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Review Article

What is the future for immersive virtual reality in memory rehabilitation? A systematic review

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Abstract.
BACKGROUND: A growing interest in non-pharmacological approaches aimed at cognitive rehabilitation and cognitive enhancement pointed towards the application of new technologies. The complex virtual reality (VR) presented using immersive devices has been considered a promising approach.
OBJECTIVE: The article provides a systematic review of studies aimed at the efficacy of VR-based rehabilitation. First, we shortly summarize literature relevant to the role of immersion in memory assessment and rehabilitation.
METHODS: We searched Web of Science, ScienceDirect, and PubMed with the search terms “memory rehabilitation”, “virtual reality”, “memory deficit”. Only original studies investigating the efficacy of complex three-dimensional VR in rehabilitation and reporting specific memory output measures were included.
RESULTS: We identified 412 citations, of which 21 met our inclusion criteria. We calculated appropriate effect sizes for 10 studies including control groups and providing descriptive data. The effect sizes range from large to small, or no effect of memory rehabilitation was present, depending on the control condition applied. Summarized studies with missing control groups point out to potential positive effects of VR but do not allow any generalization.
CONCLUSIONS: Even though there are some theoretical advantages of immersive VE over non-immersive technology, there is not enough evidence yet to draw any conclusions.

Keywords: Virtual reality, immersion, memory, rehabilitation

1. Introduction

Virtual reality (VR) is currently applied both in diagnostics and therapy of cognitive deficits (Laamarti et al., 2014). Clinical VR applications mostly present simulations of real-world environments to observe or adjust patients’ behavior in ecologically valid situations. VR can be defined as a digitally rendered complex three-dimensional representation(s) of the virtual world enabling interaction with the computing environment and associated with the feeling of being present in the virtual environments (VEs) (Lombard & Ditton, 1997).

An important characteristic often associated with virtual reality is immersion. Immersion is a characteristic of the used technology, the higher quality

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of the system (in terms of the tracking latency, the size of the field of view, or the visual quality of the scene and images) results in a higher level of immersion. Immersion is also defined by the ability of the system to support sensorimotor contingencies, for example how the technology responds to the action performed by the user to perceive reality, e.g., turning the head to change the gaze direction (O'Regan & Noë, 2001). Higher immersion was repeatedly associated with an increased level of presence - the feeling of being inside the VEs (Cummings & Bailenson, 2015).

While in diagnostics and cognitive assessment the applied computerized cognitive tasks are often deliberately simplified to assess isolated cognitive functions, the complexity of the tasks and the level of immersion in VR tasks applied in therapeutic and rehabilitation approaches seem to be more crucial (Maggio, De Luca, et al., 2019). There are two opposing views on the role of immersion in cognitive rehabilitation. The authors either suggest that immersion is a key factor in VR applications (Slater & Sanchez-Vives, 2016) or argue that simple presentation of VR on a monitor screen with low immersion is sufficient and may even lead to better results in terms of adjusted behavior and cognitive outcome (Ausburn & Ausburn, 2004; Bowman & McMahan, 2007). It was demonstrated that immersive experience in cognitive training can facilitate the transfer of learned abilities to real-world situations (Rose et al., 2000) and that incorporating real-life situations and challenges in VR while maintaining control over presented stimuli can increase the ecological validity of cognitive rehabilitation (Rizzo et al., 2004). This is supported by the findings that virtual simulations of activities of daily living (ADL) can better predict real-life functioning than standard neuropsychological measures (Greenwood et al., 2016; Grewe et al., 2014).

To contribute to the ongoing discussion about the role of immersion of VR-based approaches in memory rehabilitation, we summarize recent studies comparing the cognitive performance in VR and studies focusing on VR efficacy in memory training and categorize them according to the applied technology. In the context of this review, we discriminate only two distinct applications of VR using either 'non-immersive' technologies (visualization on the monitor screen(s) in 2D/flat view) and 'immersive' devices enabling complex binocular visualization of the three-dimensional space using head-mounted displays.

1.1. Immersion and memory performance

The most often used "immersive" technology to present VR applications is through head-mounted displays (HMDs). Currently, the interaction with the VR is usually enabled with special controllers or hand trackers. However, in the earlier HMD versions (e.g. V6 or Z800 3DVisor) the interaction was often provided with a joystick or with a traditional computer keyboard and mouse.

It is argued that both immersive and non-immersive VR have certain advantages and disadvantages for their application in cognitive rehabilitation and/or assessment (see Table 1). Despite these theoretical advantages of immersive VR and its increasing usage in cognitive rehabilitation, only very little is known about its benefits over the less expensive desktop applications with low immersion level.

1.2. Immersive vs non-immersive VR

As studies focusing on the role of VR immersion in the cognitive rehabilitation process, where exposure to VR is long-lasting, are scarce, we first will also discuss studies focusing on the application of VR in a form of a single trial memory assessment. Here we discuss 12 studies directly comparing low and high two levels of immersion levels in a memory assessment. We briefly discuss possible applications in education in order to link the proposed benefits of the technology to cognitive performance. We classify the studies based on the cognitive performance obtained using immersive VR in comparison to non-immersive technologies. To allow the comparison of the measured effects between individual studies, we calculated effect sizes as the mean difference in memory performance using HMD and desktop platform divided by pooled standard deviations in studies providing respective descriptive data (Lakens, 2013).

A pioneering study implicating better cognitive performance associated with immersive HMD presentation was conducted by (Pausch et al., 1997), who investigated the ability to find a target that was presented in a camouflaged scene. When the target was not present in the scene, participants were able to confirm its absence faster in HMDs than on the desktop. This study triggered the investigation of possible cognitive benefits associated with VR presented using HMDs.

It was suggested that HMDs improve the perception of spatial relations due to the stereoscopic

Table 1
Advantages and disadvantages of immersive and non-immersive VE.

Category	Description	Non-immersive (monitor)	Immersive (HMD)	Possible applications in cognitive training
		Advantages of VR		
VE environment	More realistic virtual environments enable training of real-life situations in a safe controlled environment	PARTIAL	YES	Using realistic VE results in higher ecological validity and thus facilitates the transfer of learned abilities to real life
	Investigate the neural correlates of task-related behavior and neuroplasticity changes as an effect of the therapy	YES	PARTIAL	The effect of therapy or training can be investigated when solving VE tasks in fMRI or using EEG
Interaction with VE	Realistic and intuitive interaction	NO	YES	Motor activation, the combination of body movement and cognitive therapy, the inclusion of body movement in navigation tasks
Stimuli control	Combination of the maximal control over the stimuli and realistic environment	PARTIAL	YES	The possibility to investigate the effect of ecological valid cognitive training while providing the same condition for each participant
	Engaging multiple sensory channels - making the experience more realistic	PARTIAL	YES	To engage participants in multisensory cognitive training which would enhance motivation for the training
	Incorporating number, form or combination of stimuli which would not be possible in the real world	PARTIAL	YES	The possibility to expose the participant to the conditions which would be difficult to simulate (e.g. rainy weather) and test/train the specific ability in different conditions
	Manipulation with the level of presence	NO	YES	The possibility to investigate the importance of the level of presence for training purposes
		Disadvantages of VR		
Category	Description	Non-immersive (monitor)	Immersive (HMD)	Possible solutions
Vision	Compression of estimated distances (depth perception)	YES	PARTIAL	Some of these disadvantages can be partly compensated by monocular visual effects that mimic the spatial cues, such as the size of objects and objects overlay, or by simple shadowing cues presented with the illumination direction. Binocular cues provided by HMD solve to some extent issues related to depth perception - dependent on the eye's accommodation
	Narrow field of view (FOV)	YES	YES	
	Distortion of angular declination (determining the angle between the visual target and the height of the viewer's eye) and restrictions of oculomotor cues	YES	PARTIAL	
	Lack of binocular depth cues	YES	NO	
	faster fatigue and overloading of the visual apparatus	PARTIAL	YES	

