among people with CI [12]. Accordingly, the aim of this study was to synthesise the knowledge on facilitators and barriers to IAT use, including acceptance and adherence to IAT, among older people with CI and their informal and formal caregivers.

2. Materials and Method

2.1. Research Questions and Search Strategy. We performed a systematic review of the published literature, using two broad research questions:

(1) What facilitators and barriers are related to acceptance and use of IAT among older people with CI and their informal and formal caregivers?

(2) Are there differences regarding acceptance and adherence of IAT according to the generation of the technology?

Starting from these research questions, and together with an expert librarian, we developed a detailed search strategy. We used the PICO framework [17] as reference (excluding the C=comparison since this did not apply to our study); i.e., we limited our search to articles fulfilling the following inclusion criteria:

(i) P (Participants): studies enrolling people 65 years and older with any form of CI, and/or their informal and/or formal caregivers.

(ii) I (Interventions): studies evaluating interventions using IAT exclusively or predominantly.

(iii) O (Outcomes): studies addressing acceptance, adoption, attitude, perception, and use of the IAT based intervention, as either primary or secondary outcome.

We aimed to include articles with quantitative, qualitative, and mixed methods designs from all disciplines, with no specific restriction of study design or setting. We excluded studies addressing assistive devices, e.g., walkers, wheelchairs, and hearing and visual aids, which are considered as part of routine health care interventions and most often need a prescription or individual adaptation.

Peer-reviewed articles of primary studies fulfilling the inclusion criteria were searched in the following electronic databases: CINAHL; PubMed; Inspec; and PsycINFO, written in English and published between 2007 and 2017.

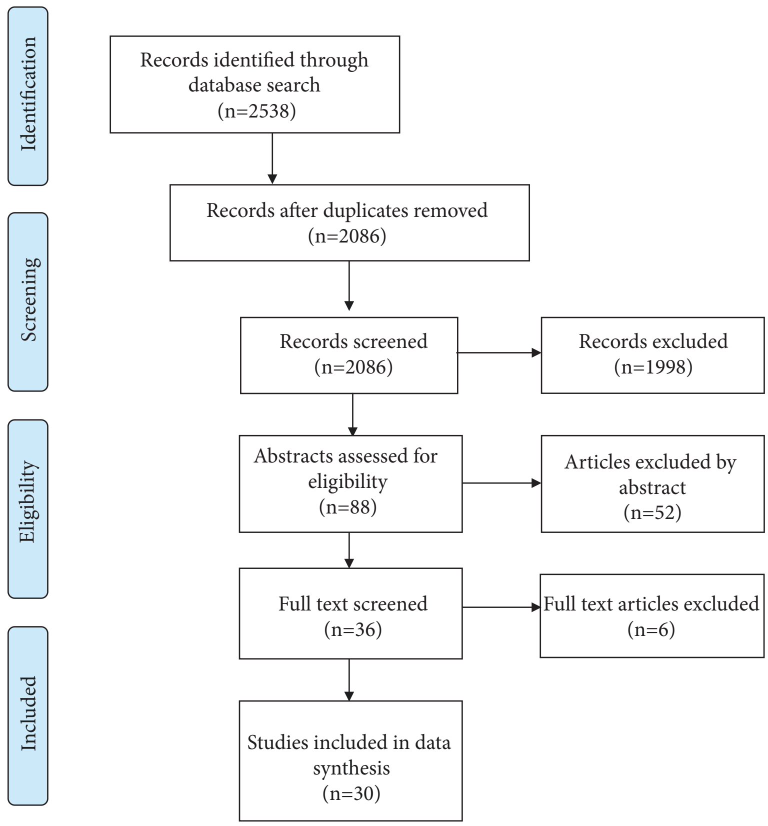

Figure 1: Flow diagram of the article selection process.

Commentaries, editorials, and conference papers were excluded, together with effectiveness studies addressing only clinical benefits of using IAT, unless the abstract indicated availability of results related to our outcomes of interest. Likewise, we excluded studies focusing only on deployment, effectiveness, gaming, and safety and studies where caregivers only were involved as proxy-respondents of people with CI. Full account of the literature search strategy is given in the Appendix.

2.2. Article Selection. One of the authors (DR) independently performed the literature search and then, in parallel with the first author (BT), reviewed the titles for eligibility. The initial titles search resulted in 2538 titles out of which 452 were identified as duplicates. DR and BT separately performed a screening process based on the titles of the remaining 2086 articles. Their results were cross-checked by a third author (CC) in order to finalize a list of eligible articles to include. This resulted in 88 potentially eligible abstracts. The abstracts retained were analysed by BT according to the research questions, in order to obtain the final list of full-text papers to be reviewed. After the analysis of the abstracts, 52 of them were excluded, as they did not fit the aim of this review. Thirty-six full-text papers were then analysed, to ensure that the studies addressed actual use of the technology, as opposed to merely investigate attitudes towards possible use, resulting in a final number of 30 papers included for the full review (Figure 1).

