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Orientadores: Prof. Doutora Ana Isabel Figueira Verdelho
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Tese especialmente elaborada para obtenção do grau de Doutora em Ciências e Tecnologias da Saúde, especialidade em Saúde Ambiental.

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Dedico esta tese às mulheres da minha vida,
à minha filha Clara e à minha mãe Luísa

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## ABSTRACT

Digital technologies have become an indispensable resource for developing effective digital health interventions. The number of digital applications in the health sector has increased over the years, with the neuropsychological rehabilitation field being no exception. One clinical population that can benefit from digital neuropsychological interventions is vascular mild cognitive impairment (VaMCI). Epidemiological studies have shown that almost half of VaMCI patients develop dementia within five years. Therefore, secondary prevention interventions that aim to slow or stop the progression of symptoms should be considered a priority.

Virtual Reality and gamification processes have been extensively used to develop engaging and ecologically valid platforms for patients to train cognition and the execution of instrumental activities of daily living. Although virtual reality and gamified applications have become progressively affordable, there is still a lack of theoretical frameworks for developing digital neuropsychological rehabilitation platforms, particularly in VaMCI rehabilitation. Moreover, most user-centred design approaches for developing such platforms need a thorough process of feasibility evaluation.

This dissertation aims to 1) describe and present the conclusions of two literature reviews on the use of game elements and video games to assess, train or rehabilitate cognition-related outcomes, 2) describe the development process and [feasibility] evaluation of NeuroVRehab.PT, a gamified digital neuropsychological rehabilitation platform (i.e., an applied game) aiming to train the cognitive functions and behavioural strategies required to execute an instrumental activity of daily living (i.e., shopping) in VaMCI patients. For this purpose, the present project was structured into five studies.

First, to identify the most frequently used game elements in game-based interventions for neuropsychological assessment, training, or rehabilitation, we conducted a systematic review of the literature (according to PRISMA guidelines[1]) (study 1). We searched PubMed/MEDLINE, SciELO, and EBSCO electronic databases for full-text available articles published in peer-reviewed journals between 2006 and 2019 in English, Portuguese, or Spanish. To be included, papers had to present empirical and original data


[1] The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement.

on the impact of game-based interventions on attention, working memory, and inhibitory control outcomes. A total of 72 game-based interventions were identified, of which 16 were used for cognitive assessment, 46 for cognitive training, and 18 for cognitive rehabilitation. Our findings reveal that narrative context and score systems were the most frequently used game elements (both present in 79.2% of the game-based interventions analysed). Time pressure was present in 51.4% of the interventions, while win/lose condition, reward systems, avatars, and multiplayer component were used in 44.4%, 43.1%, 38.9%, and 25% of the interventions, respectively. We also found a statistically significant difference ($p <$ .001) between the number of game elements reported in the articles we analysed and those actually incorporated into game-based interventions.

In study 2, we conducted a meta-analysis (according to PRISMA guidelines) aiming to analyse the impact of video games on cognition (e.g., attention, working memory, memory/learning) and functional capacity in MCI/dementia patients. We searched PubMed/MEDLINE, Web of Science, Epistemonikos, CENTRAL, and EBSCO electronic databases for randomised controlled trials published between 2000 and 2021 in peer-reviewed journals in English, Portuguese, or Spanish. A total of nine studies (n = 966 participants) were included in the qualitative analysis. Two researchers independently assessed the Risk of Bias and the quality of evidence using the RoB2 tool and GRADEpro software, respectively. A significant estimated effect was found on the Mini-Mental State Examination (MMSE) scores (MD = 1.64, 95%, CI 0.60 to 2.69, $I^2$ = 0%, $p$ = 0.002), favouring the video game group.

Study 3 described the development process and a first-phase feasibility evaluation of NeuroVRehab.PT (according to the COREQ guidelines[2]). NeuroVRehab.PT is a gamified digital platform composed of three game modes and a photo-realistic virtual supermarket where users can train the cognitive functions and behavioural strategies used during a shopping activity. The platform's features were based on the results obtained in the two previous studies (i.e., study 1 and study 2) and on the results obtained in a Shopping Behaviours Questionnaire applied to 110 older adults (70.92 ± 5.94 years). The results obtained informed design decisions regarding the virtual supermarket's characteristics (e.g., grocery store *versus* supermarket *versus* hypermarket), type of game elements used, and other platform's features such as the use (or not) of shopping lists, number of products

[2] Consolidated criteria for reporting qualitative research guidelines.

included in the shopping list, among other components. After platform development, a group of health professionals (n = 7; $\bar{x}$ = 17 years of clinical practice) were invited to evaluate NeuroVRehab.PT rehabilitation potential and feasibility in VaMCI patients. Individual interviews were conducted using the Think-Aloud method and a semi-structured interview script. Interviews were audio-recorded and transcribed, and the *corpus* of the interviews was analysed using the 6-phase approach to Thematic Analysis proposed by Braun and Clark[3]. Four themes (i.e., Experience with NeuroVRehab.PT, Rehabilitation Potential, Potential Barriers, and Opportunities) and seven subthemes were identified based on an inductive-deductive Thematic Analysis protocol. Our results showed that health professionals considered NeuroVRehab.PT feasible in VaMCI patients. Furthermore, health professionals deemed the platform a significant step toward effective and ecologically valid digital neuropsychological rehabilitation interventions.

In study 4, we conducted a second-phase feasibility study (according to COREQ guidelines) to analyse the impact of noncognitive factors such as computer confidence and computer self-efficacy on NeuroVRehab.PT interaction experience (IX) in less technologically savvy individuals. A group of community-dwellers (n = 8; 70.6 ± 6.1 years) with no cognitive impairment diagnosed and different levels of computer confidence was invited to use and evaluate NeuroVRehab.PT. Individual interviews were conducted and analysed using a similar research protocol to the one used in study 3. We identified three themes (i.e., Interaction Experience, Digital Literacy, and Attitudes toward NeuroVRehab.PT) and eight subthemes. The data collected showed that NeuroVRehab.PT is feasible among older adults with different levels of computer confidence and computer self-efficacy.

Additionally, other non-user-related variables, such as the inclusion of a training period supported by someone more familiar with technology, were identified as a crucial component to the adoption and long-term use of digital healthcare services in populations less proficient in technology use. Also, based on participants' observed interaction patterns with the platform, a set of changes were implemented, aiming 1) to provide a more fluid and smooth interaction with the platform; 2) to promote adherence to NeuroVRehab.PT in older adults with low familiarity with technology; 3) with or without cognitive impairment.

[3] Braun and Clarke. 2012. Thematic analysis. DOI:https://doi.org/10.1037/13620-004

With NeuroVRehab.PT (2.0) new version developed, we invited five VaMCI patients (73.2 ± 6.7 years) to use and assess the platform (study 5). A similar protocol to the one reported in study 3 and study 4 was applied. Three themes (Interaction Experience, VaMCI and NeuroVRehab.PT, and NeuroVRehab.PT as a Rehabilitation Instrument) and eight subthemes were identified. Our results showed that NeuroVRehab.PT is feasible among VaMCI patients.

Furthermore, although some participants had never used a tablet before, they were able to learn how to use the platform, with some showing increased autonomy in platform use as the session went on. In addition, it was possible to identify overlap between NeuroVRehab.PT's activities flow and some of the rehabilitation principles present in widely used rehabilitation models for the rehabilitation of executive deficits, including the Goal Management Training model.

The findings collected through the five studies presented in this thesis laid the foundations for an innovative approach to developing accessible, personalised, and ecologically valid digital neuropsychological rehabilitation interventions. As part of this project, we developed and tested an ecologically valid photo-realistic, gamified digital platform to promote the cognitive and behavioural skills required for shopping activity. Preliminary data supporting the feasibility of NeuroVRehab.PT in VaMCI patients is also presented, along with data on the platform's ecological validity and clinical utility. In addition to the preliminary data on the ecological validity and clinical utility of NeuroVRehab.PT, we contributed to the debate on the utility, adequacy and implications of using gamified digital platforms in clinical and less technologically savvy populations.

Keywords: applied games, photo-realistic virtual environments, cognitive impairment, ecological validity, user-centred design

## RESUMO

As tecnologias digitais são um recurso essencial para o desenvolvimento de intervenções em saúde eficazes, acessíveis e sustentáveis. Como consequência, o número de aplicações digitais no setor da saúde, assim como na área da reabilitação neuropsicológica tem aumentado nos últimos anos.