(Continued)

Table 1
(Continued)

Disadvantages of VR				
Category	Description	Non-immersive (monitor)	Immersive (HMD)	Possible solutions
Vision/side effects	Discomfort caused by the curvature of the lenses, which are primarily designed for eyes looking forward, as the head movement is used to directly control the rotation of FOV. This is in contrast to real-world movement, where we are accustomed to smaller head movements compensated by the saccadic eye movements	NO	YES	This disadvantage may be weakened by other systems that enable direct movement in the virtual scene without head/movements (e.g. CAVE)
	Visual strain and dry eyes problem	YES	YES	Limited duration of the session, eye drops application
Movement	The complete absence or only limited movement (motor efforts) which prevents the vestibular and proprioceptive system from receiving positional information	YES	PARTIAL	This issue is to some limited extent already addressed by new technologies which can create a very realistic perception of movement by linking real head movement (HMD) or the whole body (through the application of bikes, treadmills or sensors located on the human body/head) movements in VE and the real world. Currently, also HMD devices (e.g. HTC VIVE) enable whole-body movements and hand movements using sensors placed in the glasses and hand-holed sensors enabling body movements in small distances
	Head/body rotations disconnected from rotations in the virtual environment	YES	NO	The involvement of the rotation and tilt of the head and body and their exact synchronization during movement in VR seems to be the key aspect important for increased immersion
Side effects	Motion sickness (with symptoms of drowsiness, headaches, impaired balance and coordination, nausea, or blurred vision, etc.) due to sensory conflict, the discrepancy between information coming from external (mostly visual information about motion in VR) and internal sources (proprioception and the vestibular system informing us of our position in the real world)	YES	YES	Users often adjust to the visualization after repeated exposure. Moreover, some egocentric information can be derived also from visual inputs in the form of optical flow (visual changes resulting from the motion of the observer environment, manifesting as the apparent motion of the elements of the visual scene and indicating the direction in which the person moves. Interestingly, even this disadvantage of VR can be used as a therapeutic method for dizziness (vertigo) from travel sickness in so-called vestibular reeducation, as the VR presentation itself requires adaptation to discrepancies between internal and external information about the movement and thus supports the process of adaptation in the real world

presentation of the scene in contrast to standard "flat" desktop visualization. This hypothesis inspired the research addressing the utilization of HMDs in spatial memory. The study by Ruddle et al. (1999) was one of the first comparing navigation abilities in HMD and desktop setup. The participants were supposed to remember a layout of two buildings and then navigate from a starting point in a lobby to five rooms in a specified order. According to the obtained results, participants using HMD were faster and more accurate during the navigation task in comparison to the desktop.

A recent study by Krokos et al. (2019) in a group of 30 participants with no age specification tested the potential beneficial effect of higher immersion in spatial mnemonic strategy - so-called memory palaces or loci method. The authors used a complex VE - a palace and medieval town filled with faces and asked the participants to remember the positions of individual faces. After two-minute break participants were supposed to recall which face had belonged to a particular location. All participants were tested both using HMD and desktop in counterbalanced order. According to the results, participants were able to recall the faces more precisely using HMD in comparison to desktop condition (the mean recall accuracy percentage for HMD condition was 84.05% and the desktop condition 75.24%).

A similar approach was previously applied in the study by Mania et al. (2003) that analyzed memory performance in three scenarios: real-life room with glasses restricting the field of view, virtual room using an HMD, or virtual room presented on the desktop. The room had distinct walls and it was filled with geometrical objects. After three minutes of encoding the participants were asked to immediately recall the position of specific objects in the room. The participants recalled the information most accurately in restricted real-world and HMD scenarios (with the desktop condition being the least successful, the effect size of the difference between HMD and desktop is $d = 0.30$). However, after one week's delay, the performance did not differ across the different platforms.

In contrast to above listed spatial studies, some other studies report opposite findings. Sousa Santos et al. (2009) summarize studies on spatial memory and navigation and assume that previous findings are not conclusive. According to their findings from inter-subject design comparing 42 healthy volunteers (age of 14 to 40 years) in navigation tasks using HMD and desktop application, the participants performed globally better with less immersive technology (Sousa Santos et al., 2009). Similarly, studies applying non-spatial memory paradigms, mainly focused on the role of immersion in episodic memory recall, showed superior memory performance in the case of non-immersive VR presentation. In the study by Mania and Chalmers (Mania & Chalmers, 2001) a lecture was presented in four conditions: in a real environment, on a desktop, in HMD, and in audio-only. The HMD presentation resulted in the lowest recall performance in contrast to the best performance achieved using the real-world scenario. Similar results were concluded by Rand et al. (2005) who reported lower cognitive performance in groups of seniors ($d = 0.52$) and young adults ($d = 0.22$) when using HMD in comparison to desktop. Similar results were also found when using augmented reality (Rohrbach et al., 2019). Our recent study (Plechata et al., 2019) focused on the age-related differences in non-immersive and immersive shopping tasks also reported lower recall performance in the case of HMD. However, this effect was specific for the elderly participants ($d = 0.53$) and was absent in young adults.

With the increasing application of the new technology in the classrooms, possible benefits of immersive VE were intensively studied also for educational purposes. Originally, it was presumed that the more immersive technology might lead to higher motivation and increase focused attention in students. Increased knowledge gain when using immersive VR was confirmed by a recent meta-analysis with effect size $d = 0.24$ (Wu et al. 2020). However, some of the studies showed that higher immersion leads paradoxically to a lower ability to remember studied material (Frederiksen et al., 2019; Makransky et al., 2019; Moreno & Mayer, 2004). Yet, these studies helped to clarify the negative effect of immersion on memory recall observed in the studies reported below. It was suggested that the lower cognitive performance reported in the case of tasks presented using HMD was linked to the increased cognitive load associated with higher immersion. This hypothesis was studied by Makransky et al. (2019), who investigated the increase in cognitive load associated with higher immersion using EEG-based measures, leading to lower knowledge gain in HMD in comparison to the desktop presentation (effect size $d = 0.48$). Similar results were also reported by Frederiksen et al. (2019) who compared learning outcomes and cognitive load in students learning surgical skills using immersive and non-immersive VE training.

While most of the population is currently experienced with desktop devices such as PCs, tablets, and smart mobile phones, immersive technologies are not yet used on an everyday basis. Thus, it could be argued that the lack of previous experiences with immersive VR devices may affect performance in studies applying only a single session assessment. However, according to Frederiksen et al. (2019), repeated exposure leads to cognitive performance improved to the same extent for both more and less immersive technology. This finding implies that the lower performance in immersive VR (persisting after repeated exposure) arises indeed from the higher cognitive load (Frederiksen et al., 2019; Makransky et al., 2019) and not from the novelty of the technology used. Moreover, the cognitive load can be manifested more profoundly in the elderly (Plechata et al., 2019) as the higher age is associated with a decline in working memory functions, which are directly connected to workload processes (Cantin et al., 2009).

1.3. Memory rehabilitation in a virtual environment

Memory impairments were reported not only in heterogeneous mental and neurological disorders, such as schizophrenia (Forbes et al., 2009), depression (Rock et al., 2014), bipolar disorder (Bora & Özerdem, 2017), obsessive-compulsive disorder (Olley et al., 2007), Alzheimer disease (Bäckman et al., 2005) Parkinson disease (Whittington et al., 2000), Huntington disease (Montoya et al., 2006), multiple sclerosis (Lafosse et al., 2013) but also in AIDS (Watkins & Treisman, 2015) or stroke (Al-Qazzaz et al., 2014). Besides pathological changes, memory decline is also a part of healthy aging processes (Harada et al., 2013). Therefore, memory deficits may represent an important target for cognitive training in the elderly as well as cognitive rehabilitation in the above-mentioned mental and neurological disorders (Rodriguez et al., 2009; Sitzer et al., 2006).