2.3. Data Synthesis and Quality Assessment. Data extraction and synthesis were performed using a Summary of Findings (SoF) table, designed according to the aim of the study. The SoF table summarizes data on study context, outcomes, sample characteristics, design and type of data, characteristics of technology, and main results in terms of acceptability and adherence. In order to develop an understanding of whether acceptance and adherence were related to different generations of technology, the categorization proposed by Blackman and colleagues [7] was utilized for data synthesis. The quality of the included papers was evaluated using the Mixed Methods Appraisal Tool (MMAT), revised version [18]. This assessment tool applies different quality criteria for different study designs, thereby taking the unique characteristics of each design into consideration. In order to carry out an objective assessment of the study quality, two authors (BT and AMF) evaluated each paper separately. Disagreements between the authors (n=4 papers) were solved by means of discussions between the two until they reached consensus.

3. Results

3.1. Participants and Study Designs. The design and quality of studies according to the MMAT are presented in Table 1, which includes also more details on participants and type of data. Facilitators and barriers related to acceptance and adherence are presented in Table 2, including details on type of technology and outcomes.

Table 1: Description of study details and design.

First author, title. MMAT -design/ score[1]	Study design, duration and participants (n, age)[2]	Type of data
(1) Boise et al 2013 [19] Willingness of older adults to share data and privacy concerns after exposure to unobtrusive home monitoring. 3/∗	Cross sectional survey after monitoring for 1 year in clients homes (n=119), mean age 83 years. Groups: Cognitively Intact n= 92 Cognitively impaired n=27 (MMSE≤24)	34 questions on e.g. computer use, attitudes about unobtrusive monitoring and monitoring of computer use, attitudes about sharing monitoring information with one's family or doctor, and concerns about privacy or security.
(2) Cahill et al 2007 [20] *"It gives me a sense of independence"* – Findings from Ireland on the use and usefulness of assistive technology for people with dementia. 5/∗ ∗ ∗∗	Semi-structured questionnaire after 3 months of use in clients homes, client/family caregiver dyad[3] (n=40), 60-90 years old.	Baseline and follow-up data on use and usefulness of the product both from the individual's perspective along with from the perspective of the primary family caregiver.
(3) Cavallo et al 2015 [21] An Ambient Assisted Living Approach in Designing Domiciliary Services Combined With Innovative Technologies for Patients With Alzheimer's Disease: A Case Study. 4/∗ ∗ ∗∗	Experimental study at home and in residential living, client/formal caregiver dyad (n=30), mean age of client 84.5 years.	Interviews with 15 *socio-medical operators* before and after the experimentation phase. Information on study duration not provided
(4) Chen et al 2012 [22] Exploring functions of the lost seeking devices for people with dementia. 4/∗ ∗ ∗∗	User-centred design for 12-36 months among family – or formal caregivers (n=37), mean age 58.8 years.	In depth interview and survey on experiences and requirements of caregivers.
(5) Engström et al 2009 [23] Staff members perceptions of a ICT support package in dementia care during the process of implementation. 1/∗ ∗ ∗ ∗ ∗	Descriptive study for18 months at a residential home among formal caregivers (n=14), 25-56 years old.	Interviews in groups, once before the new ICT, twice during its implementation and once after.
(6) Granata et al 2013 [24] Robot services for elderly with cognitive impairment: Testing usability of graphical user interfaces. 4/∗ ∗ ∗∗	Usability testing comparing two groups - one trial only in clients homes (n=22), mean age 76.5 years. Groups: Elderly with MCI (n=11) Elderly cognitively healthy (n=11)	Performance measures (task completion time and number of errors) were collected
(7) Hattink et al 2016 [25] The electronic, personalizable Rosetta system for dementia care: exploring the user-friendliness, usefulness and impact. 2/-	Controlled trial with pre- and post-test measures in clients homes for 0-8 months, among clients, family- and formal caregivers (n=80, 32+42+6) mean age of clients 79.5 years.	Self-developed semi-structured questionnaires

Table 1: Continued.

First author, title. MMAT -design/ score[1]	Study design, duration and participants (n, age)[2]	Type of data
(8) Hebesberger et al 2017 [26] A Long-Term Autonomous Robot at a Care Hospital: A Mixed Methods Study on Social Acceptance and Experiences of Staff and Older Adults. 5/* * **	Mixed-method design; 15-day-trial following a 5-day-pilot testing phase at a care-hospital among formal caregivers (n=70).	Observations (12 h), questionnaires and in-depths interviews(n=10)
(9) Imbeult et al 2013 [27] Electronic organiser and Alzheimer's disease: Fact or fiction? 4/* * *	Experiment at home with 2 clients aged 71 and 80 years old; 8-20 tests each <12 months.	Qualitative interviews and quantitative analysis of sensor and camera-based data on activity and behaviour.
(10)Karlsson et al 2015 [28] The Challenge of Coming to Terms with the Use of a New Digital Assistive Device: A Case Study of Two Persons with Mild Dementia. 1/* * * *	Explorative user study in the home of 2 clients 60 and 80 years old for 6-18 months.	Participant observations and interviews
(11) Kerkhof et al 2015 [29] Experiences of using a memory aid to structure and support daily activities in a small-scale group accommodation for people with dementia. 1/* * * *	Explorative study for 3 months at a residency among clients 60-80 years old and their family- and formal caregivers (n=17, 6+5+6).	Individual interviews with residents, focus groups interviews with family- and formal caregivers.
(12) Kerssens et al 2015 [30] Personalized Technology to Support Older Adults With and Without Cognitive Impairment Living at Home. 4/* * **	Exploratory intervention for 1-2 months in 7 homes with client and family caregiver dyads (n=14) 60-88 years old.	Life Story and Care Needs interviews Engagement assessment and robot acceptability survey.
(13) Khosla et al 2017 [31] Human Robot Engagement and Acceptability in Residential Aged Care. 3/* * * *	Technology development and action research trial for 3 years among clients at a residency (n= 115), 65-90 years old.	Observations and questionnaires
(14) Lazar et al 2015 [32] Involving Family Members in the Implementation and Evaluation of Technologies for Dementia: A Dyad Case Study. 1/* * * *	Explorative use of touch screen at a residency with a client/family caregiver dyad, 86/ 60 years old.	Interview with a family member at baseline, 3 months and 6 months.