Uma população clínica que pode beneficiar de intervenções neuropsicológicas digitais são pacientes com défice cognitivo ligeiro vascular (DCL vascular). Estudos epidemiológicos mostram que perto de 50% dos pacientes com DCL vascular desenvolvem demência em cinco anos. Estes dados reforçam a noção que esta é uma população de risco e, portanto, intervenções de prevenção secundária devem ser consideradas uma prioridade.

A realidade virtual (RV) e os processos de gamificação têm sido intensivamente utilizados para o desenvolvimento de plataformas digitais com validade ecológica e com capacidade para promoverem uma elevada adesão por parte dos utilizadores finais. No entanto, apesar do acesso a ferramentas de RV e aplicações gamificadas ser cada vez mais difundido, existe ainda a falta de modelos teóricos que guiem o desenvolvimento destas plataformas para reabilitação neuropsicológica, e em particular para a reabilitação de pacientes com DCL vascular. Além disso, embora se verifique a uma crescente utilização das abordagens centradas no utilizador, a maioria das plataformas desenvolvidas com recurso a esta abordagem de desenvolvimento tecnológico, carece de um processo de avaliação exaustivo da sua viabilidade e adequação aos utilizadores finais.

Esta dissertação tem por objetivos descrever e apresentar as conclusões de duas revisões sistemáticas de literatura sobre o uso de elementos de jogos e vídeo jogos para avaliação, treino ou reabilitação de *outcomes* cognitivos, e 2) descrever o processo de desenvolvimento e avaliação [da viabilidade] do NeuroVRehab.PT, uma plataforma digital (i.e., *applied game*) desenvolvida para a promoção das funções cognitivas e estratégias comportamentais recrutadas durante a execução de uma atividade instrumental de vida diária (i.e., compras de supermercado) em pacientes com DCL vascular. Para tanto, o presente projeto foi estruturado em cinco estudos.

No estudo 1, realizamos uma revisão sistemática de literatura (de acordo com as diretrizes PRISMA[4]) para identificar quais os elementos de jogo (EsJ) mais frequentemente utilizados em intervenções baseadas em videojogos (IBVJ) para avaliação, treino ou reabilitação


[4] The Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) statement.

neuropsicológica. Três bases de dados foram consultadas (i.e., PubMed/MEDLINE, SciELO e EBSCO) e a pesquisa bibliográfica restrita a artigos com texto integral disponível, publicados entre 2006 e 2019 em inglês, português ou espanhol, em revistas científicas com revisão por pares. Foram incluídos apenas artigos focados no estudo do impacto de IBVJ para avaliação, treino ou reabilitação neuropsicológica em medidas de atenção, memória de trabalho e controle inibitório. Foram identificadas 72 IBVJ, das quais 16 usadas para avaliação cognitiva, 46 para treino cognitivo e 18 para reabilitação neuropsicológica. Os EsJ mais frequentemente utilizados foram: o contexto narrativo e os sistemas de pontuação ambos presentes em 79,2% das IBJV analisadas. O fator tempo de execução (i.e., *time pressure*), ganhar versus perder, sistemas de recompensa, *avatars*, e componente multijogador foram identificados em 51,4%, 44,4%, 43,1%, 38,9%, e 25% das intervenções analisadas, respetivamente. Adicionalmente, identificamos uma diferença estatisticamente significativa ($p < 0,001$) entre o número de EsJ descritos nos artigos analisados e o número de EsJ que compõem estas intervenções.

No estudo 2, realizamos uma meta-análise (de acordo com as diretrizes PRISMA) com o objetivo de analisar o impacto de videojogos (VJs) na cognição (e.g., atenção, memória de trabalho, memória/aprendizagem) e na capacidade funcional em pacientes com DCL/demência. Analisamos cinco bases de dados (i.e., PubMed/MEDLINE, Web of Science, Epistemonikos, CENTRAL e EBSCO) e restringimos a pesquisa de artigos a ensaios clínicos aleatorizados e controlados, publicados em revistas científicas com revisão por pares, em inglês, português ou espanhol, entre 2000 e 2021. Nove artigos (n = 966 participantes) foram incluídos na análise qualitativa. A avaliação do risco de viés e da qualidade da evidência recolhida, foi realizada de forma independente por dois investigadores, usando a ferramenta RoB2 e o software GRADEpro, respetivamente. Um efeito estimado significativo foi identificado para os resultados do Mini Mental State Examination (MD = 1,64, 95%, IC 0,60 a 2,69, I2 = 0%, p = 0,002), no grupo de VJs comparativamente com o grupo que utilizou intervenções cognitivas mais tradicionais (e.g., exercícios de papel-e-lápis).

No estudo 3, descrevemos: 1) – o processo de desenvolvimento e 2) – avaliação do potencial de reabilitação do NeuroVRehab.PT e a sua adequação/viabilidade enquanto ferramenta de reabilitação em pacientes com DCL vascular (de acordo com as diretrizes COREQ[5]). O NeuroVRehab.PT é uma plataforma digital gamificada composta por três modos de jogo, e

[5] Consolidated criteria for reporting qualitative research guidelines.

um supermercado virtual fotorrealista onde os utilizadores podem treinar as funções cognitivas e as estratégias comportamentais utilizadas durante a atividade de compras. A decisão sobre quais os EsJ a incluir na plataforma foi baseada nos resultados obtidos nos dois estudos anteriores (i.e., estudo 1 e estudo 2) e nos resultados obtidos no Questionário sobre os Hábitos e Rotinas de Compras aplicado a uma amostra de 110 idosos (70,92 ± 5,94 anos). Após o desenvolvimento da plataforma, um grupo de profissionais de saúde (n = 7; $\bar{x}$ = 17 anos de experiência clínica) foi convidado a avaliar o potencial de reabilitação e adequação do NeuroVRehab.PT a pacientes com DCL vascular. Foram conduzidas entrevistas individuais, onde se aplicou o método *Think-Aloud* e um guião de entrevista semiestruturada. As entrevistas foram gravadas em áudio, transcritas e o *corpus* das entrevistas analisadas utilizando o método de Análise Temática segundo abordagem de 6 fases proposta por Braun e Clark[6]. Quatro temas (i.e., Experiência de Utilização com NeuroVRehab.PT, Potencial de Reabilitação, Potenciais Barreiras e Oportunidades) e sete subtemas foram identificados. Os resultados mostram que os profissionais de saúde consideram o NeuroVRehab.PT adequado às necessidades de pacientes com DCL vascular. Adicionalmente, o NeuroVRehab.PT foi considerado um avanço significativo no desenvolvimento de plataformas digitais neuropsicológicas eficazes e ecologicamente válidas.

No estudo 4, analisamos o impacto de fatores não cognitivos (i.e., confiança e autoeficácia percecionada na utilização de tecnologia) na adaptação, aprendizagem e uso do NeuroVRehab.PT. Um grupo de idosos (n = 8; 70,6 ± 6,1 anos) sem diagnóstico de DCL foi convidado a utilizar e avaliar o NeuroVRehab.PT. Foram realizadas entrevistas individuais e analisadas segundo um protocolo de pesquisa semelhante ao utilizado no estudo 3. Após análise das entrevistas, foram identificados três temas (i.e., Experiência de Interação, Literacia Digital e Atitudes face ao NeuroVRehab.PT) e oito subtemas. Os dados recolhidos demonstram que o NeuroVRehab.PT pode ser aprendido e utilizado por idosos com diferentes níveis de confiança e autoeficácia percecionada. Além disso, outras variáveis não associadas ao utilizador, como a inclusão de um período de treino orientado por alguém mais familiarizado com tecnologia, foram identificadas como componentes cruciais para a adoção e uso continuado de serviços digitais de saúde em populações menos familiarizadas com tecnologia. Com base na observação das dificuldades e padrões de interação dos

[6] Braun and Clarke. 2012. Thematic analysis. DOI:https://doi.org/10.1037/13620-004

participantes com a plataforma, foram identificadas e implementadas um conjunto de alterações com o objetivo de: 1) proporcionar uma interação mais fluida com a plataforma; 2) promover a adesão ao NeuroVRehab.PT em idosos com baixa familiaridade com a tecnologia; 3) com ou sem comprometimento cognitivo.

