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VIRTUAL REALITY IMMERSIVE ENVIRONMENTS FOR MOTOR AND COGNITIVE TRAINING OF ELDERLY PEOPLE – A SCOPING REVIEW

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Abstract: *The contemporary development of immersive virtual reality interfaces holds untapped potential for the rehabilitation and motor-cognitive training of older adults. Despite the parallel development of gamification methods involving users in interactive experiences and the dynamic development of sensors and techniques for tracking human bio-physiological activities, the cognitive and motor experiments for the elderly, proposed in the literature, are relatively schematic, have limited modalities, and fail to exploit the capabilities of contemporary VR infrastructure. Moreover, the proposed state-of-the-art solutions are arbitrary and their authors usually do not go beyond a simple compilation of popular computer games supported with alternative displays. There is a shortage of exploration of new scenarios combining contemporary immersive virtual environments and the results of experiments on cognitive and motor stimulation of elderly people in an acceptable way for seniors. This paper provides a critical analysis of the contemporary state-of-the-art, followed by constructive insights into the potential of technology and provides inspiration and proposals for solutions that represent a new quality in cognitive-motor rehabilitation.*

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INTRODUCTION

Ageing society and the accompanying problems of both cognitive and motor skill deterioration can be mitigated by emerging computer technologies. Three-dimensional interactive visualizations providing immersive experiences can stimulate the elderly beyond their limited experience with new technologies. Modern virtual environments (VE) have modernized the clinical approach to rehabilitation practises; virtual reality (VR) systems have proved their therapeutic potential regarding falls prevention and balance rehabilitation and finally, virtual reality training can stimulate functional activities and promote social interaction when collectively performed and encourage the elderly to adhere to their rehabilitation programme (Amorim et al., 2019, Taipale & Hänninen, 2018). On the other hand, virtual reality systems for the elderly are still designed with limited consideration of the expectations and limitations of the target users. Interactive virtual systems are rarely built based on a critical and systematic analysis of seniors' expectations but rather based on an arbitrarily selected subset of older adults' cognitive and/or motor deficits and the alleged computer simulations' corresponding functionalities. There is a shortage of studies comparing the effectiveness of various virtual reality systems in cognitive and motor rehabilitation. Papers evaluating the effectiveness of a particular system on a predetermined group of target users are most common. Among the solutions described, although not very numerous, non-immersive systems predominate. Virtual immersive systems based on popular and widely available virtual head-mounted displays and dedicated controllers are extremely rare, especially in the field of motor training. Concurrently, the technological awareness of the older generation, especially in large aglomerations of highly developed countries, continues to grow (Jouhki, 2019). The state-of-the-art derived conclusions are therefore the direct inspiration for writing the following elaboration which aims to elicit a set of design recommendations that combine the potential of contemporary immersive virtual reality interfaces with the growing expectations of an ageing society. Indeed, the development of effective and ubiquitous computer-based systems, both for cognitive and motor training, determines wellbeing and independence in late adulthood.

On the other hand, VR interactive systems and their interfaces' functionalities as well as simulation scenarios, when carelessly designed or implemented, directly affect system usability and may evoke some side effects. The implementation of interactive VR systems, especially for the elderly, should be carried out primarily with safety in mind, then taking into account the needs and elderly person's possibilities as well as the gradation of the occurrence of involutional changes. Additionally, the issues of digital skills of older people and ability to use the interface self-sufficiently and effectively should be respected.

Virtual reality systems could be a promising solution for cognitive and physical debilities in the elderly, especially through combining cognitive and physical activities, along with entertainment. Immersive VR allows the creation of flexible, personalized, and safe multimodal training, using naturalistic and real-time settings. VR systems for the elderly are increasingly reported to be highly effective, achieving better effects than traditional activities (Bauer & Andringa, 2019).

The main contribution of the provided study is an in-depth analysis of state-of-the-art VR systems. The study inclines towards immersive solutions in terms of both the psychologically motivated expectations and motor limitations of older adults as well as the IT limitations of contemporary technology. The study was developed by an interdisciplinary team consisting of computer scientists, psychologists and physiotherapists who, in addition to their academic background, have extensive practical experience focused on seniors. The review concludes with a set of recommendations that find a compromise between user expectations and the capabilities of existing VR technologies.