Table 1: Continued.

First author, title. MMAT -design/ score[1]	Study design, duration and participants (n, age)[2]	Type of data
(15) Lazar et al 2016 [33] Evaluation of a multifunctional technology system in a memory care unit: Opportunities for innovation in dementia care. 5/∗ ∗ ∗ ∗ ∗	Explorative use of touch screen, at a residency with client, family- and formal caregiver (n= 16, 5+4+7) age 32-88 years,	Interviews at baseline and 6 months, with an optional interview at 3 months.
(16) Lim et al 2013 [34] Usability of Tablet Computers by People with Early-Stage Dementia. 4/∗ ∗ ∗∗	7-day trials of use of a tablet computer at home with client/family caregiver dyads (n=48), ages 34-91.	Questionnaires
(17) Lindquist et al 2013 [35] Significant junctures on the way towards becoming a user of assistive technology in Alzheimer's disease. 1/∗ ∗ ∗ ∗ ∗	Explorative usability testing for 6 months in the home with client/family caregiver dyads (n=20). Mean age of client 67 years.	Semi-structured interviews
(18) Lindquist et al 2015 [36] Experienced usability of assistive technology for cognitive support with respect to user goals. 1/∗ ∗ ∗ ∗ ∗	Explorative usability testing – 2x 6-month interventions in the home with client/family caregiver dyads (n=28). Mean age of client 69.6 years	Semi-structured interviews on expectations, interviews on experience and field notes
(19) Magnusson et al 2014 [37] Extended safety and support systems for people with dementia living at home. 4/∗ ∗ ∗∗	Intervention study with a pre-post design, 8 months at home with clients, family-and formal caregivers (n=155, 63+62+30) mean age of clients 75.7 years	Questionnaires and Extended Safety and Support (ESS) logs.
(20) Mitseva et al 2012 [38] Gerontechnology: Providing a Helping Hand When Caring for Cognitively Impaired Older Adults—Intermediate Results from a Controlled Study on the Satisfaction and Acceptance of Informal Caregivers. 3/∗∗	Controlled study in the home with client/family caregiver dyads (n=142). Mean age of client 77.4 years. Follow-up at 15 months with intermediate evaluation.	Questionnaires, interviews and structured observations

Table 1: Continued.

First author, title. MMAT -design/ score[1]	Study design, duration and participants (n, age)[2]	Type of data
(21) Niemeijer et al 2014 [39] The Use of Surveillance Technology in Residential Facilities for People with Dementia or Intellectual Disabilities: A Study Among Nurses and Support Staff-Exploring the benefits and drawbacks. 1/* * * * *	Ethnographic field study among nurses and support staff (n=38) using surveillance technology for 4 months at a residential home.	Field observations, formal interviews and informal conversations
(22) Nijhof et al 2012 [40] How assistive technology can support dementia care: A study about the effects of the IST Vivago watch on patients' sleeping behavior and the care delivery process in a nursing home. 5/* * *	Explorative mixed-method design for 6 months at a residential home, with client/ formal caregiver dyads (n=14), 45-95 years old.	Monitor log of sleep/wake rhythm, a diary about usage, care- interventions related to the monitoring data; observations, and in-depth interviews with caregivers about implementation and usage.
(23) Nijhof et al 2013 [41] A personal assistant for dementia to stay at home safe at reduced cost. 5/**	Explorative mixed-method design for 9 months at home with client/family caregiver dyads (n=14), 35-86 years old.	Log files, interviews with family caregivers, a focus group made up of professional caregivers, observations of project group meetings and a cost analysis
(24) Oderud et al 2015 [42] Persons with Dementia and Their Caregivers Using GPS. 5/*	Cohort study, 36 months between in/outside the home with clients/family caregiver dyads (n= 416), 59-90 years old.	Questionnaires, semi-structured interviews, focus groups, discussion groups and home visits.
(25) Olsson et al 2013[43] A passive positioning alarm used by persons with dementia and their spouses – a qualitative intervention study. 1/* * * * *	Qualitative intervention study 6 months, client/family caregiver dyads (n=10), 55-73 years old.	Interview text transcripts and field notes analysed using qualitative content analysis.
(26) Perilli et al 2013 [44] A computer-aided telephone system to enable five persons with Alzheimer's disease to make phone calls independently. 4/* * **	Explorative intervention with a non-concurrent multiple baseline design, individual sessions across two groups at a daycentre, n=40, mean age 80 years old.	A social validation assessment: rate the patients' performance with the technology and with the help of a caregiver. Group 1=28 sessions; Group 2=58 sessions.

Table 1: Continued.