Com a nova versão do NeuroVRehab.PT (2.0), um grupo de idosos com DCL vascular (n = 5, 73,2 ± 6,7 anos) foi convidado a usar e a avaliar a plataforma (estudo 5). Foram realizadas entrevistas individuais e analisadas com base no protocolo de pesquisa descrito nos estudos 3 e 4. Da análise das entrevistas, foram identificados três temas (Experiência de Interação, DCL vascular e o NeuroVRehab.PT, e NeuroVRehab.PT como Instrumento de Reabilitação) e oito subtemas. Os nossos resultados demonstram que NeuroVRehab.PT pode ser utilizado para a reabilitação neuropsicológica de pacientes com DCL vascular. Adicionalmente, e embora a sessão experimental fosse para alguns dos participantes o primeiro contacto com um tablet, a plataforma mostrou estar adaptada às necessidades e limitações desta população, com alguns dos participantes a demonstrarem, uma progressiva autonomia no uso da plataforma à medida que a sessão avançava. Paralelamente, foi possível identificar uma sobreposição do fluxo das atividades apresentadas no NeuroVRehab.PT e alguns dos pressupostos da reabilitação neuropsicológica presentes em outros modelos de reabilitação de défices executivos, como por exemplo, *o Goal Management Training model*.

Os resultados alcançados nos cinco estudos apresentados nesta tese lançam as bases para uma abordagem inovadora ao desenvolvimento de intervenções neuropsicológicas acessíveis, personalizadas e com validade ecológica. No âmbito do presente projeto desenvolvemos e testamos uma plataforma digital fotorrealista para o treino das competências cognitivas e comportamentais recrutadas durante uma atividade de compras em pacientes com DVC vascular. Apresentamos dados preliminares que suportam a adequação/viabilidade do NeuroVRehab.PT em pacientes com DCL tipo vascular. Por último apresentamos também dados preliminares relativos à validade ecológica e utilidade clínica do NeuroVRehab.PT e contribuímos para o debate sobre a utilidade, adequação e implicações do uso de plataformas gamificadas em populações clínicas e/ou com pouca familiaridade com a tecnologia.

Palavras-chave: applied games, ambientes virtuais realistas, défice cognitivo, validade ecológica, design centrado no utilizador.

## LIST OF ABBREVIATIONS IN ENGLISH

**AD –** Alzheimer's Disease

**ADL –** Activities of daily living

**AGs –** Applied games

**BTG –** Brain Training Games

**CCTP –** Computerized Cognitive Training Programs

**CG –** Commercial video games

**COREQ –** Consolidated Criteria for Reporting Qualitative Research Guidelines

**EF** – Executive functions

**GBI** – Game-based interventions

**GEs** – Game elements

**GMT** – Goal Management Training

**IADL** – Instrumental activities of daily living

**ICT –** Information and Communication Technologies

**IX** – Interaction experience

**MCI** – Mild cognitive impairment

**MCID** – Minimal clinically important difference

**MD** – Mean difference

**MeSH –** Medical Subject Headings

**MMSE –** Mini-Mental State Examination

**PRISMA –** The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) Statement

**QoL** – Quality of life

**RCT** – Randomised controlled trial

**SMD** – Standardised Mean Difference

**SoP –** Sense of Presence

**TA** – Thematic analysis

**VaMCI** – Vascular mild cognitive impairment

**VEs –** Virtual Environments

**VGs** – Video games

**VR –** Virtual reality

**UX** – User-experience

**WHO –** World Health Organization

**WML –** White matter lesions

## LIST OF ABBREVIATIONS IN PORTUGUESE

**DCL –** Défice cognitivo ligeiro

**DCL vascular** – Défice cognitivo ligeiro vascular

**EsJ –** Elementos de jogo

**IBVJ –** Intervenções baseadas em videojogos

**RV –** Realidade Virtual

**VJ** – Videojogos

## LIST OF TERMS AND DEFINITIONS

**Action games** – games in which players are required to have good reflexes, hand-eye coordination, and quick reaction times to overcome challenges such as combats, avoiding traps, jumping, running, completing tasks within a pressing time limit, etc. (cit. by [1])

**Adventure games** – games that involve the exploration of, and interaction with, the environment as a central facet of gameplay (cit. [1]).

**Applied games** – video games that seek to employ games or substantial game elements to educate and change patterns of experience and/or behaviour [2]. According to [2], applied games include serious games (computerised games for serious purposes) and gamification (game elements used outside of video games).

**Assistive device** – any product, device, or equipment, whether acquired commercially, modified, or customised, used to maintain, increase, or improve the functional capabilities of individuals with disabilities (according to Assistive Technology Act of 2004 cit. [3]).

**Assistive environments** – the physical or digital spaces that foster independent living and assist daily-life routines through an easy-to-use interface [3].

**Augmented reality** – augmented reality is a technology which allows computer-generated virtual imagery to overlay physical objects in real-time (cit. [1]).

**Brain games** – consumer technologies designed to train and improve the brain through challenging cognitive exercises [4].

**Digital gaming activity** – interaction between a player or players and the tools to perform this activity (both software and hardware) within an environment and time [5].

**Digital health** – the field of knowledge and practice associated with developing and using digital technologies to improve health-related outcomes [6].

**Disability-adjusted life years** – a time-based measure that combines years of life lost due to premature mortality (YLLs) and years of life lost due to time lived in states of less than full health or years of healthy life lost due to disability (YLDs). One DALY represents the loss of the equivalent of one year of full health [7].

**Ecological Validity** – "*VR has an enhanced ecological validity, that is, a higher degree of similarity between the training environment and real world; this is supposed to represent an added value for predicting an improvement in everyday functioning*." [8]

**Exergames** – games that combine exercise equipment with video games to encourage people to exercise by making the activity fun (cit. by [1]). Exergames are interactive video games that require the player to produce physical body movements to complete set tasks or actions in response to visual cues [9]. Exergames also appear under other terminologies, such as active gaming and motion-based videogaming [10].

**Functional capacity** – the ability to perform the physical and cognitive activities needed to execute daily-living activities and maintain an independent living with quality of life [11].

**Flow** – the subjective experience of engaging in challenging yet manageable activities, further characterised by complete cognitive absorption, time distortion and enjoyment (cit. by [12]).

**Game –** physical or mental contest with a goal or objective, played according to a framework or a set of rules, which determines what a player can and cannot do inside the game world. (Homo Ludens, cit. by [1]).

**Gameplay** – interactions of the player with the environment through the manipulation of rules and game mechanics and through the creation of strategies and tactics that make the game experience exciting and fun (Vannucchi & Prado, 2009, cit. [13]).

**Game elements –** a set of video game components which include patterns, objects, principles, models, or methods [14,15].

**Game enjoyment** – positive cognitive and affective appraisal of the game experience and may, in part, be associated with the support of player needs (need of satisfaction) and values [12]. It is distinct from flow and may occur independently of the challenge and cognitive involvement [12].

**Game metrics** – the quantified measures of in-game data (e.g. time spent playing, actions taken by the player [12].

**Gamification** – "… *the use of game design elements in non-game contexts*" [14].

**Heuristic** – design principles [16].

**Heuristic Evaluation** – inspection process where a set of usability heuristics is established and used by evaluators to explore an interface [17] [18]. In [18], the authors propose their list of heuristics for a Heuristics evaluation process. Further gathering all heuristics violations, they asked evaluators to score it on a scale of 0, "cosmetic problem", to 4 ", usability catastrophe".

**Interaction experience** – includes usability aspects (i.e., the extent to which a system can be used to achieve specific goals with efficiency); user experience (i.e., user's perceptions and responses that result from the use and/or anticipated use of a system); and accessibility (i.e., the extent to which a system addresses the needs, and abilities of a large spectrum of users with or without impairments) [19].

**Intrinsic motivation** – is "*the inherent tendency to seek out novelty and challenges, to extend and exercise one's capacities, to explore, and to learn*" [20].

**Immersion –** subjective feeling characterised by real-world dissociation and cognitive and emotional involvement [12].

**Mobile device** – portable computing devices such as a smartphone, which is, in turn, a mobile phone that performs many computer functions, typically having a touchscreen interface, Internet access, and an operating system capable of running downloaded apps (Oxford Dictionary of English).