PSYCHOMOTOR EXPECTATIONS OF OLDER PEOPLE RESULTING FROM THE LIMITATIONS OF LATE ADULTHOOD

Cognitive functioning, defined as multiple mental abilities, such as attention, memory, executive cognitive function, and language, are crucial for independent living, communicating, or integrating sensory information. Cognitive abilities often deteriorate throughout life, contributing to several limitations. The most perceptible changes in cognition are declines in performance on attentional tasks, such as selective or divided attention. Healthy adults encounter such difficulties progressively with age. Episodic or sensory memory remains stable with normal ageing, but there are relevant changes in learning new abilities, short-term memory, working memory (relevant for holding information temporarily), or even prospective memory (remembering to perform intended action in the future). Furthermore, executive functioning also declines throughout one’s life span. Decision-making, problem-solving, planning, or multitasking become challenging. The decline in cognitive functioning is mostly associated with age-related changes in brain structure and function, like neuronal dysfunction or neuronal loss (Murman, 2015).

The elderly are not a homogeneous group and typically suffer from various disease entities or disorders, including cognitive functioning. At the same time, the dynamic development of information technologies, including virtual reality, provides a number of opportunities that allow them to positively affect the comfort of life and the rehabilitation of physical and cognitive deficits as well as training the corresponding skills. Using the achievements of modern technology, however, requires searching for such a range of stimuli and modalities that, on the one hand, allow the individualization of user interfaces and, on the other hand, maximize the experience. Additionally, a balance must be found between individualizing needs and the universality of the solution, which may limit the usability of the systems designed. In the case of usual or successful ageing, we can talk about the management of the ageing process, which determines both independence and quality of life.

The main priority of successful management of ageing is enabling older people to be healthy, active and autonomous for as long as possible. Accordingly, functional decline is one of the key issues to be managed (WHO, 2015). These key issues might be supported, among others, by different assistive health technologies or medical devices, but their effectiveness depends on accessibility and familiarity with the exploited technologies. Virtual environment systems are examples of emerging assistive technologies supported by medical devices in ageing and disabilities treatment. Virtual environments interventions have several determinants of successful cognitive and motor rehabilitation. These are repetitive practice, feedback about performance, multimodal stimulation and a secure and ecologically valid environment (Bahil, 2011).

At the same time, the use of technology is usually hindered by several groups of barriers (Wildenbos et al., 2018). Among the most important are cognitive limitations and motivational limitations. The former include working memory, spatial cognition, attention, language and reasoning, whereas the latter include self-efficacy, self-confidence, integration in daily life. Physical limitations relate to motor speed, flexibility, hand-eye coordination, strength and the perception of the efficiency of the fundamental sense organs (sight, hearing and touch). These limitations increase the risk of falls (Duray & Genç, 2017). In addition, motor activity itself may be affected by cognitive disorders, creating limitations related to learning, remembering, concentration, effectiveness and passing individual tasks. In the case of older people, where depression is one of the great geriatric problems, motivation and well-being might be activated through modern technology. In the case of elderly people, the implementation of scenarios related to relaxation and stress reduction should also be taken into account (Riches et al., 2021).

It must be noted that VR system usability and the resulting impact is determined by users' presence in VE (Riva & Waterworth, 2014). This is only partly related to the realism of the environment but also to the interaction flow performed by means of controlled actions satisfying users' intentions. This in turn can be facilitated by an easy-to-learn interface, understandable serious game structure and engaging storytelling (Triberti & Riva, 2016).

Cognitive-Related Limitations

Cognitive impairment and psychomotor deterioration among older adults make it difficult to experience modern interactive virtual simulations. Dynamic changeability of surrounding environments and non-intuitive methods of environment visualizations control seems to be one of the most crucial bottlenecks hindering the perception of virtual worlds.

Among others, a set of requirements should concern user interface appearance and functionality. Adequate colour contrast and pictographic metaphors rather than textual information, implying legibility and clarity of instructions, constitute another group of regulations recommended for elderly users. Due to miscellaneous deficits in elderly users' senses, psychologists suggest also multimodality of communication, preferably audio-visual. Some users may prefer voice commands or auditory displays supporting visual stimuli rather than a single modality of interaction. At the same time, voice synthesizers and high tones in sounds are recognized as unpleasant by older adults.(Billis et al., 2010).

Another set of requirements concerns virtual simulation scenarios (experience flow) which should gradually introduce new elements and challenges. Besides some introductory exercises familiarizing users with a virtual environment interface, adequate stimulation pace – adjustable to individual perception requirements, should be provided. In the further stages of experiments, appropriately staged training and an extensive number of hints are more than recommended. Additionally, the ecological validity paradigm recommends the exploitation of well-known real environment elements rather than abstract ones, i.e. phantasy, etc.