First author, title. MMAT -design/ score[1]	Study design, duration and participants (n, age)[2]	Type of data
(27) Pot et al 2012 [45] A pilot study on the use of tracking technology: Feasibility, acceptability, and benefits for people in early stages of dementia and their informal caregivers. 4/* * **	Quasi-experimental pre-post pilot study -three-month use of GPS at home/outdoor with client /family caregiver dyads (n=56), 63-73 years old.	Impression of the device on a scale ranging from 1 to 10. Several questions on the use of the device with structured response categories ranging from 'Totally agree' to Totally disagree' and agree to disagree, respectively.
(28) Thorpe et al 2016 [46] Pervasive assistive technology for people with dementia: a UCD case. 4/* * *	Controlled usability testing for one week at home with client/family caregiver dyads (n=10), 61-73 years old.	Video recordings, interaction logs, system usability scales, logbooks and interviews.
(29) Topo et al 2007 [47] *"I don't know about the past or the future, but today it's Friday"* – Evaluation of a time aid for people with dementia. 4/* * **	Assessment study for 3 months at home with client/family caregiver dyads (n= 74), 29-99 years old	Findings from the first three months, interviews and home visits
(30) Wu et al 2014 [48] Acceptance of an assistive robot in older adults: a mixed-method study of human–robot interaction over a 1-month period in the Living Lab setting. 5/*	Explorative mixed methods study on robot-acceptance in a Living Lab once a week for 4 weeks, n=11, 76-85 years old.	Questionnaire, semi-structured interviews, usability-performance measures, and a focus group

[1] The number/asterisk refer to design/quality according to the Mixed Method Appraisal Tool (MMAT) [18].
[2] Diagnosis is presented in comparative studies.
[3] Dyads are equally represented by a client and a caregiver, unless otherwise specified.

Table 2: Acceptance and adherence to innovative assistive technology (IAT).

First author, year Tech generation[1]	Type of technology	Outcome(s)	Facilitators	Barriers
(1) Boise et al 2013[19] 2nd generation	Sensor technology to detect cognitive changes and other health problems.	Willingness to share health- or activity data.	Acceptance of in-home monitoring and willingness to share data with one's doctor or family members.	Concerns related to privacy or security after one year of participation.
(2) Cahill et al 2007[20] 1st generation	The Automatic Night & Day Calendar; The Lost Item Locator; The Automatic Night Lamp; The Gas Cooker Device; The Picture Button Telephone	Use and usefulness of assistive technologies Possible refinement and financially viable on the open market.	Familiarity may influence use and usefulness. Low level of technical demands means high level of acceptance and adherence. Informal caregiver was willing to pay for useful technology	Products should be more fully refined and pre-tested on a sample of cognitively intact people before being trialled in the homes of people with dementia. High level of technical demands means low level of use/ acceptance and adherence.
(3) Cavallo et al 2015[21] 2nd generation	A modular technological system to help caregivers monitor the health status, safety, and daily activities of patients with Alzheimer Disease.	Acceptability and usability features.	To support caregivers, not replace them, to guaranty suitability and thereby acceptance and adherence.	No information was given on the time frame of the experimental phase
(4) Chen et al 2012[22] 1st generation	Lost seeking devices	Actual needs of the elders in using the lost seeking devices and the problems they encountered.		The choice of lost seeking device depends on the education level of the caregivers. Support in that respect is needed to overcome barriers.
(5) Engström et al 2009[23] 2nd generation	Alarms, fall detectors, sensor-activated night-time illumination of the lavatory, and communication technology: Internet communication and additional computers.	Staff members' perceptions of an information and communication technology (ICT) support package during the process of implementation.	"Moving from fear of losing control to perceived increase in control and security" Improvements in both formal and informal care.	"Struggling with insufficient/deficient systems"
(6) Granata et al 2013[24] Robot (4th generation)	Social assistive robot providing grocery shopping list and an agenda application.	Usability of robot interface.	Younger participants and those with previous computer experience were faster at completing the tasks.	More errors among participants with neurocognitive disorder (NCD). Being slower at completing tasks than peers contributed to less adherence
(7) Hattink et al 2016[25] 3rd generation	The Elderly Day Navigator; The Early Detection System; and The Unattended Autonomous Surveillance - Advanced Awareness and Prevention System.	Usefulness and user-friendliness of the Rosetta system.		The user-friendliness of the system was not rated highly. Further development is needed.
(8) Hebesberger et al 2017[26] Robot (4th generation)	Long-term autonomous robot able to navigate and function independently over a longer period of time without any intervention by technicians.	Usability, social acceptance.		Interacting modalities have to meet the very needs of specific end-user. Perceived utility of a robot is very much tied to its tasks and proper functioning. Social acceptance was ambivalent.
(9) Imbeult et al 2013[27] 3rd generation	Virtual assistance system with cameras and motion sensors.	Workload reduction for prof caregivers, user satisfaction, acceptance and engagement for older people.	Positive results in terms of the satisfaction of the elderly and interaction in event handling, despite progression of the disease.	

Table 2: Continued.