**Mobile Health** –implementation of digital health services with mobile and wearable devices [21].

**Neurofeedback –** self-regulation of an individual's brain activity based on the real-time visual/auditory feedback of his brain patterns [22,23] through signals recorded using an electroencephalogram (EEG) [24].

**Neurocognitive rehabilitation – "***a multi-layered treatment approach when treating cognitive disorders. Patients with various cognitive disorders are treated by an interdisciplinary team of clinicians that includes: a clinical neuropsychologist, a clinical psychologist or behaviourist, a cognitive rehabilitation, a speech-language therapist, and a neuromodulation clinician*" [25].

**Neurorehabilitation –** the clinical subspecialty devoted to restoring and maximising functions lost due to impairments caused by injury or disease of the nervous system [26]

**Onboarding phase** – a phase that typically covers the first few minutes of play [27]. This is a crucial phase since it is during this phase that most players choose to continue to play or abandon the game. According to [27], in free-to-play games (F2P), seven minutes were established as a general timeframe for onboarding. Nevertheless, the same authors claimed that the onboarding phase begins from the first time a player starts the game until the basic mechanics have been utilised.

**Puzzle games** – games that require "*the player to solve a puzzle such as a maze, logical problem or positioning different pieces together*" (cit. by [1]).

**Quality of life –** the subjective perception of an individual's position concerning his/her physical health, psychological health, social relationships, and environment [28].

**Role Playing games** – games "*in which the player's character has skills and abilities represented by statistics. The gameplay involves the characters exploring and completing quests that build up their statistics and possessions*" (cit. by [1]).

**Sense of Presence (SoP)** - the feeling of "being physically present" in the virtual world, allowing the user to respond realistically to the virtual stimuli by eliciting a physiological reaction as if the subject is physically situated in a real place [29].

**Serious Games** – "… *games specifically designed to achieve some change in the player (…) in knowledge, attitude, physical ability, cognitive ability, health, or mental wellbein*g" [30].

**Simulation games** – games that attempt to realistically mimic the conditions of a particular environment or activity (cit. by [1]).

**Sports games** – games that emulate traditional physical sports such as basketball, golf, football, etc. (cit. by [1]).

**Strategy games** – games in which players require tactics and sagacity to achieve the targets (cit. by [1]).

**Usability** – "*the extent to which users can use a system, product, or service to achieve specified goals with effectiveness, efficiency, and satisfaction, in a specified context of use."* [19].

**User experience** – user-experience (UX) can be interpreted in two different ways. One is to denote the design and use of user interfaces, effectively working as a synonym for interaction, usability, or even user-centred design [31]. In the second perspective, UX is a person's perception and responses that result from the use and/or anticipated use of a product, system, or service [19]. According to [31], UX englobes: (a) the anticipated use and experiences following the use situation, (b) focuses on positive aspects of un-related product qualities interaction such as visual aesthetics and beauty, the joy of use, stimulation, personal growth, or surprise; (c) emphasises the situational and dynamic aspects of using interactive products. In a systematic review of the literature conducted by [31], emotion and affect,

enjoyment and aesthetics were the most mentioned core dimensions of UX (24%; 17%; 15%, respectively).

**Virtual Embodiment –** the illusion that the virtual body and its actions belong to the observer [29]

**Virtual Reality** – refers to computer-simulated environments that can simulate physical environments in imaginary worlds. It is commonly associated with immersive technology, which provides perceptually real environments with special equipment such as holography, head-mounted displays (HMDs), and haptic tactile equipment [1].

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# CHAPTER I. INTRODUCTION

## 1.1 Ageing and Cognitive Impairment

According to the World Health Organization (WHO), there are currently 55.2 million people living with dementia worldwide [1,2]. However, as the global population ages, it is expected that by 2050, 2.1 billion people will be over 60 years old, with the number of dementia cases estimated to reach 131.5 million globally. This represents an increase of 116% in high-income countries and 264% in low-income countries compared to the number of dementia cases reported in 2015 [2,3].

In Portugal, it was estimated that in 2014, 160.287 people were affected by dementia, which accounts for 5.91% (95% CI 5.88 – 5.93) of individuals aged 60 years and over [4]. However, recent data from 2017 suggests that the prevalence rate of dementia in older adults aged 65 years and over has increased to 9.23% (95% CI 7.80 – 10.90) [5,6]. This represents a significant increase compared to the European trend of 1.57% in 2018, with Portugal's prevalence rate already at 1.88% [6–8]. It is predicted that Portugal's dementia prevalence rate will double by 2050, reaching 3.82%. [6–8].

Dementia is one of the most burdensome diseases with significant costs associated with its care [9]. In Europe, dementia care costs an average of €32,506.73 per person per year, while in the United States, this figure rises to €42,898.65 per person per year. The costs of dementia care increase with the severity of the disease, ranging from €17,000 for mild dementia to €36,000 for severe dementia [10]. In Portugal, the costs of dementia care are also substantial, amounting to €2 billion in 2018, which includes both direct medical costs, such as inpatient and outpatient treatment and medication, and non-medical direct costs, such as medical devices, home adaptations, and transportation [11]. Additionally, there are indirect costs associated with dementia care, including the unpaid informal care provided by family members, the sacrifice of leisure time, self-care, and other health expenses [10]. For a Portuguese household, caring for a patient with dementia represents spending around 78% of their monthly income ($\tilde{x}$ = €800), which constitutes a significant financial, psychological, and emotional burden to most Portuguese households [12].

### 1.1.1 Mild Cognitive Impairment

The notion that older adults may transition between healthy and pathological ageing was first introduced in the literature on ageing and dementia about thirty years ago (cit. by [13]). In 1988, Reisberg and colleagues introduced the term Mild Cognitive Impairment (MCI) to

describe stage 3 of the Global Deterioration Scale [14]. In 1995, Petersen and colleagues presented MCI as an independent clinical entity with specific criteria, including memory complaint, normal activities of daily living (ADL), normal general cognitive function, abnormal memory for age, and no dementia [15]. Implicit in the requirement of a memory deficit was the early assumption that MCI was (exclusively) a prodromal phase of Alzheimer's disease [16].

Over time, the concept of MCI has evolved to include other phenotypes (i.e., other cognitive deficits rather than memory), aetiologies (e.g., vascular diseases) and long-term outcomes (e.g., vascular dementia, dementia with Lewy bodies). Currently, there are four recognised subtypes of MCI: amnestic MCI, characterised by a memory deficit as the primary feature, and non-amnestic MCI, characterised by cognitive impairments other than memory deficits [17,18]. Each subtype can be further subcategorised into single- or multiple domains, depending on the number of cognitive functions compromised [18]. More recently, a classification system based on the identified cortical or subcortical patterns of deficits has also been proposed [19].

Scientific literature highlights that individuals with MCI are at a significantly higher risk of converting to dementia (10-15%) and experiencing a decreased quality of life, including reduced autonomy, social participation, and intimacy, compared to healthy controls (1-2%) [15,20,21]. Moreover, MCI is associated with high morbidity and mortality rates [21–25]. Although MCI prevalence and incidence rates vary greatly, recent epidemiological studies estimate an MCI incidence rate of 41.0 [35.5, 47.3]/1,000 person-years in older adults (> 65 years old), with an annual conversion rate to dementia of 241.3 [189.6, 307.0]/1,000 person-years [26].

Currently, MCI is considered an intermediate phase between normal and pathological ageing [27,28], characterised by a cognitive compromise greater than expected in healthy ageing but not severe enough to fulfil dementia criteria [29,30]. Although there is no gold standard for determining the presence of MCI, a commonly used method is to use scores that fall between 1.0 and 1.5 standard deviations below the normative mean in neuropsychological tests [16,19,31,32]. More recently, the presence of subtle difficulties in instrumental activities of daily living (IADL) has also been included as part of MCI clinical criteria [33]. MCI patients with impairments in more complex IADL are more likely to progress to dementia (30.7%) within two years compared to those without IADL impairments (7.8%) [34]. These findings emphasise the need to develop strategies that target both cognition and

functional capacity (i.e., the ability to perform ADL) to improve the quality of life and autonomy of these patients [35,36].