Cognitive training represents the process of repeated cognitive exercises and interventions aimed at the enhancement of cognitive functions (Medalia & Choi, 2009) based on neuroplasticity principles (Rohling et al., 2009). The term *cognitive rehabilitation* or remediation is used in the clinical population to describe training aimed at the restoration of impaired cognitive functions. Further, we will address cognitive rehabilitation in general, regardless of the chosen rehabilitation approach and the target group.

A large part of current studies investigates the efficacy of computerized cognitive training (CCT). CCT enables the precise and repetitive presentation of the stimuli and typically applies elementary tasks focusing on one cognitive domain. Recent meta-analyses focusing on the efficacy of computer-assisted rehabilitation (Grynszpan et al., 2011; Hill et al., 2017; Motter et al., 2016) show a small to moderate effect on memory functions, confirming comparable efficacy to the paper-pencil approach (Elliott & Parente, 2014). A meta-analysis by Hill et al. (2017) reports the effect size of Hedges' $g = 0.35$ for general cognition in MCI and $g = 0.26$ for dementia. The studies included in meta-analysis mostly used simple computer tasks with gamification elements or computerized neuropsychological tests (e.g. Boendermaker et al., 2018).

Regarding complex three dimensional VEs, current reviews summarize studies focusing on the cognitive rehabilitation in traumatic brain injury (Maggio, De Luca, et al., 2019; Pietrzak et al., 2014; Shin & Kim, 2015), in post-stroke patients (Maggio, Latella, et al., 2019) or multiple sclerosis (Maggio, Russo, et al., 2019) showing improvement not only in balance and upper extremity functions but also in cognitive functions. Pietrzak et al. (2014) conclude the positive effect of VR on spatial memory but these findings are based on case studies results which are difficult to generalize.

Recent reviews support the application of VE also in cognitive rehabilitation in healthy and pathological aging (García-Betances et al., 2015; La Corte et al., 2019). The benefit of VE in comparison to the traditional motor or cognitive interventions was associated with a more positive attitude and increased motivation towards training (Hill et al., 2017). La Corte et al. (2019) points out that the rehabilitation results stay preliminary and provide data about feasibility but not enough data about efficacy.

Here we systematically review studies focusing particularly on memory training using complex three-dimensional VEs.

2. Method

A comprehensive literature search was conducted utilizing PubMed, Web of Science, and ScienceDirect. Search terms used included *memory rehabilitation AND virtual reality AND memory deficit*. The references of all selected studies were reviewed to search for additional studies not found in the initial search. Studies that did not utilize complex three-dimensional VE, did not measure the efficacy of the intervention, did not report any outcome measures besides VR and did not report memory outcome measure, studies written in other than the English language and case studies were excluded from the review.

To allow comparison in efficacy of VE in memory rehabilitation an effect size (d) was generated for each VE intervention in nine of the 21 studies included in this systematic review. The effect size was calculated as the mean difference in memory measure between an intervention condition and a control condition divided by the pooled standard deviation (Malloy & Milling, 2010; McGough & Faraone, 2009). For studies including more than one memory measure, the effect sizes were averaged across all standard memory measures. Effect sizes were not calculated for eight studies (Amado et al., 2016; Dehn et al., 2018, 2020; Gamito et al., 2014, 2019; Hofmann et al., 2003; Shema-Shiratzky et al., 2018) as they did not incorporate a control group. Studies by Gamito et al. (2012) and (2018) did not include control groups per se as they compare the efficacy between immersive and non-immersive VE, therefore we will discuss respective effect sizes in another chapter. We did not calculate the effect sizes for Gamito (2015), Optale (2010), and Cho and Lee (2019) because complete post-intervention descriptive data were not presented. Faria et al. (2016) reported as descriptives only medians and interquartile range (IQS), thus medians were used instead of means, and standard deviations were calculated as IQS/1.35.

3. Results

The study selection process is presented in Fig. 1. Table 2 summarizes 21 original studies observing the efficacy of VEs in the enhancement of memory functions published until now. While some of these studies were using specific task(s) designed for the training of memory (Dehn et al., 2018; Hofmann et al., 2003; Man et al., 2012; Optale et al., 2010; Yip & Man, 2013), part of the studies focused on practicing ADLs involving the use of memory abilities (Amado et al., 2016; Ana Lúcia Faria et al., 2016; Gamito et al., 2011, 2014, 2015, 2019; Man, 2018; Schreiber, 1999). ADLs use complex three-dimensional VEs for simulation of real-life situations, e.g. shopping, navigation, going to the post office, which is usually cognitively demanding. We also report studies aimed at the application of VR in the training of spatial navigation (Amado et al., 2016; Caglio et al., 2012; Hofmann et al., 2003). To add more clarity to the discussion of the role of immersion we divide the studies according to the used technology.

3.1. Effect sizes

The calculated effect sizes for memory outcome measures are summarized in Table 3. Effect sizes ranged from –1.41 to 1.41. According to Cohen's classification (1988) where $d = 0.2$ is considered a small effect, $d = 0.5$ is the medium effect, and 0.8 large effect size, four studies found small effect (Ana Lúcia Faria et al., 2020; Maier et al., 2020; Man, 2018; Man et al., 2012), two studies found medium effect (Ettenhofer et al., 2019; Yip & Man, 2013) and one study (Schreiber, 1999) is reporting large effect size. Four studies found no effect on memory (Ana L. Faria et al., 2018; Ana Lúcia Faria et al., 2016; Maier et al., 2020; Park et al., 2019) in comparison to active control conditions. Man et al., (2018) found a negative effect of VR in comparison to standard CCT programs.

It is important to mention that the control group conditions differed across the studies. Only two studies used a passive control group reporting medium (Ettenhofer et al., 2019) or small effect sizes (Man, 2018). Two studies used an active control condition not directly affecting cognition (e.g. music therapy) from which one found the large effect size (Schreiber, 1999) and one resulted in medium effect size (Yip & Man, 2013). In comparison to standard intervention programs, four studies found either a small effect of VR (Ana Lúcia Faria et al., 2020; Maier et al., 2020; Man et al., 2012; Park et al., 2019) or no effect of VR (Ana L. Faria et al., 2018; Ana Lúcia Faria et al., 2016; Maier et al., 2020; Park et al., 2019) One study favored the standard approach over VR, reporting the negative effects of VR (Man, 2018). Importantly, only one study using immersive VR allowed us to calculate the effect size, which showed a small additional value of immersive VR in comparison to standard CCT (Park et al., 2019) which is in consensus with benefits associated with non-immersive VR.

3.2. Non-immersive VR in memory training

The non-immersive technology, using standard computers and monitor screens, is currently a cheaper