First author, year Tech generation[1]	Type of technology	Outcome(s)	Facilitators	Barriers
(10) Karlsson et al 2015[28] 3rd generation	The device consists of two parts: support memory, social contact, daily activities; and enhance the feeling of safety. Adjustable to meet the needs of the individuals using them.	Acceptance and usage of a new digital assistive device		Participant needs encompassed occupation, safety, social interaction, and memory support together with the receipt of general support. Requirement for both participants was a need to maintain their self-image. When the digital assistive device did not correspond with the participants' expectations or view of themselves, their interest in using it faded.
(11) Kerkhof et al 2015[29] 3rd generation	Digital planning boards	To improve the use of these devices from the users' perspectives.	The majority of the residents were happy with the use and function of the memory aid.	The occurrence of errors limits ease of use and lack of knowledge on function and use among user's prevented adherence
(12) Kerssens et al 2015[30] 3rd generation	Touchscreen computer using audio-visual programs ("shows"). Menu created based on Life Story and Care Needs interviews.	Usability, feasibility, and adoption	The technology was easy to use and significantly facilitated meaningful and positive engagement, and simplified daily lives.	
(13) Khosla et al 2017[31] Robot	Reminder on daily schedule, weather, news, date, and time. The robot can also make skype calls.	Acceptability while interacting with a social robot.	By using engagement assessment methods and robot acceptance model, the post-trial survey verified acceptance of and adherence to the interaction with social robots.	
(14) Lazar et al 2015[32] 3rd generation	Touchscreen- a variety of applications	Perception of intervention - qualitative design.	By being aware of interests and limitations, facilitate participation and acknowledge emotions and individual barriers to adoption, and fitting technology into an establish routine, the informal caregiver was able to benefit from using the technology.	
(15) Lazar et al 2016[33] 3rd generation	Same as above.	Perception of intervention - quantitative design.	The technology facilitated enjoyment, interactions, connections and mental stimulation.	
(16) Lim et al 2013[34] 3rd generation	Tablet IAT	Usability of tablet as a source of leisure.	When clients were able to use the tablet computer independently, it proved to be helpful to their informal caregivers.	Adherence needs further exploration (only 7-day-in-home trial).
(17) Lindquist et al 2013[35] 3rd generation	Mobile phone, item locator, information panel, reminder, electronic calendar, alarm, digital note taker.	What the use of IAT came to mean to these users and their significant others.	How the initial decision was made, how routines to incorporate the IAT were adjusted, whether the participants trusted the IAT, and whether the participants felt an increased sense of capacity when using the IAT.	The user has to be able to identify difficulties and needs and be motivated to become a user.
(18) Lindquist et al 2015[36] 3rd generation	Mobile phone, item locator, information panel, reminder, electronic calendar, alarm, digital note taker	Experienced usability of features in AT to support users in desired goals in everyday activities.	Constant visible information. User's sense of control was promotional for achieving user goals.	Lack of clarity and feedback of the IAT prompted uncertainty and ineffectiveness. The users has to see the need to become a user

Table 2: Continued.

First author, year Tech generation[1]	Type of technology	Outcome(s)	Facilitators	Barriers
(19) Magnusson et al 2014[37] 3rd generation	Extended safety and support (ESS).	Complexity surrounding the implementation of advanced electronic tracking communication and emergency response	The clients were more independent. Half of the formal caregivers considered that nearly half of their clients could remain living at home with the ESS. Informal caregivers were less stressed or anxious	Informal caregivers did not have more time for their own activities.
(20) Mitseva et al 2012[38] 2nd generation	Platform of personalized home telecare for intelligent home support services.	The informal caregiver user acceptance satisfaction	The most successful adoption of the services can happen when they are offered as early as possible in the history of the disease	Decrease in quality of life among informal caregivers.
(21) Niemeijer et al 2014[39] 2nd generation	Surveillance technologies.	Benefits and drawbacks of technology to support caretakers		The formal caregivers were worried about clients' safety. They need to understand and feel comfortable in using IAT to facilitate the clients' autonomy.
(22) Nijhof et al 2012[40] 1st generation	A special watch which measured sleep/wake rhythm.	The research questions focus on the introduction of the watch, its usage and usability, the interventions that have been taken based on using the watch and the effects of the watch on the sleeping behaviour of the clients.		The IAT was described as big, clumsy and uncomfortable.
(23) Nijhof et al 2013[41] 3rd generation	Support touch-screen.	The advantages and disadvantages of the system from the perspective of the client, informal/formal caregiver and the potentials to upscale its use.	Clients and informal caregiver reported good support of daily life activities, the system could help the client to live at home for a longer period of time, despite e.g. limited user friendliness of the lay-out.	Insufficient quality, caregiver know-how and limited involvement of informal caregivers limited usability. Electricity was considered a cost barrier.
(24) Oderud et al 2015[42] 3rd generation	GPS Technologies.	Autonomy and independence among clients.	Increased safety for all participants. Clients maintain autonomy and continue their outdoor activities.	Half of the participants had stopped using the IAT after 3 years due to their worsening physical or mental level of functioning
(25) Olsson et al 2013[43] 3rd generation	GPS Technologies.	Describe and explore the use and experiences of using a positioning alarm,	Previous use of technology and flexibility of the system facilitates trust in the alarm and in one own ability to use it.	
(26) Perilli et al 2013[44] 1st generation	A net-book computer with specific software, a global system for mobile communication modem (GSM), a micro-switch, and lists of partners to call with related photos	To make phone calls independently.	All the patients learned to use the system and made phone calls independently to a variety of partners, such as family members, friends, and caregivers.	No information.

Table 2: Continued.