### 1.1.2 Vascular Mild Cognitive Impairment

Vascular mild cognitive impairment (VaMCI) is a term used to describe patients who experience cognitive changes due to a cerebrovascular disease but do not reach the severity level of dementia (i.e., vascular dementia) [19,37,38]. Considering the spectrum of cognitive impairments due to vascular disease (i.e., vascular cognitive impairment), VaMCI is situated on the less severe side. In contrast, vascular dementia is on the most severe side of the spectrum [38,39]. Although several cerebrovascular diseases can cause VaMCI [19,37], the main neuropathological substrate that has been identified is the disruption of the frontal-subcortical network, which is associated with cerebral small vessel disease, such as white matter lesions (WML) [39,40] and lacunar infarcts [41,42].

Although epidemiological data on VaMCI are scarce, evidence points toward a high prevalence of this condition [38,43,44]. For instance, in a well-characterized cohort of stroke survivors, 36.7% of the patients developed VaMCI within three to six months of the vascular event [45]. In another cohort study, 19.6%, 26.8%, and 21% of stroke survivors without cognitive impairment before the vascular event developed VaMCI at 3, 12, and 24 months, respectively [46]. Similarly to other forms of MCI, a significant percentage of VaMCI patients (46%) progressed to dementia after five years [47]. Other studies have shown that patients with mild, moderate, and severe WML have adjusted hazard ratios of 1.09 (95% CI 0.74 to 1.59), 1.51 (95% CI 1.07 to 2.14), and 2.50 (95% CI 1.72 to 3.65), respectively, for progressing from independence in IADL to dementia or death [48]. These data demonstrate the importance of early detection and management of VaMCI, especially in patients with severe WML, to prevent progression to more severe forms of cognitive impairment.

Patients with VaMCI frequently present a cognitive profile characterised by a dysexecutive syndrome, which is associated with subcortical pathology and consequent disruption of frontal-subcortical networks [41]. This syndrome manifests as deficits in complex attention, including selective, divide, and sustained attention, as well as executive functions (EF) such as initiation, planning, decision making, hypothesis generation, cognitive flexibility, judgement, and slowed processing speed [37,49]. Memory deficits are also common in VaMCI patients [40,50].

Furthermore, VaMCI patients often experience difficulties executing IADL, especially those that heavily rely on EF, and require constant information updates and adaptation to changing circumstances and/or unpredictable outcomes [51,52]. Moreover, depression and apathy are the most common neuropsychiatric symptoms identified in VaMCI patients [19,37], with irritability (12.9% to 44.7%), anxiety (11.6% to 26.3%), and agitation (11.3% to 38%) also reported in some patients [53]. Other less frequent neuropsychiatric symptoms identified in VaMCI patients include euphoria, disinhibition, delusions, hallucinations, and sleep disorders [54].

## 1.2. Cognition-based Interventions

Cognition-based interventions are therapeutic activities that aim to enhance cognitive functioning, improve functional capacity and self-esteem, and enhance patients' quality of life (QoL) [55]. These interventions are categorised into three groups, namely cognitive stimulation, cognitive training, and neuropsychological rehabilitation, based on their underlying theoretical assumptions, core elements, contexts of application, and general purpose [56,57].

Cognitive stimulation is rooted in Reality Orientation Therapy, developed in the 1950s to respond to the symptoms of disorientation and confusion observed in dementia patients [58]. Cognitive stimulation may or may not target individual cognitive functions and includes activities such as reading, writing, playing games, and arts and crafts [58]. Cognitive stimulation programs are usually conducted in groups and aim to improve general cognition and social functioning [56].

Cognitive training is a cognition-based approach that uses standardised tasks to target individual cognitive functions, such as attention, memory, and EF [56]. Furthermore, cognitive training considers that regular practice can improve or at least maintain functioning in a given domain which can potentially be generalised to other related and non-related cognitive domains [56]. Usually, cognitive training is delivered in an individual format, through paper-and-pencil or computer exercises, with an adaptive training structure that adjusts the difficulty level according to the patient's performance [58].

Finally, neuropsychological rehabilitation is a personalised intervention that focuses on the preserved aspects of cognition to develop behavioural strategies that compensate for impairments, reduce disability, and promote daily-life functioning, autonomy, and QoL [59]. Unlike cognitive training, which aims to enhance cognitive functioning, neuropsychological rehabilitation is tailored to the patient's individual goals, jointly identified by the therapist, patient, and patient's family [58–60].

Although meta-analytic studies have shown that cognition-based interventions, especially cognitive training, can improve cognitive functioning in patients with MCI [57,61], the low methodological quality and high heterogeneity of the studies [54,62–64] make it difficult to determine with a high degree of confidence the magnitude of their impact [36,65].

Neuropsychological rehabilitation poses an even greater challenge due to its individualised, patient-tailored nature [54,56,61].

Tailored neuropsychological rehabilitation programs are crucial for VaMCI patients to improve their cognitive abilities and independence and reduce the negative impact of the disease on their daily lives [60]. More data and intervention programs for VaMCI patients are needed, including new design solutions focused on developing widely accessible, affordable, and efficient digital neuropsychological rehabilitation tools.

### 1.2.1 Transfer capacity, ecological validity, and executive functions

Despite some exceptions [66], scientific literature indicates that cognitive training has limited efficacy in enhancing cognitive functions beyond those specifically targeted by the program [67]. This suggests that the benefits associated with cognitive training are typically specific to the domain being trained and do not transfer to patients' everyday life activities, indicating a lack of far-transfer capacity [67].

Whether cognitive training programs can promote far transfer is a subject of much debate. Some researchers suggest that the limited transfer capacity may be due to insufficient exposure to the intervention [56]. In contrast, others argue that the difference between the activities performed in cognitive training programs and those performed in real-world settings may be the main reason for their limited impact on patients' daily functioning [68].

The extent to which the results obtained in an instrument can be generalised to the real world is known as the ecological validity [68]. Over time, the concept of ecological validity has evolved, and there are currently two main approaches for assessing it: the veridicality and verisimilitude approach [69].

The veridicality approach evaluates the ecological validity of an instrument by examining the degree to which the results obtained in a test or intervention are statistically associated with standardised measures of daily life functioning. In contrast, the verisimilitude approach focuses on the similarity between the test or interventions' demands and the demands imposed by a task when executed in a real-world environment [69,70].

The verisimilitude approach is commonly used in neuropsychological rehabilitation; however, these interventions often rely on limited and inflexible tools such as video monitors, imagery and physical mock-ups, making their widespread applicability challenging [71]. Additionally, developing instruments that are both accessible and

ecologically valid while also training patients' capacity to generate novel solutions to non-routine tasks (i.e., goal-oriented behaviours) presents an additional significant challenge [72].

The function-led instruments approach is a promising method for developing ecologically-valid instruments [73]. This approach is closely related to the verisimilitude approach and states that neuropsychological instruments should be based on directly observable behaviours that researchers and clinicians aim to study and rehabilitate [73]. This means these instruments should accurately represent/mimic the characteristics, demands, and environmental constraints of real-world tasks [74].

Shallice and Burgess (1991) were among the first authors to develop a function-led instrument, the Multiple Errands Test (MET) [75]. In its original form, the MET requires patients to perform various tasks of varying difficulty levels in an unknown real-world pedestrian area where minor unforeseen events could occur. However, using real-life contexts for neuropsychological rehabilitation presents practical and ethical issues that limit the use of this approach in clinical contexts [72]. For instance, clinicians have limited control over unwanted stimuli, such as patients' emotional distress from interacting with people outside the clinical team or feelings of embarrassment. Additionally, accidents and misunderstandings can occur, negatively impacting the therapeutic alliance and the patient's commitment to the rehabilitation program [72]. Moreover, these interventions require considerable human, time, and financial resources, making their large-scale application difficult, if not impossible.

The efficacy of cognition-based interventions has been limited, leading experts to call for a paradigm shift to address this issue [72,74,76]. A new generation of interventions is needed, one that is easy to administer, ecologically valid, and motivates patients to engage in therapy and adhere to their rehabilitation plans. This approach should prioritise the transfer of trained abilities and skills to patients' daily lives, with the potential to enhance their real-world functioning capacity.

## 1.3. Digital Health

The use of digital health, which involves the use of digital, mobile, and wireless technologies [77] to support and promote health-related outcomes, has revolutionised the delivery of healthcare services [78]. This has led governments worldwide to develop digital health strategies aiming to provide equitable, affordable, and universal access to healthcare services [79].