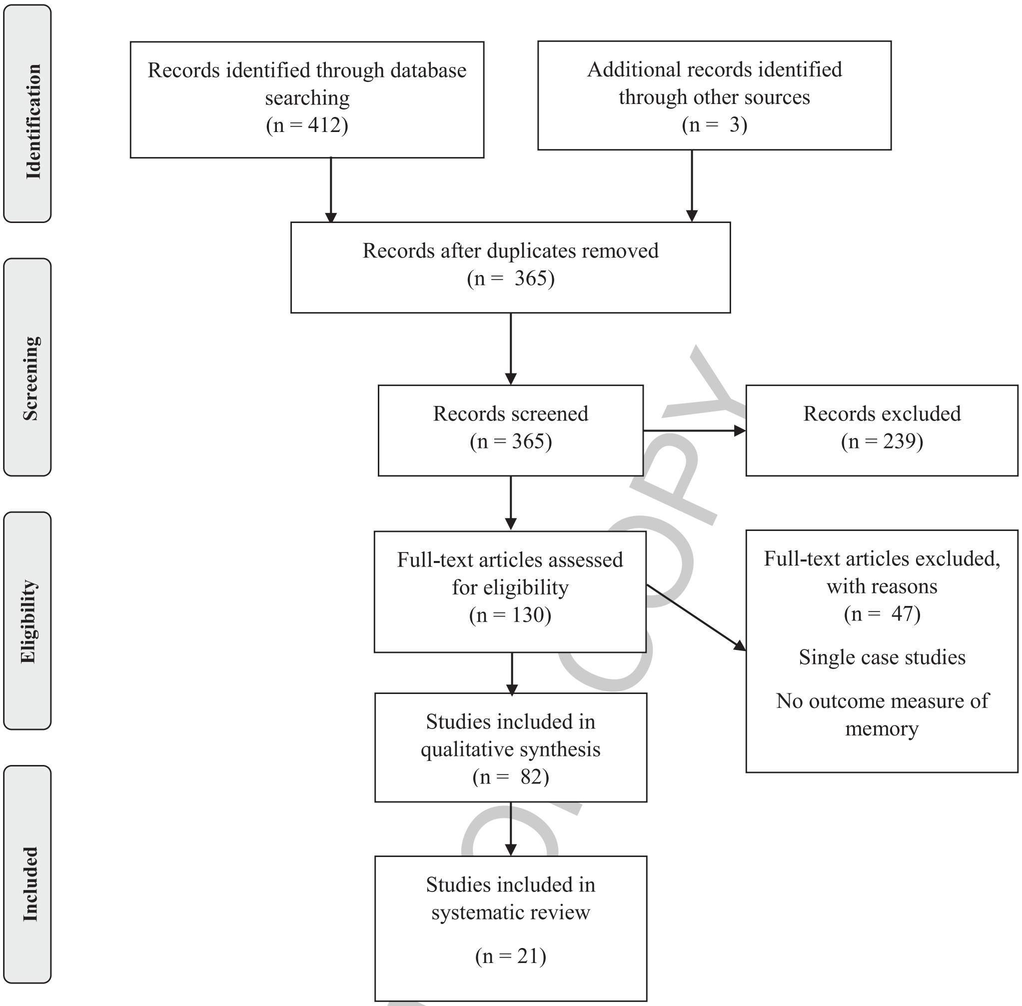

Fig. 1. Flowchart of the review proces.

and more available option for cognitive rehabilitation. In comparison to immersive technology, it can be also more suitable for training in a group setting, as there is no need to supervise each individual as may be the case in immersive VR. As a result, most of the studies were conducted using non-immersive VE. Here we review the findings of research studies applying non-immersive VE technology in cognitive rehabilitation (for calculated effect sizes see Table 3).

The first study using complex VEs was carried out in 1999 (Schreiber, 1999). Schreiber‘s study (1999) was one of the first to simulate a household environment and used ADLs for cognitive rehabilitation in patients with dementia. In comparison to the control group, the experimental group exhibited improvement in visual recall, but not in other cognitive measures. Later other studies successfully applied ADLs using apartments/supermarkets simulation in various clinical populations (Amado et al., 2016; Dehn et al., 2018; Ana Lúcia Faria et al., 2016; Gamito et al., 2014, 2015, 2019; Hofmann et al., 2003).

Hofmanm et al. (2003) applied a shopping scenario and navigation tasks in nine patients with Alzheimer’s disease and nine patients with depression using a touch screen for the VE interaction. Even though patients with Alzheimer’s disease improved in the VE task itself, they did not improve in the standard cognitive tests. On the other hand, depressed patients and control improved also in standard outcome measures. The fact that the study failed to show significant effects can be associated with a small sample size ($n = 9$). Another study focusing on patients with questionable dementia using VE ADLs was conducted by

Table 2
Virtual environments in memory training

Number	Memory domain	Reference	Study sample	Training task	Technology/ device	Training program duration	Outcome measure	Control group/ treatement	Results
1	Visuospatial memory and verbal memory	Schreiber, 1999	Mildly to moderately cognitively impaired adults (aged 65 years or above) alternately assigned to a training ($n = 7$) and control group ($n = 7$)	The VE tasks consisted of a simulation of real-life tasks simulated in a virtual environment of an apartment. The subjects were asked to find certain targets or rooms in an apartment	Non-immersive/ monitor and joystick	30-minute sessions 5 days per week (10 sessions)	Five tests of memory functions from the Rivermead Behavioural Memory Test and the Nürnberger Alters Inventar	A chat with a psychologist to keep social stimulation comparable	The analyses of the change scores revealed different effects of the training group in comparison to the control group for the conditions immediate recall of meaningful visual Information (NAI Picture Test) and to a lesser degree for retention of topographical information (RBMT Route learning). The control group, on the other hand, showed neither improvement nor decline in performance
2	Verbal memory, free/cued recall, implicit/explicit learning	Hofmann et al, 2003	Patients with the diagnosis of probable AD ($n = 9$), patients with a major depressive episode ($n = 9$), age-matched healthy subjects ($n = 10$)	The VE training compromised of daily living activities. The participant had to find a predefined shopping route, buy three items, and answer 10 follow-up questions	Non-immersive/ touch-screen	3 times per week (12 sessions)	Mini-Mental State Examination, The Trail-Making-Test (Version A), Montgomery and Asberg Depression Rating Scale, subjective training effects evaluated with a home-made questionnaire	Control group N/A	Substantial training gains were observed, including a significant reduction of mistakes. Training effects were sustained until follow-up 3 weeks later. But no significant improvement was found for the outcome measures of cognitive performance
3	Verbal and spatial memory	Optale et al, 2010	Older adults (aged 65 years or above) with memory deficits randomly assigned to VR group ($n = 15$) and control group ($n = 16$)	The VE training involved remembering taken routes and their orientation	Immersive/ HMD and joystick	3 sessions per week over 3 months for a total of 36 sessions; 2 sessions per week over 3 months for a total of 24 sessions (50 sessions)	Mini Mental State Examination; Mental Status in Neurology; Digit Span; VSR Test; Verbal Fluency; Dual-Task Performance; Cognitive Estimation Test; Trail Making Test; Clock Drawing Test; Activities of Daily Living Functions and Mobility; Instrumental Activities of Daily Living; Geriatric Depression Scale	Music therapy in the control group	VR group showed significant improvements in memory tests, especially in long-term recall and in several other aspects of cognition. In contrast, the control group showed a progressive decline

(Continued)

Table 2
(Continued)

Number	Memory domain	Reference	Study sample	Training task	Technology/ device	Training program duration	Outcome measure	Control group/ treatement	Results
4	Semantic and episodic memory	Man, Chung & Lee, 2012	Adults (65 years or above) with questionable dementia randomly assigned to VR group ($n = 20$) and therapist-led memory training group ($n = 24$)	The VR training included tasks to memorize certain items and placing them in the right places or to search and buy requested items in a shop	Non-immersive/ monitor and key-board/joystick	2-3 sessions per week for 30 min each (10 sessions)	Multifactorial Memory Questionnaire; Fuld Object Memory Evaluation; Hong Kong Chinese version of the Lawton Instrumental Activities of Daily Living	Therapist-led training similar to the VR, but with color-print images that matched the VR images	The results demonstrated positive training effects in both groups, with the VR group showing greater improvement in objective memory performance and the non-VR group showing better subjective memory results
5	Prospective memory	Yip & Man, 2013	Adults with acquired brain injury were randomly assigned to the VR group ($n = 19$) and control group ($n = 18$)	The VR training consisted of event-based tasks completed in a VR convenience store. The participants were required to remember and perform tasks in the VR store	Non-immersive/ monitor and keyboard and mouse/joystick	2 sessions per week for 30–45 minutes (12 sessions)	Behavioral checklist of a prospective memory task in a real environment; Cambridge Prospective Memory Test – Chinese Version; Hong Kong List Learning Test; Frontal Assessment Battery; Word Fluency Test – Chinese Version; Colour Trails Test; Chinese Version of the Community Integration Questionnaire; Self-efficacy questionnaire in performing everyday prospective memory tasks	Reading and table games activities during the treatment phase	In the VR group, significant improvements were demonstrated in VR-based assessment and in the real-life behavioral prospective memory test in event-based and time-based tasks, but not in ongoing tasks. The self-efficacy questionnaire also showed significant improvement. For other standardized assessments, a significant improvement was shown in prospective memory measures, in frontal assessment, and verbal fluency. No significant difference was found in any outcome measure in the control group
6	Working memory, visuospatial memory, and navigation	Gamito et al., 2014	Stroke patients were randomly assigned to the desktop VR group ($N = 8$) and the HMD VR group ($N = 9$)	The VR training was compromised of daily living activities conducted in the virtual town	Non-immersive/ monitor and keyboard and mouse+immersive/HMD	Once a week (12 sessions)	Wechsler Memory Scale, Rey Complex Figure, the Toulouse-Piéron	Control group N/A	The results showed increased working memory and sustained attention from initial to final assessment regardless of the VR device used