The level of task difficulty should be both acceptable for elderly users as well as adequately challenging. Task difficulty should balance easiness and challenge. Too much of the former usually results in boredom and overstimulation which may result in discouragement. The level of difficulty should increase gradually. One innovative method that can help organise the level of difficulty for older adults is based on the impression curve (Anrzejczak, 2020). Environment designers should also avoid multitasking, which can become troublesome especially when operating with new technologies – something that is ubiquitous in virtual environment infrastructure. New technology interface operating skills might arise simultaneously with user experience, but if not, the skills should be supplemented by adequately designed and elaborated tutorials and introductory warm-up tasks.

Cognitive tasks should also address many rules to evoke expected consequences in real-life cognitive activity. Preferably, implemented tasks should consider prospective memory estimation. The malfunctioning of this type of memory influences the perception of the person in real life as unreliable and disorganized. Operational memory and coding new information in long-term memory should especially be intensively trained as this helps real-life skills development.

Ecologically relevant challenges should be designed in such a way that users themselves "figure out" the puzzle solution and best remember the information given – without being given a direct key. The environment interface should also respect individual, though different, cognitive styles.

Motor-Related Limitations

Motor-related tasks, conducted within virtual environments, especially immersive ones, may become extremely challenging for elderly people. Visual stimuli presented with immersive displays (especially head-mounted displays) deprives people of ground (physical environment) reference points. Additionally, unsupervised control over the digital camera or its uncalibrated navigation may result in nausea and physical discomfort, which may result in discouragement towards using the VR system. At the same time, physical activities, performed by moving the limbs and tracked with dedicated controllers, should provide visual feedback and be mapped onto avatar or virtual objects' behaviour. Otherwise, miscorrelation between proprioceptive systems and visual stimuli usually result in nausea and cybersickness. Thus, an appropriate design, as well as elderly-oriented navigation and interaction modes, seem to be more than necessary. Challenges concerning VR interaction in motor rehabilitation include the limited feasibility of VR training, lack of functional relevance and adequate feedback caused by a shortage of environmental factors that link to motor performance (Teo et al., 2016).

A constraints-aware philosophy of user interface design should correlate with observations articulated by physiotherapists. Intuitive and understandable correspondence between body activity and visual stimuli does not seem to be satisfactory for efficient motor rehabilitation. One of the suggestions is that physiotherapy-efficient systems might monitor the intensity of users' physical effort, e.g. by measuring heart rate during a task/exercise, instead of, or simultaneously checking the frequency of the performed movements. Thanks to this, planned, structured and purposeful physical activity can be used. In this way, body performance and fitness can be better stimulated. The second observation postulates the possibility of measuring range of motion by a system that can help monitor limited mobility resulting from limited daily movement. Maintaining the correct ranges of motion or extending it among people suffering from contractures is one of the priorities of geriatric physio prophylaxis. Adequate mobility in the joints determines the appropriate posture that allows functional movement in everyday life. Another observation concerns the dosing of external resistance. Physiotherapists have noticed that reducing daily exercise reduces muscle strength and causes muscle tissue atrophy (sarcopenia). Resistance exercises are the main means of preventing these ailments, additionally they will also contribute to the increase of bone mass, reducing the symptoms of osteopenia which usually develops into osteoporosis. Additionally, among older people, balance training is recommended, which contributes to the reduction of falls in this age group (WHO, 2020).

The literature also claims that dynamic and reactive virtual environments should be avoided. This observation may be due to the common delayed reactions among seniors that may have a demotivating effect when unsupervised. In such a situation, it seems sensible to adapt environmental variability to the user's mental state and predisposition. Some authors have advocated the consideration of reaction time and action dynamics as a factor that may become apparent with the user's experience and practice (Su et al., 2013, Antunes et al., 2017, Rutkowski et al., 2021).

METHODOLOGY

Data for this work was collected based on the exploration of leading publishers' databases: Elsevier, Wiley, PsychArticles, Pubmed, Medline, ACM, WoS. The inclusive criteria for cognitive and motor training in immersive virtual environments concerned both keywords sets and year of publication. The cognitive functions were addressed by key phrases: "cognitive functions", "cognitive interfaces", "cognitive skills", and "cognitive games". The aspects of motor skills were fulfilled by the phrases: "motor functions", "motor skills", "exergaming interfaces", "exertion" and "physical treatment". All of the above issues were considered in the context of virtual reality technologies which was addressed by means of the following phrases: "virtual reality", "virtual environment", "immersive interfaces", "interactive interfaces", "technology", and "interface". Potential beneficiaries of virtual systems are to be elderly people who were retrieved from the context of analyzed research by means of the subsequent phrases: "elderly people", "cognitive ageing", "cognitive impairment", and "physical impairment". The publications were analyzed from the perspective of the last five years. Due to rapidly developing virtual reality technologies, especially in recent times, a limited time period seems to provide a complex and adequately representative review of advanced solutions to cognitive and motor stimulation among the elderly. It must be noted that all inclusive criteria resulted in a very limited number of manuscripts simultaneously addressing all the aforementioned keywords, thus the scoping review was extended by selected research which investigates limited modalities only or discusses cognitive or motor aspects in non-immersive scenarios.