One area that has undergone significant transformation in the digital health landscape is the cognition-based interventions [78,80]. However, in an era characterised by the large-scale implementation of healthcare services, conventional cognition-based interventions' in-presence and one-to-one administration format have been proven to be a major limitation [81,82]. For instance, the administration model of traditional cognition-based interventions is time-consuming, costly, and unengaging for patients [81–83]. Therefore, Information and Communication Technologies (ICTs) have been widely adopted as a means to develop accessible, engaging and affordable cognition-based interventions [84,85], with Virtual Reality (VR), gamification, and applied games (AGs) as the cornerstone of this [still incipient] paradigm-shift [76].

### 1.3.1. Applied games and cognition-based interventions

In healthcare, AGs have emerged as a tool to promote patient therapeutic adherence [86,87]. This term encompasses game-like software that is designed to serve a "serious" purpose, such as improving health and wellbeing-related outcomes, rather than solely for players' entertainment (as with off-the-shelf video games) [88,89]. The concept of AGs includes serious games and gamified applications [90]. Serious games utilise video games (VGs) or game elements (GEs) to bring about changes in players' knowledge, attitude, physical or cognitive ability, health, or mental wellbeing [91]. On the other hand, gamified applications incorporate game-design elements and mechanics into existing activities/tasks to make them more enjoyable and engaging for patients [90].

The increasing use of AGs in the health field is supported by the assumption that the engaging and entertaining format of VGs, AGs can drive health-related outcomes through the same intrinsic motivation processes that make VGs enjoyable and engaging [92–94]. By integrating the relaxed and playful nature of VGs into cognition-based interventions, patient motivation and engagement towards the intervention can be promoted. This perspective

suggests that increasing patient engagement could lead to more exposure to the intervention, reduced dropouts, and potentially increased intervention success (i.e., efficacy) [76,89,95].

In addition to AGs, VR has been explored as a technological resource for the neuropsychological rehabilitation [96]. Virtual reality provides users with an interface through which they can be exposed to and interact with 3-D environments that simulate sensory information similar to that received from real-world scenarios and objects [96]. Virtual reality is a valuable resource in the study and training of human functional performance, providing a safe and controlled environment for simulating real-world scenarios that elicit genuine reactions and realistic perceptions in patients [74,86,97–100].

Virtual environments (VEs) have been developed to assess and train patients' ability to perform daily activities, including virtual cities [101–103], malls [104,105], libraries [106], offices [107], supermarkets [99,108–115], kitchens [85,116], apartments [101,109,117–120] and museums [85,121]. Compared to traditional cognition-based interventions, VR offers several advantages, including accurate stimulus delivery, standardised administration processes, real-time feedback, multiple administrations, unbiased behavioural tracking, and performance recording [74,80,86].

However, despite the increasing use of AGs for cognitive purposes [88], there is a lack of a theoretical framework that guides the development of these platforms to adapt and respond to patients' clinical and non-clinical needs and limitations [122,123].

### 1.3.2. Evaluation of applied games for neuropsychological rehabilitation

The WHO Global Strategy on Digital Health 2020-2025 emphasises the importance of people-centred health systems in guiding the digital health era [79]. According to WHO, to achieve an equitable and accessible digital health system, it is essential to consider the needs and limitations of different stakeholders in the healthcare ecosystem, including patients, families, communities, and health professionals [79].

Despite the recognised potential of VR and AGs as rehabilitation tools, a significant discrepancy exists between their intended use in the experimental setting and their current use [124]. Reasons for this include immature engineering processes (e.g., no use of systematic methods that guide software development) and poor integration with the clinical practice and theoretical approaches [125]. In addition, despite the extensive literature, most digital neuropsychological rehabilitation platforms are mainly driven by technical

considerations (i.e., medical and engineering perspectives) rather than stakeholder perspectives, needs, and values.

To close the gap between technology availability and its use in clinical practice, user-centred design approaches and rigorous feasibility evaluation protocols should be implemented [124]. This combined approach will help identify and distinguish between the barriers to the use of such platforms due to poor interface design from those raised by the mismatch between platform requirements and objectives and end-users/patients' abilities, skills, and preferences, and those associated with patients' clinical condition (e.g., cognitive impairments) [126,127]. Only by addressing the factors that potentially impact patients' capacity to use digital neuropsychological rehabilitation platforms effectively and efficiently can the scientific community ensure equitable and universal access to digital health services.

# CHAPTER II. RESEARCH PROBLEM AND OBJECTIVES

Research Problem and Thesis Objectives

## 2.1 Research Problem and Objectives

Vascular mild cognitive impairment is characterised by a dysexecutive syndrome, memory deficits, and subtle impairments in more complex IADL [39]. To improve patients' QoL and reduce the burden of disease, developing digital neuropsychological rehabilitation programs that train cognitive functions and behavioural strategies necessary to regain the capacity to live independently is crucial [60].

However, despite the potential benefits of resources such as VR and AGs, scientific literature suggests that most digital platforms lack the transfer capacity from experimental settings to the real world and do not significantly impact patients' daily functioning. Moreover, other factors besides cognitive impairment, such as patients' digital literacy, perceived computer confidence and self-efficacy, can affect users' willingness to adopt and use digital healthcare services over the long term, overshadowing the potential impact of digital neuropsychological rehabilitation platforms.

Based on the research mentioned above, the current project has five main goals:

1. To systematically review the scientific literature available to identify the GEs most used in digital game-based platforms (GBI) for cognitive assessment, training, or rehabilitation.
2. To analyse the impact of VGs on cognitive and functional capacity outcomes in patients with (mild to severe) cognitive impairment.
3. To develop a digital neuropsychological rehabilitation AG using a participatory design approach that combines image-based VEs, gamification processes, and neuropsychological rehabilitation principles. Then, we aimed to evaluate the feasibility and rehabilitation potential of the AG developed to train cognitive and behavioural strategies recruited during an IADL, such as shopping.
4. To evaluate the impact of non-cognitive factors, such as perceived computer confidence and computer self-efficacy, on the interaction experience (IX) in a group of community dwellers.
5. To evaluate the feasibility of the AG developed in VaMCI patients.

## CHAPTER III. STUDIES

**Study 1** – Ferreira-Brito, F., Fialho, M., Virgolino, A., Neves, I., Miranda, A. C., Sousa-Santos, N., Caneiras, C., Carriço, L., Verdelho, A., & Santos, O. (2019). Game-based interventions for neuropsychological assessment, training and rehabilitation: which game-elements to use? A systematic review. *Journal of Biomedical Informatics*, *98*(August), 103287. doi:10.1016/j.jbi.2019.103287.

**Study 2** – Ferreira-Brito, F., Ribeiro, F., Aguiar de Sousa, D., Costa, J., Caneiras, C., Carriço, L., & Verdelho, A. (2021). Are Video Games Effective to Promote Cognition and Everyday Functional Capacity in Mild Cognitive Impairment/Dementia Patients? A Meta-Analysis of Randomized Controlled Trials. *Journal of Alzheimer's Disease*, *84*, 329–341. doi:10.3233/jad-210545.

**Study 3** – Ferreira-Brito, F., Alves, S., Santos, O., Guerreiro, T., Caneiras, C., Carriço, L., & Verdelho, A. (2020). Photo-Realistic Interactive Virtual Environments for Neurorehabilitation in Mild Cognitive Impairment (NeuroVRehab.PT): A Participatory Design and Proof-of-Concept Study. Journal of Clinical Medicine, 9(12), 3821. doi:10.3390/jcm9123821.

**Study 4 –** Ferreira-Brito, F., Alves, S., Guerreiro, T., Santos, O., Caneiras, C., Carriço, L., & Verdelho, A. (n.d.). Adherence to health technologies in older adults: challenges and lessons learned. *In review in the Digital Health journal*.

**Study 5 –** Ferreira-Brito, F., Alves, S., Guerreiro, T., Santos, O., Caneiras, C., Carriço, L., & Verdelho, A. (n.d.). Neuropsychological rehabilitation in vascular mild cognitive impairment: a feasibility study of NeuroVRehab.PT. *In Preparation for Submission*.

*The candidate contributed substantially to the study concept and design, data collection, analysis, and interpretation, and drafted and revised the manuscripts critically for important content.*

## ***Study 1:*** Game-based interventions for neuropsychological assessment, training and rehabilitation: which game-elements to use? A systematic review.