7	Working memory tasks, visuospatial memory, recognition	Gamito et al., 2015	20 stroke patients were randomly assigned to the experimental group ($n = 10$) and the wait-listed control group ($n = 10$)	The VR tasks constituted of daily living activities, e.g. shopping or finding VE characters dressed in specific colors in a virtual town. The tasks had increasing difficulty	Immersive/ HMD and keyboard and mouse (not specified)	2 to 3 sessions per week for 4–6 week (12 sessions)	Wechsler Memory Scale, Toulouse–Pieron Test, Rey Complex Figure	Waiting list	The results showed significant improvements in attention and memory functions in the experimental group, but not in the controls
8	Prospective memory	Mathews et al., 2016	15 stroke patients	The memory training had two parts. In the first part, the participants were taught visual imagery to remember prospective memory tasks better. After the treatment, participants practiced their memory skills using VE games where they could perform the tasks	Non-immersive/ monitor and joystick	2 sessions per week for one hour for 5 weeks (10 sessions)	Cambridge Prospective Memory; Paired Associates	Control group N/A	The prospective memory skills of participants have improved significantly after the treatment. The improvement was stable 4 weeks after training
9	Visuospatial memory and navigation	Amado et al., 2016	7 patients with schizophrenia	The VR training consisted of daily living activities conducted in VR town, e.g. shopping or memorizing the route to the supermarket	Non-immersive/ monitor and joystick	Once a week for 90 min (12 sessions)	D2 cancelation test; WAIS: code; WAIS: Digit Span; WAIS: Visuospatial span; Grober and Buschke verbal learning test; Zoo map; Battery for assessment of dysexecutive syndrome; Rey–Osterrieth Complex Figure Test	Control group N/A	The results showed improvement in attention, working memory, prospective, and retrospective memory benefits. No improvement was found in planning

(Continued)

Table 2
(Continued)

Number	Memory domain	Reference	Study sample	Training task	Technology/ device	Training program duration	Outcome measure	Control group/ treatement	Results
10	Declarative memory	Faria et al., 2016	18 stroke patients were randomly assigned to the experimental group ($N=9$) and to the control group ($N=9$)	The VR training compromised of activities of daily living conducted in VE town, e.g in a supermarket, a post office, or a bank (Reh@City)	Non-immersive/ monitor and joystick	20 min sessions from 4 to 6 weeks (12 sessions)	Addenbrooke Cognitive Examination, Trail Making Test A and B, Picture Arrangement from WAIS-III and Stroke Impact Scale 3.0	Conventional rehabilitation	The results showed significant improvements in global cognitive functioning, attention, memory, visuospatial abilities, executive functions, emotion, and overall recovery in the VR group. The control group only improved in self-reported memory and social participation. A between-groups analysis showed significantly greater improvements in global cognitive functioning, attention, and executive functions in the VR group in comparison with the conventional rehabilitation
11	Verbal memory	Dehn et al., 2018	37 patients with depressive disorders were assigned to the VR-environment group ($n=21$) and the desktop group ($n=19$)	The VE training consisted of a VE simulation of grocery shopping	Non-immersive/ the OctaVis - eight LCD-touch-screens surrounding participant and non-immersive/monitor	8 sessions during 8 consecutive days (no time restriction for a session) (16 sessions)	Questionnaire for Complaints of Cognitive Disturbances, Digit Span Task (forward and backward, the Rey Auditory Verbal Learning Test; Rey/Taylor-Complex-Figure, Regensburg Verbal Fluency Test, Bergen Right-Left Discrimination Test+Real-life shopping task	Control group N/A	The results did not show significantly greater improvement using more immersive technology. Both groups improved in visuospatial memory, phasic alertness improved only in the desktop condition in contrast to mental rotation which showed improvement only in the more immersive group

12	Transfer of vocational training and spatial navigation in VR on memory performance	Man, 2018	90 young ketamine users were randomly assigned to the VR group ($n = 30$), to the tutor-administered group ($n = 30$) or to the wait-listed control group ($n = 30$)	The VE training consisted of vocational training activities in a boutique, e.g. sorting clothes according to the category or color; identifying clothes based on criteria, handling customer requests, etc.	Non-immersive/ monitor and joystick, keyboard and mouse	5-6 sessions per weeks for 60 min (15 sessions)	TONI-III, The Digit Vigilance Test, Memory test. The Rivermead Behavioural Memory Test, The Wisconsin Card Sorting Test	Tutor administred manual-based train-ing/waiting list	The significant improvements in attention and improvements in memory were found in the VR group and were stable after 3 months. Both groups exhibited significantly improved vocational skills after training which were maintained during follow-up, and improved self-efficacy
13	Working memory	Faria et al., 2018	24 participants in the chronic stage of stroke were allocated to the VR group ($N = 12$) and the control group ($N = 12$)	The VE tasks included finding targets within a pool of distractors. In the memory variant, the targets had to be memorized	Non-immersive/ monitor with movement tracking software	3 sessions per week for 1 month (12 sessions)	Montreal Cognitive Assessment; Single Letter Cancelation; the Digit Cancelation, Bells Test; Fugl-Meyer Assessment Test; Chedoke Arm and Hand Activity Inventory; Modified Ashworth Scale; Barthel Index	Conventional occupational therapy	Our results show that both groups improved in motor functioning, but the VR group showed significantly higher outcomes in the arm subpart of the Fugl-Meyer Assessment Test. Improvements in cognitive function were significant and similar in both groups
14	Working memory and auditory memory	Gamito et al., 2019	25 healthy participants in age 65–85	The VE training was compromised of several daily living activities, e.g. selecting ingredients to bake a cake, shopping, remembering news from TV	Non-immersive/ monitor	2 sessions per week for 30 min for 6 weeks (12 sessions)	The Frontal Assessment Battery, Wisconsin Card Sorting Test; the Rey Complex Figure, Beck Depression Inventory-II, Everyday Competence Questionnaire	Control group N/A	A significant improvement was found in visual memory, attention, and cognitive flexibility. Results also suggest that participants with lower baseline cognitive performance levels improved most after these sessions

(Continued)