All selected manuscripts were discussed from different perspectives in an interdisciplinary team composed of computer scientists, psychologists and physiotherapists. Such a multiperspectival evaluation, addressing the functionality of the systems in the context of the expectations and capabilities of older adults, adds additional value to the presented review, as there is no universally accepted and recognized methodology for critically evaluating the functionality of immersive virtual reality systems across the aforementioned disciplines.

EVALUATION OF EXISTING COGNITIVE AND MOTOR STIMULATING VIRTUAL ENVIRONMENTS

There are several approaches towards elderly-oriented virtual environment usability metrics in the literature, which might be exploited for the evaluation of existing VR-based motor and cognition training systems. For example, in one recent review, Tuena et al. (2020) presented a systematic evaluation of non-immersive VR systems with particular attention paid to motor/physical rehabilitation. The authors quite extensively systemized usability, user experience and feasibility evaluation of VR systems for monitoring and rehabilitation in healthy and pathological ageing. The recommended technology evaluation methods referred to the Technology Acceptance Model (TAM), the User-Centred Design approach or its modification, namely the Senior Citizens' Acceptance of Information Systems (SCAIS) questionnaires. Concerning the assessment of the usability of VR systems, a wide range of quantitative and qualitative methods were proposed. Among others, System Usability Scale (SUS) questionnaires or User Experience (UX) questionnaires are usually preferred. These well-established methodologies may become pointers for further immersive VR systems evaluation, but they require direct examination of subjects with the specific systems. Due to the very limited direct accessibility of VR systems and a lack of reviews regarding immersive virtual environments evaluation, we propose a critical functional evaluation based on the collation of expectations arising from psychologists’ and physiotherapists’ recommendations, with a documented potential of the immersive VR systems.

Even though Tuena et al. have reported just a few immersive VR environments (Fordell et al., 2011, Corno et al., 2014, Pedroli et al., 2018, Trombetta et al., 2017, Plechata et al., 2019) which accounted for only 8% of the total reviewed VR systems, plenty of research has indirectly imposed requirements on VR systems' functionality. The provided review may become a nucleus of immersive VR systems’ functionality evaluations that may result in a set of design recommendations, usable for the domain community. It is particularly important since off-the-shelf immersive VR hardware has become increasingly affordable and available for the elderly. Although the main target recipients are people with decent computer experience and those who are not afraid to experiment with new technologies, older people are becoming indirect beneficiaries of the emerging systems. At the same time, it should be noted that immersive VR systems are usually not created with the elderly in mind, who usually have a different set of expectations. Elderly-oriented immersive VR systems are still rare. The authors of this review claim that criticisms of immersive VR systems, particularly when compared to non-immersive systems, result from the inadequate exploration of the domain and the selective application of guidance from psychologists and physiotherapists.

For example, Corno et al. (2014) have reported, among others, that multitasking in virtual reality induced cybersickness symptoms, interaction with the controller (wand) was cumbersome and instructions were hard to remember. Placheta et al. (2019) reported that immersive VR systems (i.e. exploiting Head Mounted Displays), in comparison with non-immersive VR systems, deteriorates memory performance. Tuena et al. (2019) have argued that executive functions of older adults (over 65 years old) are overloaded by input devices and consequently weaken memory performance. Some of the authors reported the attractiveness of immersive virtual supermarket shopping tasks, but among young rather than older adults. The authors' conclusions suggested general non-immersive scenarios for older adults.

On the other hand, Fordell et al. (2011) reported that a VR version of the "paper and pencil" tests revealed higher performance than classic evaluation among post-stroke patients. Semi-successful experiments with a fully immersive version of a VR motion rehabilitation system were discussed by Trombetta et al. (2017). The authors suggested that a semi-immersive rehabilitation system was more comfortable for post-stroke patients than a fully immersive one (third-person perspective).

The optimism and prospects for the development of immersive systems have been emphasized by Plechata et al. (2019), who recommend further investigation in immersive technology as rapid technical development causes costs reduction and may benefit from a reduced cybersickness effect in comparison with desktop-based VR. Even though several authors (Corno et al., 2014, Pedroli et al., 2018, Plechata et al., 2019) considered the non-HMD system as better for elderly people, Huygelier et al. (2019), recently postulated that older adults can positively accept and tolerate HMD VR.