**ABSTRACT**

Game-based interventions (GBI) have been used to promote health-related outcomes, including cognitive functions. Criteria for game elements (GE) selection are insufficiently characterized in terms of their adequacy to patients' clinical conditions or targeted cognitive outcomes. This study aimed to identify GE applied in GBI used for cognitive assessment, training, or rehabilitation. A systematic review of literature was conducted. Papers involving video games were included if: *1)* presenting empirical and original data; *2)* video games were used for cognitive intervention; and *3)* attention, working memory or inhibitory control were considered as outcomes of interest. Ninety-one papers were included. A significant difference between the number of GE reported in the assessed papers and those composing video games was found ($p < .001$). The two most frequently used GE were: score system (79.2% of the interventions using video games; for assessment, 43.8%; for training, 93.5%; and for rehabilitation, 83.3%) and narrative context (79.2% of interventions; for assessment, 93.8%; for training, 73.9%; and for rehabilitation, 66.7%). Usability assessment was significantly associated with six of the seven GE analysed (*p-values between* $p \leq .001$ and $p. = 027$). The use GEs that act as extrinsic motivation promotors (*e.g.,* numeric feedback system) may jeopardize patients' long-term adherence to interventions, mainly if associated with progressive difficulty-increase of gaming experience. Lack of precise description of GE and absence of a theoretical framework supporting GE selection are important limitations of the available clinical literature.

**Keywords:** Video games; Serious games; Cognitive functions; Attention; Working memory; Inhibitory control

## INTRODUCTION

Game-based interventions (GBI) are built on the assumption that specific human skills and behaviours can be more easily promoted when the required training is conducted within a playful and entertaining context, such as the ones entailed by video games [1]. Gamification processes [2], serious games [3] and applied games [4] are, currently, relevant, and innovative approaches in the study of human behaviour change through the use of video games.

Game-based interventions have been used in clinical contexts to promote adherence and cognitive capacity among both healthy and clinical populations. Directly inspired on traditional games, game elements (GE) can be defined as a set of video games components which include patterns, objects, principles, models, or methods [2,5]. Points, levels of difficulty, badges, storyline and plot, progression based on success or failure to achieve the game's goals, and multiplayer component are just a few examples of GE typically present in video games.

The use of GE to promote learning and motivation finds support on traditional psychological theories [6]. According to the Self-Determination Theory [7], intrinsic-motivated behaviour (or at least more autonomous motivated behaviour) is developed when the person achieves a sense of competence towards the activity and when it is allied with an internal perceived locus of control of the task. In video games, some GE such as positive feedback messages can promote a sense of competence while playing the game. Also, internal perceived locus of control is promoted with tooltips or help buttons showing the player what he or she did wrong and how to correct the action [7].

Another possible example is the implementation of tutorials and other on-boarding tools to introduce game's mechanics that are initially beyond the newbie's capacity. The acquisition and development of new skills, supported by such "external" help or by a more experienced agent, finds theoretical support in Vygotsky's concept of zone of proximal development [8], as well as in the concept of scaffolding proposed by Wood and colleagues [9]. Within these two conceptual views, learning and problem solving are depicted as constructive processes that can be fostered if guided by more capable peers. This is also the case in Massively Multiplayer Online Games, where interaction and collaboration with more skilled players is not only available but highly sought through participation in both in- and out-game activities, such as raids, parties, chats, and discussion forums.

The study of the impact of video games on human cognition and behaviour has been heavily focused on the downsides of such playing. Notwithstanding, existing results are conflicting. On one side, excessive exposure to video games, especially to those with violent content [10], has been associated with increased aggressiveness (at behavioural, cognitive, or emotional levels), and decreased prosocial behaviour, empathy, and sensitiveness to aggression [11]. On the other side, there are studies where these results were not replicated [12]. A recent study proposed that the increase of aggressive behaviour associated with playing video games is mainly the result of a priming effect (which increases accessibility to aggressive/violent thoughts) and, so, the effects are short-lived, occurring only immediately after video game exposure (no more than 15 minutes) [12]. Przybylski and Weinstein [13], on the other hand, propose that the aggression associated with video games may be better explained by background-factors present in specific cohorts (e.g., technology use and material deprivation). Additionally, the authors highlighted the high methodological flexibility present in aggression behaviour and violent gaming measures that contributes to selective reporting of results [13].

The scientific community has recently been also interested on the beneficial impact that video games may have in human behaviour. For instance, in a recent meta-analysis about the efficacy of serious games to reduce cognitive decline among psychiatric patients, a moderate effect size of this ludic-therapeutic approach was found ($g = 0.79$ (95% CI 0.36 – 1.21); $p<0.05$) [14]. In another systematic review of literature, where the impact of video games was compared to other computer-based interventions, Kueider and colleagues concluded that video games constitute an effective intervention for global cognition stimulation ($d = 0.69$), with relevant results also on reaction time ($d = 0.77$), processing speed ($d = 0.72$), executive function ($d = 0.25$), and attention ($d = 0.21$) [15]. Anguera et al. [16] showed a significant reduction in multitasking cognitive cost in a group of older adults after playing NeuroRacer – a 3D multitasking training video game designed to improve cognitive control – when compared to an active control (single-task training) and to a non-contact group. Furthermore, improvements identified in Anguera's experiment persisted after six months without boosting sessions, with benefits being transferred to other cognitive domains than those directly targeted by the video game (i.e., sustained attention and working memory).

Nonetheless, important methodological shortcomings (e.g., lack of concise terms or of standardized methods to develop and assess GBI) and ethical concerns (e.g., unfamiliarity

or technophobia, unrealistic expectations of improvement and skill generalization, the possibility of physical harm, addiction, or social isolation) have been reported [5,17,18].

From a clinical point-of-view, it is of great concern the absence of any conceptual or clinical rationale supporting GE selection depending on patient's clinical conditions and/or on targeted cognitive outcomes. One rare exception can be found in Lumsden et al. [17], where authors clearly stated that GE such as rewards and feedback seem to be particularly suitable for persons with Attention Deficit Hyperactivity Disorder (ADHD), who are especially responsive to immediate reinforcement, feedback and clear definition of goals and objectives. On the other hand, the subjective and somehow arbitrary use of GE in vulnerable populations [18] can impair the successful clinical usage of GBI and can introduce deleterious effects on users' performance [19] or psychological/emotional health. Take as example a life bar (score system element) in a serious game for cancer survivors, where patients lose points every time, they do not achieve the game's goal.

To the author's knowledge, this research represents a first effort to overcome the aforementioned limitations, namely the lack of a theoretical framework supporting GE selection in interventions focused on cognitive promotion. To this purpose, a systematic review of literature (following PRISMA guidelines [20]) was conducted to identify which GE were most frequently present in GBI used for cognitive assessment, training, or rehabilitation. Furthermore, considerations were taken regarding the capacity of those GE to promote patient's adherence to the cognitive intervention, reflecting about the adequacy of such GE to the study of the targeted cognitive outcomes.

## MATERIAL AND METHODS

### 2.1. Search strategy

Search-terms related to "game-based interventions" and "cognitive outcomes" were identified on basis of an exploratory narrative review and discussion between members of the research team. Medical Subject Headings (MeSH) terms were used whenever possible. A total of 46 "game-based interventions" terms were combined listwise with 14 search-terms related with "cognitive outcomes" (i.e., each search-term of the first category was individually combined with each term of the second category) (see Supplementary Table S1 for details on the search strategy). This keyword combination allowed us to minimize the exclusion of potential entries that could be masked by the use of less common terms, which is not unusual in recent research fields.

2.2. Information sources and search

Electronic database search was conducted on 24th January 2017 and then updated on 22nd of March 2019. PubMed, SciELO, and EBSCO – Psychology and Behavioral Sciences Collection were searched, with a restriction to the following inclusion criteria: 1) publication date (PubMed: 24th January of 2006 to 21st March of 2019, SciELO: 2007-2019; EBSCO: 1st January of 2006 to 21st March of 2019); 2) full text in English (PubMed and EBSCO); and 3) search field (title and abstract). Furthermore, search was restricted to peer-reviewed papers (EBSCO database) and studies with humans as study's subjects (PubMed). Book chapters were excluded.