First author, year Tech generation[1]	Type of technology	Outcome(s)	Facilitators	Barriers
(27) Pot et al 2012[45] 3rd generation	GPS Technologies.	Feasibility, acceptability, and effectiveness.	The majority of the informal caregivers were able to integrate the use in their daily life. The clients experienced more freedom and were less worried going out alone.	
(28) Thorpe et al 2016[46] 3rd generation	Smartphone, smartwatch and *various applications* to offer six support features.	User-centred approach to developing and testing IAT based on off-the-shelf pervasive technologies.	Clients' motivation, personalized fit and familiarity of the technology.	Clients' motivation, personalized fit and familiarity of the technology.
(29) Topo et al 2007[47] 1st generation	Night and Day calendars (NDC)	How the time-aid was used; and did they find it useful.	Clients' motivation and a personalized fit of the technology.	Clients' motivation and a personalized fit of the technology.
(30) Wu et al 2014[48] Robot (4th generation)	An indoor mobile platform with two propulsive wheels used as a generic platform and designed to ease the development of advanced robotics solutions. It can recognize and synthesize voices, and navigate in unknown environments. It also remembers appointments, manages shopping lists, plays music, and can be used as a video conference system.	To observe robot-acceptance in older adults.		Participants with neurocognitive disorder (NCD) needed more time to adjust to robot use than their cognitively intact peers. Both groups showed low intention to use the robot, as well as negative attitudes toward this device since they did not perceive it as useful

[1] According to Blackman et al. [7].

A total of 1655 individuals participated in the 30 included studies (Table 1). They were people diagnosed with mild cognitive impairment (MCI), or advanced or severe dementia or Alzheimer Disease (AD), their formal and/or their informal caregivers. The included studies were performed in Europe (22), USA/Canada (5), Australia (2), and Asia (1). The studies were conducted in people's own home (20), formal residence (8), day-care centre (1), and Living Lab (1). One study was conducted in both home and formal residence. Four studies addressed the use of social robots and could thus not be categorized according to Blackman et al. (7), while the IAT in all other studies could be classified into 1st, 2nd, or 3rd generation. The IAT included in the four remaining studies thus were categorized as 4th generation.

Eight studies had a qualitative design, while 22 applied a quantitative or mixed methods design: one randomized controlled trial, three nonrandomized trial, eleven observational studies using quantitative measures only, and seven studies using a mixed methods design. Out of the 30 studies included, n= 20 had a dyads-based approach, i.e., involved people with CI and informal or formal caregivers, while the remaining 10 studies included either people with CI (6), formal (3), or informal caregivers (1) only (see Table 1 for details).

3.2. Quality of the Papers. The papers were rated according to the MMAT [18] (Table 1). Ten papers were rated as high-quality studies (*****), meeting all five quality criteria. Eleven papers were rated with four stars (****), meeting 80% of the quality criteria; three articles met 60% of the criteria (***), two met 40% (**), and three studies met only 20% of the quality criteria (*). One article received no star, i.e., met none of the quality criteria. This study was the only randomized controlled trial (RCT) included.

3.3. Acceptance and Adherence to IAT Use. Twelve studies presented results on IAT that were both accepted and used by the participants [19–21, 23, 27, 30–33, 42, 43, 45]. In eleven studies, the IAT was accepted but not used in the following implementation period, therefore resulting in poor adherence [24, 29, 34–38, 41, 44, 46, 47]. The main facilitators identified were ease of use, familiarity with technology, improvement of care, low technical demands, and personalized fit of IAT to daily routines. In addition, enjoyment, possibilities for new interactions, and feelings of safety also motivated the participants to use IAT. Moreover, how and when the IAT was introduced as well as the provision of support before and during the implementation were highly relevant for acceptance and adherence of the IAT (see Table 2 for details).

Regarding the barriers, the main factors hindering adherence to IAT were the participants' lack of experience of technology in general, and the age of the person using the technology [24]. This affected time-use and increased the occurrence of errors significantly [24, 29]. Other issues affecting adherence were the needs for further development of the technology [29] and that more time was necessary for the users to learn how to use IAT in order to make adherence successful [29, 34, 44, 46]. The participants had to be motivated and encouraged to make adjustments to everyday routines, and to trust their own capacity to use the technology [35]. Likewise, an immediate recognition of the benefits of IAT facilitated acceptance. In some cases users did not even mind being monitored by IAT if this was understood as a useful strategy to allow their physician to provide a better care [19].

Some studies [46, 47] also indicated the need for transparent and easy-to-understand information feedback for increasing the perceived efficiency of the technology and the need for a personalized fit between the technology and preferences of the participants [36]. Conversely, lack of clarity and feedback from the technology conveyed uncertainty, hindering acceptance and adherence. Other contextual factors potentially influencing the use of IAT include mobile network issues and internet-access (see [36] for details). User interfaces (i.e., how the technology looks like) are also of great importance. In this respect, one of the studies showed that only 1/3 of the participants were satisfied with the "look and feel" of the IAT [37]. It was found that caregivers have a significant role in the process of IAT implementation among people with CI. While some informal caregivers were less anxious after accepting to use IAT, others reported a decrease in their quality of life [38]. It was stated that IAT should support the caregivers and not replace them [21]; i.e., using only technology to monitor their health was not an option. The caregivers anticipated a reduction of the burden of care when IAT was implemented; however, stress increased when this was not the case [38]. Lastly, electricity cost was a barrier for use [41]. Summing up, our results show that when the IAT prompted safety and freedom and enhanced autonomy for people with CI [42–44], as well as relief and less worry for the caregivers [45] it was accepted and adhered to.