The potential of VR is still uncovered as many authors report that non-immersive VR-based rehabilitation is not significantly more beneficial, comparing to conventional rehabilitation, likely due to the lack of relevant tasks provided by immersive VR systems (Saposnik, 2016). The relevancy and functionality issues become the essence of this study.

The core functional objectives to be addressed encompass the elaboration of user interfaces' requirements as well as content and structure of the virtual exercises/experiences. VR controllers and their friendly use without professionals' assistance is necessary to provide training autonomy, i.e. at home. The key role lies in appropriate feedback that fosters or inhibits specific users' behaviours. The structure of the experiments should be well balanced and address complementary senses in progressively more difficult challenges.

Considering the above as well as psychologists' and physiotherapists' recommendations, the subsequent evaluation aspects are proposed for consideration in the conducted review:

1. Ecological validity of environment, provided through an engaging flow of environment, adequate hints and feedback, allowing for self "figure-out" set tasks;
2. Multitasking which integrates complementary cognition and motor stimulation, secure and assuring overloading prevention;
3. Multimodal communication (audio, video, feedback, etc.) taking into account possible auditory and visual changes of the elderly;
4. Cybersickness prevention due to adequate dynamism of the environment and appropriate navigation modes;
5. Addressing a wide scope of cognitive issues, like attention, perception, memory, cognitive styles, and executive functions;
6. Differentiation of motor training taking into account their intensity, dosage of external resistance and the implementation of balance positions, taking into account the physical fitness (including ranges of movement, the possibility of maintaining a standing / sitting position, respiratory capacity) of the recipient.

Proposed criteria become a novel framework for a functional evaluation of immersive VR systems from the perspective of motor training, cognitive rehabilitation and dual-task motor-cognition activity.

Motor Functions Perspective

Motor training is one of the popular applications of VR systems, but it is a real scarcity among immersive systems. Among the few, Arlati et al. (2019) have presented a SocialBike system (successor of Positive Bike system) which performs a home-based dual-task (motor and cognitive) exergame intervention to prevent falls in frail elderly persons. It is a multiplayer, collaborative or competitive, exergaming virtual environment performed in an immersive CAVE or normal screen settings. In the context of motor activity, it stimulates balance improvement and gait patterns. A workload of the cycle ergometer allows the user to maintain a constant level of effort that produces a training effect (65% of the maximum heart rate value). The scenario is performed in the ecological environment of a park (trees, grass, lakes, animals, etc.) where cognitive challenges (objects of certain colour or names starting with certain letters) are provided. The system is supported with several modalities of communication and integration with a social media network. Besides the evident merits of the system, aspects of experiment flow, as well as cognitive improvement, are documented in a very limited manner. The dual-task paradigm, inherently implemented in SocialBike, proves that the problematic nature of multitasking in older adults can be mitigated when designed thoughtfully and argues against the problematic nature of multitasking in older adults. The authors also postulate beneficial results, however, the reports are motor rather than cognition oriented. Among numerous weaknesses of the system, lack of cybersickness prevention should be noted, and limited cognitive stimulation was undisputed.

Huang et al. (2019) examined an immersive VR system for rehabilitation of upper limbs functions in post-stroke patients. The authors planned to assess effectiveness in eliciting upper limb motor recovery in comparison with traditional rehabilitation training, but they have not published the results.

In one recent report, Osaba et al. (2020) investigated the aspects of gait adaptability to discordant sensorimotor stimulations. The study of age-related modifications and propensity for visuomotor adaptations during walking in virtual reality headsets can be easily transferred into immersive virtual rehabilitation scenarios. Older adults, examined during virtual visual perturbations experiments, walked with shorter and slower strides but did not reduce stride velocity nor did they increase stride width variability during mediolateral perturbations. These findings may help in elaborating new methods of digital camera navigation in virtual environments that can help in the identification and remediation of elderly gait deficits.

An elicitation of proxy gestures for locomotion in HMD-based immersive virtual environments in the sitting position was studied by Ganapathi et al. (2019). The sitting position is much more challenging for travelling than natural walking interaction controlled with full-body position tracking. The sitting position does not produce usually vestibular and proprioceptive feedback. Hence it confuses the senses which leads to VR sickness (Bhandari, 2018). The authors have confronted several gestures (calling gesture, bike riding gesture, torso leaning, walk in place, pointing, tapping the legs, etc.) for virtual travel in different virtual environments. They have proved the superiority (appropriateness, effort, ease of use) of selected methods depending on the environmental context. In the process of searching for natural, easy and comfortable methods of virtual travel devoid of the assignment of excessive attention to virtual camera navigation, a hand calling gesture, torso leaning and walk in place achieved the best overall scores regardless of the context.