Table 2
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Number	Memory domain	Reference	Study sample	Training task	Technology/ device	Training program duration	Outcome measure	Control group/ treatement	Results
15	Working memory	Ettenhoffer et al., 2019	17 participants with chronic TBI were randomly assigned to the VR group ($N = 11$) and the wait-listed control group ($N = 6$)	The VE training consisted of a driving simulator with cognitive tasks	Non-immersive/ curved screen and a driving console (with brake and gas pedals, steering wheel, etc)	90-minute sessions during 4 weeks (6 sessions)	WAIS-IV Digit Span; Trail Making Test Part A; WAIS-IV Symbol Search; WAIS-IV Coding; Trail Making Test Part B; Controlled Oral Word Association Test, Letters & Animals; California Verbal Learning Test-II: Grooved Pegboard; Neurobehavioral Symptom Inventory; PTSD Checklist-Civilian; Beck Depression Inventory-II; Epworth Sleepiness Scale; Fatigue Severity Scale; SF-36v2 Health Survey; Satisfaction with Life Scale; Test of Premorbid Functioning; Glasgow Outcome Scale-Extended	Waiting list	The results show significantly greater improvement in working memory and visual search and selective attention in the VR group in comparison to the control group. The change in other cognitive domains did not differ across the groups
16	Working memory	Cho & Lee, 2019	42 patients with acute stage stroke were randomly assigned to the VR group (n = 21) and control group in CCT (n = 21)	The VE training consisted of two tasks. The first task was to catch a specific number of fish with the upper extremity. The second task consisted of a picture matching program where participant flips cards and has to find a matching picture	Immersive/ HMD and hand trackers/non-immersive monitor and keyboard	5 sessions per week for 30 minutes (20 sessions)	Loewenstein Occupational Therapy Cognitive Assessment; the Visual Continuous Performance Test; Auditory Continuous Performance Test; Verbal Learning Test; Visual Recognition Test	Computerized cognitive training (Korean Rehacom version)	The results showed improvement of attention and memory and activity of daily living performance in both groups. But the effect of rehabilitation was larger in the experimental group, specifically for auditory attention and visual memory recall and recognition

17	Working memory and navigation	Shema-Shiratzky, 2019	14 non-medicated school-aged children with ADHD	The VE training combined physical activity (walking on a treadmill) with cognitive tasks. By changing the speed, adding obstacles, or changing path complexity the training focused on sustained and divided attention, navigation and memory	Non-immersive/ motion capture camera, screen, and treadmill	3 sessions per week for 30 min to 1 hour for 6 weeks (18 sessions)	The NeuroTrax™ computerized neuropsychological battery ("Stroop test", "Go-NoGo", verbal and non-verbal memory tasks, a "Catch game", which tests set-shifting, adaptation, and planning)	Control group N/A	Based on parental reports, there was a significant improvement in children's social problems and psychosomatic behavior after the training. Executive function and memory were improved post-training while attention was unchanged. Long-term training effects were maintained in memory and executive function
18	Verbal working memory and visuospatial memory	Park, 2019	26 adults aged 65 years and older diagnosed with MCI were randomly allocated into two VR group ($n = 10$) and in the control group ($n = 11$)	The VR training consisted of several tasks conducted in a virtual home setting scenario in four different rooms (different tasks were designated to specific rooms)	Immersive/ HMD with hand tracking and heat cameras (augmented reality)	3 sessions per week for 30 min for 6 weeks (18 sessions)	Mini-Mental State Examination, the Clinical Dementia Rating Scale, the Beck Depression Inventory, and the Modified Barthel Index consists of nine cognitive tests: the Verbal Fluency Test, the Boston Naming Test, the Word List Learning Test, the Word List Recall Test, the Word List Recognition Test, the Constructional Praxis Test, the Constructional Recall Test, Trail Making Test A and B	Conventional computer-assisted cognitive training system	The results showed significant improvement in the VR group in comparison to the control group only in visuospatial working memory ($d = 1.14$) but not in other measures of memory or different cognitive functions
19	Verbal memory	Faria, 2020	36 stroke patients were randomly assigned to the VR group ($n = 14$) and paper-pencil group ($n = 18$)	The VR training compromised of activities of daily living conducted in VE town, e.g in a supermarket, a post office, or a bank. The patients used their paretic arm to solve the tasks (Reh@City v2.0)	Non-immersive/ LCD monitor and customized handle with a tracking pattern on the surface	12 sessions (frequency not specified)	Montreal Cognitive Assessment; Trial Making Test A and B, Wechsler Memory Scale-III (WMS-III), Digit Span, Digit Symbol Coding (WAIS-III), Symbol Search (WAIS-III), Vocabulary (WAIS-III)	Personalized and adapted paper-and-pencil training	The VR group improved significantly in general cognitive functioning, attention, visuospatial ability, and executive functions. The control group improved in orientation

(Continued)

Table 2
(Continued)

Number	Memory domain	Reference	Study sample	Training task	Technology/ device	Training program duration	Outcome measure	Control group/ treatement	Results
20	Visual memory	Dehn, 2020	20 stroke patients and 20 healthy controls completed the VR training program	The VR training consisted of a VE simulation of grocery shopping	Non-immersive/ the OctaVis - eight LCD-touch-screens surrounding participant	8 sessions (no time restrictions) in 14 days	The Rey-Osterrieth Complex-Figure, the Taylor Complex Figure Test, Test of Attentional Performance, the Digit Span task [forward and backward], the Corsi block tapping test, the Regensburg Word Fluency Test, The Bergen Right-Left Discrimination Test	Control group N/A	Both groups improved in visual scanning, mental rotation, visuoconstruction, and cognitive flexibility. The patient group also improved in visual memory retrieval and diminished memory complaints
21	Visuospatial short-term memory	Maier, 2020	30 stroke patients randomly divided into the VR group ($n = 16$) and control group ($n = 14$)	The VR training consisted of three scenarios for 10 minutes: the complex Spheroids focused on selecting specific colors according to the predefined sequence, the Star Constellations where a participant remembers a constellation of stars and reproduces it, and the Quality Control scenario targeting divided attention among two tasks	Non-immersive/ monitor and tracking wristbands	30 min every workday for 6 weeks (30 sessions)	The Corsi Block Tapping Test Forward, the Trail Making Test A and B, the Wechsler Adult Intelligence VI, Digit Span Forward, the Rey Auditory Verbal Learning Test Immediate and Delayed, the WAIS Digit Span Backward, the WAIS Digit Symbol Coding, the Frontal Assessment Battery, the Star Cancellation Test	Standard cognitive tasks at home	The VR group improved significantly in attention, spatial awareness, and generalized cognitive functioning. There was no change in either memory or executive functions. For the control group, no significant change over time was found

Literature traditionally differentiates memory types varying in time courses of memory retention: sensory register, short-term memory, working memory, and long-term memory (Atkinson and Shiffrin 1968). In long-term memory two major systems can be distinguished: (1) declarative or explicit memory - consciousness recollection of facts (semantic) and events (episodic) and (2) non-consciousness perceptual and motor skills (e.g. procedural memory). Another important categorization is based on the type of memory content – e.g. verbal memory, visuospatial memory, spatial/navigational memory, odor memory, etc. Memory can be divided into the prospective memory - remembering to perform planned actions or retrospective memory - remembering actions or information from the past.

Table 3
Summary of effect sizes for memory measures outcome

Study and treatment condition	Treatment condition	Control condition	Sample size treatment/control	d
Schreiber, 1999	Non-immersive VE	A chat with a psychologist	7/7	1.41
Man, Chung & Lee, 2012	Non-immesive VE	Therapist-led training similar to the VR	20/24	0.36
Yip & Man, 2013	Non-immersive VE	Reading and table games activities	19/18	0.54
Faria et al., 2016	Non-immersive VE	Conventional rehabilitation	8/8	0
Man, 2018	Non-immersive VR	Tutor-administered rehabilitation	30/30	–1.41
Man, 2018	Non-immersive VR	Waiting list	30/30	0.25
Faria et al., 2018	Non-immersive VE	Conventional occupational therapy	12/12	0
Ettenhoffer et al., 2019	Non-immersive VE	Waiting list	11/6	0.54
Park et al., 2019	Immersive VE	Computerized-cognitive training	10/11	0.29
Faria et al., 2020	Non-immersive VE	Adaptive paper-and-pencil training	14/18	0.32
Maier et al., 2020	Non-immersive VE	Standard cognitive tasks at home	16/14	0.15

Man et al. (2012). In this study, the patients were randomly divided into the VE ($n = 20$) and therapist-led ($n = 24$) cognitive training. The VE group interacted with the VE using a chosen device (keyboard or joystick according to their preference). The patients improved in both groups but performance in objective memory increased more strongly in the VE group in contrast to the superior results in subjectively evaluated memory in the group led by the therapist.