Seven studies reported that technology was neither accepted nor adhered to [22, 25, 26, 28, 39, 40, 48]. The study participants explained that this lack of acceptance and use was to be ascribed to their own lack of skills, fear of mistakes or being replaced, staff irritation, or fear of being replaced or due to an intrusive design, e.g., a big watch on a frail arm [40]. When IAT failed to correspond with the participants' identity and needs, their interest in using the device faded [28]. From a technical perspective, there were concerns in terms of data leakages and/or problems with the display of information on the screen, which led to the staff not trusting the IAT [39]. With IAT still under development, discrepancy between expectation and actual function may lead to nonacceptance and nonadherence [22, 25, 26]. More specifically, several barriers to robot-acceptance were identified, including older people's uneasiness with IAT, feeling of stigmatization, and ethical and societal issues associated with robot use [48].

Regarding clinical factors, the progression of the disease, and the onset of more severe symptoms, was found to negatively affect adherence to IAT [28] indicating the need for regular follow-ups to adapt the IAT to the changing needs of the client [30, 31], as well as to those of the formal and informal caregivers [32, 33]. When IAT does not correspond with the participants' expectations, their interest in using it faded [28]. For example, within an experiment testing a remote monitoring system in a nursing home, when the formal caregivers lost trust in the technology,they continued

Table 3: Timeline of included studies, generations according to Blackman et al. [7].

Year, title	First author	Ref.	Context	Acceptance	Adherence
1st generation					
2007	Cahill	[20]	Home	Yes	Yes
2007	Topo	[47]	Home	Yes	No
2012	Chen	[22]	Home	No	No
2012	Nijhof	[40]	Residency	No	No
2013	Perilli	[44]	Daycenter	Yes	Not adressed
2nd generation					
2013	Boise	[19]	Home	Yes	Yes
2015	Cavallo	[21]	Home+ residency	Yes	Yes
2009	Engström	[23]	Residency	Yes	Yes
2012	Mitseva	[38]	Home	Yes	No
2014	Nijemeijer	[39]	Residency	No	No
3rd generation					
2016	Hattink	[25]	Home	No	No
2013	Imbeault	[27]	Home	Yes	Yes
2015	Karlsson	[28]	Home	No	No
2015	Kerkhof	[29]	Residency	Yes	No
2015	Kerssens	[30]	Home	Yes	Yes
2015	Lazar	[32]	Residency	Yes	Yes
2016	Lazar	[33]	Residency	Yes	Yes
2013	Lim	[34]	Home	Yes	Not addressed
2013	Lindquist	[35]	Home	Yes	No
2015	Lindguist	[36]	Home	Yes	No
2014	Magnusson	[37]	Home	Yes	No
2013	Nijhof	[41]	Home	Yes	No
2015	Oderud	[42]	Home	Yes	Yes
2013	Olsson	[43]	Home	Yes	Yes
2012	Pot	[45]	Home	Yes	Yes
2016	Thorpe	[46]	Home	Yes	No
Robots (4th generation)					
2013	Granata	[24]	Home	Yes	No
2017	Hebesberger	[26]	Hospital	No	No
2017	Khosla	[31]	Residency	Yes	Yes
2014	Wu	[48]	Living Lab	No	No

to perform physical visits to the residents [39]. In this respect, one of the reviewed studies [23] describes how the struggle with imperfect systems might end up in a success when the participants felt their attitude from fear of losing control to perceived increase in control.

In relation to the typology of IAT evaluated, we found that the majority of the IAT included in the studies could be categorized as 3rd generation IAT (n=16), while five studies related to 2nd generation IAT, and five studies included 1st generation IAT. The largest proportion of studies demonstrating acceptance and adherence of the IAT targeted 3rd generation IAT, while IAT belonging to the 2nd generation were less accepted followed by the 1st and 4th generation of IAT (see Table 3). When it comes to use of robots in health care, our results show that the users had generally low interest to use the robot, as well as negative attitudes toward and negative images for this type of devices [24, 26, 48]. The users simply did not perceive it as useful in their daily life, although they found it easy to use, amusing, and not threatening. Direct experience with the robot did not change the way the participants rated robots in their acceptance questionnaire [48]. Personal aspects as not feeling comfortable with technology, feelings of stigmatization, and ethical and societal issues concerning robot use need further scrutiny to ensure quality in implementation of IAT [49].

4. Discussion

To the best of our knowledge, this review is the first attempt to systematically identify and evaluate primary studies that evaluate both acceptance and adherence to IAT among people with CI living at home, addressing also the specificity of different IAT-generations.

Our findings well represent the complexity of the two outcomes of interests: many barriers and facilitators to acceptance and adherence of IAT have been identified, each requiring duly consideration for successful implementation of IAT among people with CI and their caregivers.

From an overall perspective, difficulties and challenges in IAT research can be related to the individual technology users (micro level), the organizational processes and systems (meso level), and the national policy context (macro level) [50]. Most of the results found in our review are related to the individual user level.