Complementary distribution of the few immersive motor-related systems is the somewhat more popular non-immersive system. Non-immersive virtual reality solutions have recently become popular, especially in motor rehabilitation. In particular, Microsoft Kinect (Webster & Celik, 2014, Park et al., 2017, Prasertskakul, 2018, Liao et al., 2019, Kamińska et al., 2018) or Nintendo Wii gaming console equipment (Cho, 2014, Molina et al., 2014, Liao et al., 2015) were exploited extensively (Choi et al., 2017). Some of them incorporated a dual-task paradigm for cognitive-motor training (Prasertskakul, 2018, Arlati et al., 2019). There are also numerous attempts to exploit popular tablets or less popular hand gesture controllers (eg. Leap Motion). For example, Crocetta et al. (2018) proposed a Bridge Games non-immersive system consisting of seven logic games requiring some motor interaction performed with selected interaction devices (i.e. tablet, Kinect, Leap Motion, etc.). The goal was to elicit any motor learning.

The examples cited above clearly demonstrate that immersive environments in motor training are rare. This state was confirmed by Amorim et al. (2019), who reviewed the effects of physiotherapeutic interventions with virtual reality treatment (VRT) in balance rehabilitation of the elderly. Even though the authors reported in older manuscripts from 2011 – 2013, they reported a shortage of intervention studies in the elderly using VRT.

Additionally, many teams are trying to impersonate VR systems for the treatment of popular diseases of old age suchs as Parkinson's disease (Pazzaglia et al., 2020), back pain syndroms (Alemanno et al., 2020), obesity (Linge et al., 2021), balance disorders (Li et al., 2021) or osteoarthritis (Byra2020). An important aspect is the possibility of implementing motor and cognitive training among the elderly during an epidemic threat. The use of systems during the COVID-19 pandemic was visible in studies on back pain (Garcia et al., 2021), rehabilitation (Kolbe et al., 2021) or post-stroke physiotherapy (Tran et al., 2021).

On the other hand, a plethora of research, stimulated by the rapid development of VR technologies, provides conclusions on user-friendly navigation and interaction within immersive VR systems mitigating the cybersickness effect (Stanney et al., 2020). Computing performance allows for more sophisticated multimodal communication and high-quality rendering of ecologically oriented environments. Ultimately, contemporary psychological and physiotherapy research findings allow much better design of multi-sensory motor-cognitive exercises that address a range of social needs of older people. All this, complemented by recent achievements and experiences in the area of gamification, provides an almost unlimited workshop allowing for the creation of immersive, attractive and useful virtual simulations for older adults (Tuveri et al., 2016, Martinho et al., 2020). The main obstacle that probably explains the small number of such systems on the market is the high cost of production of such systems and the yet-insufficient number of specialists designing functional and useful interactive immersive virtual environments dedicated to elderly people.

Cognitive Functions Perspective

Stimulating cognitive functions with digital games and interactive virtual environments is not a trivial task. Many authors have investigated the protocols of cognitive neurorehabilitation, training cognitive skills and their near and far transfer to daily routines, but the results are not cohesive. For example, Bediou et al. (2018) have shown how first-person shooter games require repeated practice on selected target cognitive skills within a variety of settings to be successful, whereas Parong et al. (2020) have shown that playing for a short period with immersive virtual environment off-the-shelf brain-training games may not be effective for training cognitive skills. In consequence, recent advancements suggest design rules shift towards more focused games, designed on cognitive principles of skills learning with the extensive role of immersive virtual environments. One of the main goals of the provided review is an elicitation of design principles for cognitive neurorehabilitation and training in immersive virtual environments.

Cognitive principles were analyzed mainly individually and from different perspectives (Fang, 2019), but they were not aggregated and analyzed from the perspective of immersive virtual environments. Selected studies concentrated on interface usability (Jerald et al., 2017) and designed environment immersive-ness (Dinet & Kitajima 2018). Other authors (Vitiello & Sebillo, 2018) have noticed that especially when dealing with categories of disadvantaged users, both impaired as well as healthy users, empowerment goals are paramount to gain the true usability of a given application.