Gamito et al. (2014, 2015) compared the effect of ADLs trained in a virtual town with a group of stroke patients using non-immersive ($n = 8$) and immersive ($n = 9$) platforms. The comparison is discussed later. The group in a non-immersive setting improved in working memory and sustained attention. Another study applying similar ADLs training in 28 healthy elderly showed a significant gain in attention, visual memory, and cognitive flexibility (Gamito et al., 2019). Faria et al. (2016) also trained ADLs using software called Reh@City with nine stroke patients in the experimental group and nine stroke patients conducting conventional rehabilitation. In the comparison with the control group, the cognitive enhancement was more pronounced in the VE group, specifically in global cognitive functioning. The follow-up study by Faria et al. (2020) investigated the efficacy of the Reh@City v2.0 in the group of stroke patients who were randomly assigned to the VR group ($n = 14$) or control group ($n = 18$). The control group conducted personalized and adaptive paper-pencil training, making the condition as comparable as possible. Patients in the VR interacted with the VE using their paretic upper extremity. According to their results, the VR group showed higher improvement in general cognitive functioning. Concerning the memory domain, the additional effect of Reh@City was of small effect size ($d = 0.32$).

Mathews et al. (2016) taught stroke patients prospective memory strategies of visual imagery and then used the VE household for practicing memory skills. The improvement in prospective memory measures was stable after four weeks of the treatment, however, there was no control group included.

Yip and Man (2013) used a VE convenience store to train prospective memory in patients after brain injury ($n = 19$) whereas the patients in the control group ($n = 18$) spent time reading and playing board games. The VE group improved in the standardized and real-life prospective memory measures, suggesting the successful transfer of learned abilities into everyday life. The control group did not show any increase in cognitive performance.

In the study of Amado et al. (2016) seven patients with chronic schizophrenia completed a cognitive rehabilitation program in a complex virtual city performing ADLs. The authors report increased performance in attention, working memory, prospective and retrospective memory, while the patients did not improve in planning. Dehn et al. (2018) also focused on psychiatric patients, specifically on participants with major depression. In the study, the authors compared the efficacy of ADL training using the OctaVis - eight LCD-touch-screens surrounding participant immersive as immersive condition ($n = 21$) and non-immersive ($n = 19$) technology using PC desktop. Both groups improved in visuospatial memory, while phasic alertness improved only in the desktop condition in contrast to the mental rotation, which showed improvement only using more immersive technology. This supports the previously suggested role of immersion in the perception of spatial relations. Details are discussed in the chapter *Implications of immersion for memory rehabilitation.* A follow-up study (Dehn et al., 2020) compared the effect of the virtual shopping task presented using the OctaVis in the healthy controls ($n = 20$) and stroke patients ($n = 20$). Even though both groups improved in terms of visual scanning, mental rotation, visuoconstruction, and cognitive flexibility and patients improved in visual memory retrieval, there was no control group included to compare the effect of the intervention

Man et al. (2018) used a VE boutique for vocational therapy in drug abusers ($n = 30$) and compared it with tutor-based intervention ($n = 30$) and waiting list group ($n = 30$). The intervention in both groups had very similar content, only the tutor based program used printout materials instead of the VE boutique. Both groups significantly improved their vocational skills but only the VE group showed also increased performance in memory and attention tasks.

Some recent studies presented VE on larger screens (or several screens), while the participants interact with the VE mostly using their body movements. This experience can be due to more intuitive interaction with VE, comparable to some extent to immersive HMDs. Recently, the combination of motor and cognitive rehabilitation has been considered to be the most effective approach influencing both cognitive performance and functional outcome (Karssemeijer et al., 2017). This was also demonstrated by Faria et al. (2018) who used VE cognitive tasks requiring upper limb movement in stroke patients. The control group ($n = 12$) which attended conventional occupational therapy involving motor and cognitive rehabilitation, showed similar cognitive improvement as the VE group ($n = 12$). Nevertheless, the VE group showed a much larger improvement in the upper arm performance.

Ettenhoffer et al (2019) studied the efficacy of VE cognitive training in traumatic brain patients using a driving simulator with a curved screen while solving various cognitive tasks. The VE group ($n = 11$) improved in working memory, visual search, and selective attention in comparison to the waiting list control group ($n = 6$).

Shema-Shiratzky (2018) focused on non-medicated children with ADHD. The VE group ($n = 14$) trained memory, attention, and navigation during walking on a treadmill with specific obstacles. The training did not affect attention but led to the improvement in executive functions and memory measures. Unfortunately, the study was lacking a control group.

A recent study by Maier et al. (2020) studied the effect of a non-immersive VR program, where participants interacted with VE using tracking wristbands, with standard cognitive training conducted at home. The group of stroke patients was randomly assigned to the VR condition ($n = 16$) and the control condition ($n = 14$). In comparison to the control group, which did not improve over time, the VR group attention, spatial awareness, and generalized cognitive functioning. But no significant changes were found in the memory domain.

3.3. Immersive VR in memory training

A smaller amount of the selected studies worked with immersive technology – HMDs enabling stereoscopic presentation. One of the first studies was conducted by Optale et al. (2010) on elderly participants ($n = 15$) with memory deficits. The VE training consisted of active navigation using gentle joystick movement and was combined with sessions of auditory stimulation (listening to the stories). Participants in the VE group showed improvement in several cognitive measures with the largest increase in long-term memory with effect size $d = 0.7$. In contrast, the control group attending music therapy showed a progressive decline.

Gamito et al. used a complex virtual city environment to train ADLs in the following studies using the same interface - HMD combined with keyboard and mouse (2014, 2015). The study (2014) comparing immersive and non-immersive platforms conducted in stroke patients as discussed in another section, led to an improvement in memory and attention in both groups. Follow-up studies on the 10 stroke patients and 10 patients on the waiting list showed results, the increased improvement in attention and memory in the VE group (2015).

Cho and Lee (2019) also worked with stroke patients but approached the training design differently. The authors used HMD and hand trackers to combine cognitive training with physical activity. The patients in the VE group ($n = 21$) trained using two gamified tasks requiring upper extremity movement and compared the training benefits with CCT Rehacom ($n = 21$). The authors reported the improvement of cognitive functions and in ADLs in both groups. The rehabilitation effect was larger in the experimental VE group, specifically for auditory attention, visual memory recall, and recognition.

A recent study by Park (2019) focuses on stroke patients and compared standard CCT program with immersive VR with advanced hand tracking and heat cameras enabling natural interaction with VR. The VR group ($n = 10$) in comparison to the control group ($n = 11$) improved only in visuospatial memory

($d = 1.14$) but not in other memory measures resulting only in a small effect size (see Table 3).

3.4. Comparison between immersive and non-immersive virtual reality

With better availability of immersive HMD technology, the rising tendency in the usage of HMD in cognitive rehabilitation can be expected. The meta-analysis conducted by Hill et al. (2017) emphasizes the importance of immersive technology for cognitive rehabilitation in the population with dementia patients, as the strongest evidence for the efficacy of CCT in this population is driven by the studies with immersive VE and Nintendo Wii. However, to our knowledge, there are only two comparative studies directly focusing on the role of immersion in cognitive training (Dehn et al., 2018; Gamito et al., 2014) for more details see Table 2 (Dehn et al., 2018; Gamito et al., 2014), thus no such conclusions can be made.

Gamito et al. (2014) randomly divided 17 stroke patients into two groups, eight patients underwent twelve sessions of cognitive training using HMD and nine patients completed the training using the desktop application. In both groups, the training tasks used the same simulation of ADLs aimed at attention and memory. In both conditions, the participants used a mouse and keyboard to interact with VE. In this study, a significant improvement was documented in working memory and sustained attention regardless of the applied VE device.