One of our main findings is the importance of how the benefits of the technology are communicated first and perceived then, to the older people with CI and their formal and informal caregivers. Communication indeed seems to be an important prerequisite for acceptance and use of IAT among them. This is in line with previous research which has demonstrated that technology is not adopted at all or is soon abandoned after a short while, when end users do not perceive an immediate advantage [51]. A previous review by Peek et al. [14], targeting the general old population, provides partially overlapping results. It showed that the most important factors for acceptance of IAT were a perceived need for the technology and the expected benefits of its use. Our review integrates this knowledge, by suggesting the importance of a correct matching between expectations before implementation and the actual benefits of the technology following the initial use. Mismatch in this respect can hinder a successful implementation as consequence of the users' disappointment. Disillusion might then open the way to other factors opposing acceptance, such as perceived stigma, thus leading to the failure of the intervention [51, 52].

Our results suggest that further investigation on the mid- and long-term adherence to IAT among people with CI is needed, as many reviewed studies failed to address this perspective in the study design, i.e., had no follow-up or short time-span. Solid scientific results on postimplementation adherence are actually lacking. The lack of prospective data is particularly relevant in the context of care for people with CI, in which the "time factor" is critical. Indeed, we found that, to achieve a higher adherence, IAT needs to be introduced early in the course of the disease. Follow-up measures and adjustments for this target population are of paramount importance. As Holthe and colleagues [15] pointed out, the technology should be introduced at "the right time" and the "window" for implementation may be short in most cases. The need for adjustments has been previously underlined [53], and studies [54] have even suggested the need to create autoprompting systems that provide specific, personalized, and flexible prompts to the users. Coherently with this, our review stresses the need for personalization of technology around users' needs. The design of IAT-based interventions must consider the needs of the person with CI and the caregivers, e.g., their capabilities, preferences, and habits. In particular, our analysis underlines the importance of the caregiver role. This is in line with the results from Peek et al. [14] showing that a committed caregiver is vital throughout the technology implementation process.

With respect to the most recent technologies, such as the robots, the potential barriers for acceptance found in our review are in line with those described by Wu and colleagues [55]. The clients need to be motivated to use 4th generation IAT and to understand how they can actually benefit from them before they are willing to accept and adhere to its use. This is an interesting finding for further development of service based, e.g., on social robots in older people care. Nonetheless, studies of acceptance and adherence to these new technologies in health care are still scarce [56]. Interestingly, our review reflects the fast development of this technological field, as the older study, published 2014 [48], evaluating the use of robot was conducted in a Living Lab settings, while the newest, published in 2017 [31], was performed as action research for three years in older people's own home. Moreover, the higher acceptance rate of the 2nd and 3rd generation technology might reflect the fact that in most cases these tech-generations were substantially similar to the first generation, being based on the same devices made more intelligent thanks to a new software. These might have facilitated acceptance among users. On the contrary, the 4th generation is radically new, as it is based on new devices such as robots, with which the users are not familiar anymore. This suggests that the further development of the technologies has brought forward even more evidently the need of studies aimed at understanding acceptance among people with CI.

4.1. Potential Limitations of the Study. The search strategy was prepared in cooperation with a university librarian. Given the multidisciplinary of the study, the revision of abstract was particularly demanding. We found a broad diversity among the studies included as well as among the journals they were published in. The quality assessment according to the MMAT further highlighted the heterogeneity of the studies. In addition, our results are based to a minimal extent on evidence generated from randomized controlled studies. These studies are difficult to perform in this population, e.g., due to drop-out; therefore data on technology acceptance and adherence in this context was extremely difficult to retrieve.

5. Conclusion

Summing up, our findings show that IAT-based interventions can be accepted and used by people with CI and their caregivers. Therefore, they have the potential to compensate for functional decline, i.e., to facilitate everyday activities for several months, despite steady progression of the disease. Given their possible impact of impairment on quality of life and health, such results are promising. It is obvious that technology design and effects need to satisfy the expectations of people with CI and their caregivers. Taken together, our findings indicate a need for more individually designed IAT. Most of all, people with CI and their formal and informal caregivers need to be motivated to use IAT, i.e., understand how they can benefit personally before they are willing to accept and adhere to its use. Since most of the studies found showed that IAT was accepted by the users at the baseline assessment, our results point also to the

Table 4: History of search strategies for systematic review.

Date	Search engine	Search terms	N° of Results
06/07/17		Search terms: (i) dementia OR alzheimers OR "cognitive impairment" OR "cognitive disorders" OR "cognitive disorder" OR "cognitive decline" (ii) technology OR gerontechnology OR "smart home" OR "mobile health" OR mhealth OR telemonitoring OR monitoring OR assistive OR e-health (iii) use OR usage OR attitude OR attitudes OR perception∗ OR acceptance OR adopt∗ Filters: (i) Age: +65	*CINAHL* Results: 505 (examples: Alzheimer's disease, people with dementia) Results with age filter: 243 *MEDLINE (changing database in the previous interface)* Results: 1321 (examples: people with dementia, young onset dementia,) Results with age filter: 496 *PsycINFO (changing database in the previous interface)* Results: 1020 (examples: people living with dementia, younger people with dementia, Results with age filter: 427 *INSPEC (changing database in the previous interface)* Results: 240 (examples: people with dementia, early stage Alzheimer's disease) Results with age filter: Not applicable, the filter is not available

importance of addressing adherence to IAT among people with CI in the mid- and long-term run. Such studies would be useful for the future implementation of large-scale IAT-based interventions.

Appendix

See Table 4.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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