Benoit et al (2015) indicate that realistic virtual environments can be well tolerated by the elderly without noticeable evidence of the cybersickness effect. Graf et al (2020)) have shown that virtual natural environments can provide stimulating experiences, elicit positive emotions and provoke relaxation. Even though Gamito et al. (2020) showed positive outcomes of naturalistic virtual environments’ cognitive interventions based on everyday life tasks (executive functions, attention, visual memory, etc.) Parong et al. (2021) reported higher emotional arousal, more extraneous cognitive load and lower engagement negatively affecting learning outcomes within immersive virtual reality learning systems. One of the reasons for inducing cognitive excessive challenge lies in human-computer interface (Banville et al., 2017) and task design. The ecological validity of immersive virtual shopping and the length of movement in VR shopping becomes concordant with multi-layered learning effects (i.e. visuospatial, strategic, verbal) and task performance when designed with an adequate time budget for shopping (Grewe et al., 2013). Even though the performance of VR experiences (i.e. shopping) in immersive VR can become lower among seniors than in non-immersive environments (Plechata et al., 2019), highly immersive technology has good acceptance among ageing adults, which has implications for engagement and further use of HMDs in cognitive assessment and remediation.

At the same time, we should not forget about experiences related to non-immersive environments. Though Faria et al. (2016) marginalized several important issues like usability and functionality of the system, they considered beneficial ecological validity accessible through VR non-immersive technologies on memory, attention, visuospatial abilities and executive functions. Similarly, Reinhardt et al. (2020) proposed an interesting method for measuring mental effort via entropy in VR controller movements. Intelligent user interfaces are capable of detecting mental effort in VR and can detect when users may need assistance in decision making. These valuable findings might be transferred into immersive systems.

Several years ago Larson et al. (2014) published a review of virtual reality cognitive rehabilitation approaches. The authors' conclusions postulated the enrichment of virtual environments with haptic sensory input in addition to visual and auditory inputs and the exploitation of commercially available gaming systems to provide widespread telerehabilitation services. These findings are still valid but more achievable. Due to advancements in technology, multimodal communication can be relatively easily provided and supplemented with various visual, tactile (oscillation) or audio feedback.

It is increasingly common to find multitasking VR scenarios. For example, the benefits of cognitive-motor dual-tasking, in a non-immersive VR environment, had a positive impact on selected cognitive functions and inhibitory control as well as processing speed, attentional and inhibitory control (Wollesen et al., 2020). However, it must be noted that the selection of tasks and the whole experience scenario that stimulate several cognitive abilities seems unsatisfactorily systemized. The selection of tasks that cognitively stimulate older adults is mainly driven by the hardware layer of a system. Intentional multitasking most often occurs in the combination of cognitive and motor training, whereas the scenarios into which diversified cognitive tasks are arranged are most often secondarily inferred from the context of ready-made games or very simple systems. Multitasking issues are mapped on the existing system functionalities rather than basing constituted system functionalities on critical analyses of cognition functionality. Practically absent nowadays are systems whose construction derives, what is documented, directly from the needs of older people, designed by psychologists and made with the attitude towards progressive and complementary training of older people.

Summing up, the widely reported hopes directed towards VR systems, especially immersive ones, have not yet provided enough examples or design principles that can be used to popularize the creation of immersive systems that would benefit from their attractiveness. We believe that the aforementioned range of solutions, taken from non-immersive systems, complemented by experiments on the perception of immersive environments by older adults, can contribute to the development of dedicated, functional VR immersive systems for cognitive training.

Motor-Cognitive Scenarios

Connectivity between motor and cognitive functions is particularly noticeable if natural symptoms of ageing or various diseases, e.g. Parkinson's disease, that humans start to suffer in late adulthood are present (Lang et al., 2020). It is then that the process of declining cognitive and motor functioning is often observed. Even though the most frequent scenario regards individual motor or cognitive treatment there are selected authors postulating cognitive-motor dual-task training. Simultaneous stimulation of both cognitive and motor functions provides more comprehensive stimuli and usually results in more spectacular results rather than in the case of individual, single-modality scenarios.

Among dual-task, cognitive-motor training systems, immersive virtual reality systems are quite scarce. Most of the solutions cover non-immersive scenarios or provide invaluable findings which can be indirectly transferred into immersive virtual scenarios.

For example, Wen et al. (2021) published a narrative review analyzing the development and application of BCI-VR training systems in the rehabilitation of neurological diseases from the perspective of the BCI paradigms (motor imagery, event-related potential like e.g. P300, steady-state visually evoked potential) and provided a pathway for further research in this field. Among others, they have analyzed the BCI-VR simulation control loop in which BCI interfaces exploit the motor imagery paradigm in the recovery of motor functions, attention controled VR games for ADHD treatment or navigation ability improvement among pateints with spinal cord injuries. The authors concentrated on neurological diseases rehabilitation, where BCI paradigms are the only means of application control, thus the potential of cognitive and motor functions of healthy seniors remained beyond the scope of Wen's review.