More recently, Dehn et al. (2018) conducted a comparison study on a larger sample ($n = 38$) of depressive patients using a more immersive system with eight LCD touch screens surrounding the participant in comparison to a non-immersive system (monitor screen). The VE immersive and non-immersive training tasks consisted of the identical shopping simulation. The interaction with the device was similar in both conditions - joystick and tapping the screen for selecting products. According to the results, visuospatial imagery improved only in the more immersive group and visuospatial recall increased more profoundly in the more immersive group in comparison to the non-immersive group. On the other hand, the non-immersive condition group but not the more immersive group improved in phasic alertness. Neither the experimental nor the control group improved in real-life shopping. This suggests the importance of stereoscopic presentation for visuospatial abilities.

As only two studies are analyzing the identical VE tasks presented either in immersive or less immersive platforms we included in this section also the two studies comparing complex immersive and semi-immersive VE with standard CCT (Cho & Lee, 2019; Kim et al., 2011). Cho and Lee (2019) compared the efficacy of standard CCT using the Korean version of the Rehacom program (Yoo et al., 2015) with immersive VE rehabilitation in acute stroke patients. The participants in the VE experimental group completed a combination of CCT and immersive training. Immersive VE training consisted of two games: catching fish game and picture matching where they flipped cards to identify the same picture. The participants used HMD and hand-tracking. The authors reported the improvement of cognitive functions and in ADLs in both groups. The rehabilitation effect was larger in the immersive group, specifically for auditory attention, visual memory recall, and recognition. As the immersive group used both - the VE training system and CCT, we can assume only the added value of immersive VE.

According to the above reported results, it is very difficult to conclude the role of immersion in cognitive training. Dehn et al. (2018) and Gamito et al. (2014) compared the impact of the same training tasks presented on different platforms, but Dehn et al. (2018) used as the more immersive platform the system of eight LED screens and Gamito et al. (2014) did not use specific controllers nor hand tracking devices for the VE interaction. On the other hand, a study comparing VE incorporating body movements (Cho & Lee, 2019; Kim et al., 2011) showed added value of immersive VE for cognitive rehabilitation. The beneficial effect of immersiveness was shown also by Park et al. (2019) who combined immersive VR with augmented reality and motion tracking. According to the results, the immersive virtual reality had only a small effect on memory measures ($d = 0.29$) in general, but the effect on visuospatial working memory was in comparison to standard CCT large ($d = 1.13$).

This would suggest that the beneficial effects can be increased by the increasing level of immersion and incorporating body movements, however, studies targeting this issue directly are still missing.

4. Discussion

Even though the number of VE tasks designed for memory training is increasing, most of them are still in the process of evaluation and validation for training purposes (e.g. Canty et al. 2014; Clemenson and Stark 2015; Vallejo et al. 2017; Plechatá et al. 2021). Despite some positive effects reported in the above-mentioned training programs, it is still not possible to generalize the findings of the existing studies for cognitive rehabilitation. This is mainly due to a limited number of studies and the inconsistencies between individual studies that differed in various parameters: used VR system, the length, and frequency of the training, the design of the used VR task, the number of sessions (minimum = 6, maximum = 50), clinical population of the treated group or outcome measures. Besides that, the study samples were rather small with a maximum of 30 participants in the experimental group. Moreover, only thirteen of the 21 reported studies included control groups (see Table 2), two of these studies incorporated the control group in a waiting list (Ettenhofer et al., 2019; Gamito et al., 2015), and the study conducted by Man et al. (Man et al., 2012) included one active and one passive control group. The rest of the studies lack control groups (Amado et al., 2016; Caglio et al., 2012; Dehn et al., 2018; Gamito et al., 2011, 2014, 2015; Hofmann et al., 2003; Kim et al., 2011; Mathews et al., 2016) preventing us from calculating the relevant effect sizes.

As can be seen from the studies listed above, so far there are only a few studies using immersive technology in memory rehabilitation. Moreover, besides the problematic methodological issues such as small sample sizes (see Table 2) and missing control groups, there are also crucial differences in the technological approaches used. Older HMDs were missing interactive controllers, therefore many studies used standard keyboards and PC mouse for interaction with the environment (Gamito et al., 2011, 2014, 2015; Optale et al., 2010). This can potentially affect the intervention results, as we discuss in the following section. According to the reported effect sizes, the additional value of complex VEs applied for memory rehabilitation is only limited.

4.1. Implications for memory rehabilitation and the role of enjoyment and intuitiveness

The use of immersive VE for cognitive assessment may have some crucial limitations reported previously (e.g. Sousa Santos et al. 2009; Mania and Chalmers 2001). However, there are still some valid arguments for the application of immersive VR technology in cognitive rehabilitation. First, the lack of motivation for repetitive and monotonous tasks is an important challenge in memory rehabilitation. Some studies (Cho & Lee, 2019; Dehn et al., 2018; Gamito et al., 2014; 2011) claim that despite inferior cognitive performance the immersive platform was often rated as more enjoyable (Adamo-Villani & Wilbur, 2008; Plechata et al., 2019). In the usability studies, the immersive VE was evaluated as more motivating in comparison to standard non-immersive methods (Moreno & Mayer, 2004; Parong & Mayer, 2018). This might be an important factor for repetitive and elementary tasks applied in cognitive rehabilitation that may easily lead to decreased motivation of the participants and consequently to increased drop out. Even though above mentioned cognitive training studies postulated higher motivation associated with immersive VE, they did not investigate the difference in usability across the treatment approaches (Cho & Lee, 2019; Dehn et al., 2018; Gamito et al., 2014; 2011). Future studies addressing enjoyment and adherence in rehabilitation are needed (Rose et al., 2018).

Second, due to head and body movements linked to the rotation and movements in the real environments, the interaction with immersive VE can be more intuitive (Adamo-Villani & Wilbur, 2008) and might be easy to master even in VR technology naive participants (Trombetta et al., 2017). Finally, the potential of immersive VR experience to simulate real-like everyday situations cannot be ignored. Previous studies pointed out the important role of interactive features and immersive experience that can facilitate the transfer of learned abilities to real-world situations (Rose et al. 2000). This can potentially increase the ecological validity of cognitive rehabilitation (Rizzo et al. 2004). It was also reported that some specific areas (as specific abilities development or science education) may benefit from immersive training (Wu et al., 2020). Moreover, the immersive experience can be crucial for research in domains connected with affective functions. It fulfills all five crucial characteristics (ecological validity, temporal resolution, controllability, complexity, and emotional intensity) defined by the so-called Emotion Matrix (Grühn & Sharifian, 2016), that are extremely relevant in simulations of social and emotionally relevant situations.

5. Conclusion

This review aims to study the benefits of complex VEs in memory rehabilitation inspired by the growing interest in the application of new technologies in cognitive assessment and rehabilitation processes. The potential of immersive VE has been pointed out by several studies (Maggio, Latella, et al., 2019; Maggio, Maresca, et al., 2019) and also in the meta-analysis by Hill et al. (2017). Surprisingly, so far there are only two studies directly comparing the efficacy of immersive and non-immersive VE approaches in cognitive rehabilitation (Dehn et al., 2018; Gamito et al., 2014), which are not conclusive. Above that, it was demonstrated that immersive VE applied in memory assessment can lead to poorer performance that seems to be the result of the increased cognitive load (Makransky et al., 2019; Naceri et al., 2009; Plechata et al., 2019; Rand et al., 2005; Sousa Santos et al., 2009). Current findings show only a small additional effect of the complex VR environments in memory rehabilitation in comparison to the standard approaches. A limited number of studies using immersive VR technology does not allow an evaluation of the potential beneficial value of immersiveness in memory rehabilitation. Despite the assumption that immersive VR can increase participants' motivation towards repetitive tasks as it was previously linked to increased enjoyment, there is no data to confirm this and future studies are needed to address this issue. Concerning the extremely limited number of studies that directly compare non-immersive and immersive VE in memory training, it is not possible to draw any conclusion that would benefit one approach over the other.

Conflict of interest

The authors declare that the review was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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