One of the few examples exploiting the dual-task paradigm for both cognitive and motor functions training among older adults was described by Pedroli et al. (2018). A Positive bike system consists of a cycle-ergometer integrated into an immersive reality CAVE system, which combines motor and cognitive exercises, assuring enjoyable user experiences. The merits of the system were described above in the review.

Cognitive-motor training for adults at high Alzheimer's disease risk was presented by Doniger et al. (2018). In one of the scenarios, the authors exploited a non-immersive virtual environment (monitor + treadmill) with "real-world" tasks targeting sustained and selective attention, working memory, covert rule deduction, and planning. The authors suggest that cognitive training improves cognitive function and a more ecologically valid cognitive-motor VR setting that better mimics complex daily activities may augment the transfer of trained skills. Besides well documented selected cognitive issues, the aspects of immersive-ness, multimodal communication, presence, comfort, functionality and motor-related issues were not addressed by the authors.

Dual-tasks were researched by Tacchino et al. (2020). They investigated cognitive-motor interference among people with multiple sclerosis. According to the authors, traditional interventions may not adequately prepare patients to face the challenges of most daily living activities. However, the authors exploited a non-immersive tablet-based application. Though usable, motivating and well accepted by people, the application was not autonomous as it required therapists' control. It is worth noticing that examined subjects expressed that they intended to choose scenarios and levels of difficulty by themselves, which was not available in the experiment.

Kannan et al. (2019), in turn, evaluated the efficacy of non-immersive cognitive-motor exergame training for improving balance control and cognition among people with chronic strokes. Patients exploited the Wii Fit gaming platform in conjunction with performing cognitive tasks. This off-the-shelf solution, though usable in provided context, was not examined among healthy adults who want to take care of their physical and mental condition. The differences between immersive and non-immersive environments make this research just contextual support for ecologically valid, multitasking, immersive solutions.

Mrakic et al. (2018), on the other hand, evaluated the impact of a VR-based program combining aerobic exercise and cognitive training for subjects with mild cognitive impairment. The results were more promising than conclusive. The VR non-immersive environment exploited a cycle-ergometer and screen display situated in front of a subject. All the scenarios (trail in a park, urban scenario, supermarket), except one, did not report a level of difficulty. The level of difficulty was accomplished by incorporating distractors (similar to the intended target, semantic similarity to the target, formats and discounted products of the same products) in order to increase attentional and visuospatial demands. This study is only partially related to the focus area of this paper and contributes to motoric training.

SUMMARY

A systematic, functionality scoping analysis of state-of-the-art VR-based motor-cognitive rehabilitation systems evidently reveals a shortage of immersive multitask environments. This is puzzling since many researchers have investigated individual cognitive or motor stimulating modalities and proclaimed their interdependence and mutual support. Designers of cognitive-motor training environments concentrate more on patients with selected diseases rather than normally ageing adults. Ecological validity is rather occasional as most dual-task environments are based on off-the-shelf sports games or eye-friendly sightseeing rather than dedicated, engaging and cognitively demanding virtual environments. Individual exceptions are recurring and include supermarket shopping or trail rides. As the immersion increases, the monotonicity of the experience also increases. At the same time, the "flow" of the scenario and the range of cognitive exercises decrease. For example, there is a lack of immersive experiences with covert rule deduction, in which participants (older adults) "figure out" the rules of the challenge on their own.

The multitasking paradigm is usually limited to dual-task exercises. More sophisticated motor activities, monitoring the intensity of effort, range of movements, dosing external resistance are quite scarce and limited to professional diagnostic medical systems. Social Bike is among the few exceptions. Analogically cognitive challenges are very limited when co-existing with motor challenges or are servile to the hardware interface or off-the-shelf gaming scenarios, which are usually imposed by different target users and do not correspond to elderly-dedicated requirements.

There is a paucity of published research aiming to recognize the evident potential of multimodal communication with virtual environment systems. This is due to the rapid development of virtual environment interfaces (i.e. HMDs by HTC, Oculus), whose performance, supported by artificial intelligence provide capabilities at yet unconsumed by immersive environments dedicated to the elderly. The experiments are dominated by the default hardware infrastructure configurations that are provided by global vendors. Few examples involve non-immersive environments, but solutions that combine motor and cognitive challenges are non-existent in popular immersive variants using popular off-the-shelf VR HMDs.

An additional challenge is to develop interaction mechanisms in immersive environments that minimize vulnerability to simulator sickness among older adults. Although cybersickness comfort was monitored in some experiments, configuring complex cognitive-motor immersive experiments that provide pleasant sensations among older adults becomes an intricate endeavour and requires further in-depth research.

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