2.3. Additional sources of information

Eighteen journals with editorial interests on serious games and games for health were identified and manually searched to locate additional studies of interest published between 2012 and 2019 (see Supplementary Table S1 for details). Additionally, reference lists of (1) each paper included for data extraction and (2) the literature reviews (narrative or systematic ones) identified during the screening process were also hand-searched for identification of additional relevant papers. Literature reviews were considered only as potential source of empirical papers (i.e., for reference search purposes; not for data extraction).

2.4. Screening and eligibility

The set of initially retrieved entries was assigned to three pairs of reviewers and independently screened by each researcher in the pair considering title and abstract analysis. Studies were eligible for data extraction if: 1) empirical and original data were presented; 2) a video game (commercial, adapted or applied) was used for cognitive assessment, training, or rehabilitation; 3) the intervention targeted and explicitly reported individual measures of attention, working memory or inhibitory control outcomes; and 4) full text was available in English, Portuguese, or Spanish. To be considered as a video game, the software had to include at least one of the following GE: 1) score system (in software that presented unrelated tasks, a final/total score system had to be present); 2) performance feedback system (non-numeric); or 3) continuous narrative context between tasks. Multigame platforms (e.g., unrelated mini-games), computerized cognitive training programs (e.g., RehaCom®), software programs that are merely digital version of paper-and-pencil instruments (no GE added) and studies that used more than one video game per group were excluded. Entries from the update search (n = 464) were screened by the first author and 10% of those entries were cross-checked by the last author. Disagreements between researchers concerning data

eligibility were solved by a third independent senior element, who approved the final list of studies to be included for data extraction.

### 2.5. Data collection process

A data extraction spreadsheet, including a glossary of concepts (e.g., GE, cognitive outcomes), was developed and used by all team members. This was done to promote standardization of the extraction process. Three sections were considered: "General paper information" section, "Video game descriptive information" section, and "Interventions details and cognitive/health outcomes" section (see Supplementary Table S2 for details). Extraction fields presented two different formats of response: pre-defined option (closed-answer format), or strings of information (open-answer format). When it was not possible to characterize study's elements according to the available options, researchers could select the option not clear/not sure.

#### 2.5.1. General paper information section

In this section, information regarding title, authors' name, journal's title, year of publication, publication quartile (in 2017), and area of expertise (i.e., area in which the study had the highest quartile in 2017 according to the Scimago Journal & Country Rank) were gathered. Papers were coded according to the following four categories of scientific expertise: (1) Health Sciences (included journals focused on Neurology, Neurosciences, Paediatrics, Perinatology and Child Health, Medicine, Rehabilitation, Geriatric, Gerontology); (2) Social Sciences (Psychology, Neuropsychology, Physiological Psychology, Clinical Psychology, Cognitive Neuroscience, Behaviour Research and Therapy); (3) Computer Sciences (Computer Sciences Applications, Engineering, Health Informatics); and (4) Other (Public Health, Environment and Occupational Health, Language and Linguist, Multidisciplinary).

#### 2.5.2. Video game descriptive information section

##### General description

This section addressed information regarding the game's title, main activity, type of platform, and virtual components. The central action/task that the player must perform to achieve the game's goal was considered the main activity (e.g., drive a car, collected/find/selected stimuli, shopping, play tennis). Three types of platforms were considered: game's console, touch-based devices (i.e., smartphone/tablet) and computer. Finally, video games were classified as being or not being an exergame, having or not having virtual reality (VR), or another virtual component.

Purpose and cognitive utility of video game

Two types of video games were considered according to the purpose for which the video game was initially developed: 1) applied games (AG) [4], which encompasses serious games – video games specifically developed to achieve a change in the player's patterns of behaviour [3] – and gamified software, a software that underwent a process of intentional use of GE in order to enhance a game experience in non-game tasks [5]; and 2) commercial video games (CG), developed for the main purpose of entertainment and leisure [21]. Commercial video games which were adapted (e.g., using a different game controller or interface such as brain computer interface) were classified as AG if targeting behaviour change. Cognitive utility of game refers to the objective for which video games were used, namely: assessment, training, or rehabilitation of cognitive functions.

Game elements

Studies were searched for the presence of seven GE. Since there is no widely-accepted definition of what or how many are the basic GE that compose video games an initial set was gathered based on the information reported elsewhere [2,22–24]. That initial set was then refined to include a total of seven GE whose definitions were subject of discussion

| |
|---|
| **Narrative context** – storyline in which the main action of the game unfolds. Storytelling adds meaning and guides action whether in a fantasy (*e.g.,* save the princess) or real-like scenario (*e.g.,* shopping). |
| **Avatar/Character** – player's virtual representation whether human-like or other (*e.g.,* spaceship). |
| **Score system** – numeric feedback system that informs player about his or her performance and progression in the game. Points, money, missions, levels, leaderboards, and progression bars were included in this category. |
| **Reward system** – visual feedback system related to the achievement of specific challenges and skills. Badges, medals, awards, extra powers, access to virtual world restricted areas, and written and/or auditory messages related to player's performance were included in this category. |
| **Win and Lose condition** – it is shown to the player, in an explicit way, that he or she was able or not to achieve the goal of the game (*e.g.,* death, return to a previous level). |
| **Time pressure** – implementation of time constraints to complete a task or achieve the best score possible. |
| **Multiplayer** – more than one player influences gameplay simultaneously. This includes cooperation and/or competitive modes. |

**Fig. 1.** Game-elements description.

between research team members until a consensus was reached (see Figure 1). To obtain an in-depth description of each of the video games included in the selected papers, an additional web-based search was conducted. Official websites were the main source of information to CG. University, research groups and video-sharing (e.g., YouTube) websites were also searched in the case of AG. Information extracted from these two sources was introduced separately.

2.5.3. Intervention details and cognitive/health outcomes section

This section was dedicated to the extraction of information regarding intervention and sample characteristics. Therapy aims to help individuals to regain the capacity to self-regulate his or her behaviour in order to being able to live autonomously [25]. Having this perspective in mind, three cognitive functions were selected within the core components of cognitive control and self-regulation theory [26]:

- Attention: process that enables individuals to consciously process stimuli/information in our environment [27]. All studies that focused on attention outcomes were considered for data extraction purposes regardless of modality (e.g., visual, auditory) or type (e.g., sustained, selective) except for studies focused on sensory attention, which were excluded.
- Working memory: system that enables the temporary storage and manipulation of information necessary to adequately respond to environmental demands [28]. Working memory outcomes were always considered when presented as a single expression ("working memory") in the analysed paper.
- Inhibitory control: capacity to inhibit a dominant and automatic response in order to (deliberately) select a more adequate one regarding environment or task's characteristics [29]. Inhibitory control or inhibitory capacity were both accepted and considered as equivalent terms.

The presence of other cognitive or health-related outcomes was also registered. Finally, information on near transfer capacity (impact on related cognitive functions targeted by the video game), far transfer capacity (impact on non-related cognitive or health outcomes targeted by the video game) [30], user-experience (UX) evaluation (user's perceptions on software usability, hedonic experience), and sample characteristics were also extracted.

*2.6. Statistical analysis*

Analysis of data was done using the program Statistical Package for the Social Science (IBM-SPSS), version 24.0. Studies that presented more than one intervention arm, with a different video game per arm, provided different entries in the database. This was done because the sample unit for data analysis was the video game, not the paper. Important to highlight that this was done only when each intervention arm included only one game (as explained in the screening and eligibility section, studies which entailed more than one video game for the same intervention arm were excluded). Overall, 118 interventions with video games were identified in the 91 papers included in the qualitative analysis. Three sampling bases were considered for data analysis (see Figure 2). For GE frequency analysis, video games reported in different papers were considered only once ($n_{video.games}$ = 72); this is, therefore, the total number of video games without duplication across papers. For GE frequency analysis by cognitive utility of the games (i.e., assessment, training or rehabilitation), video games reported in different papers targeting the same cognitive utility were considered only once ($n_{cog.utility}$ = 80). For instance, if one video game was reported in two or more papers for assessment purposes, the video game was counted only once; but if the same video game was reported for assessing cognitive functions in one paper and for training cognitive functions in another paper, then the video game was considered twice.

Finally, for two types of analyses (comparing the number of GE described in the papers and the number of GE really existent in the video games; and characterizing the association between GE really existent in the video games and cognitive outcomes), the total sample of

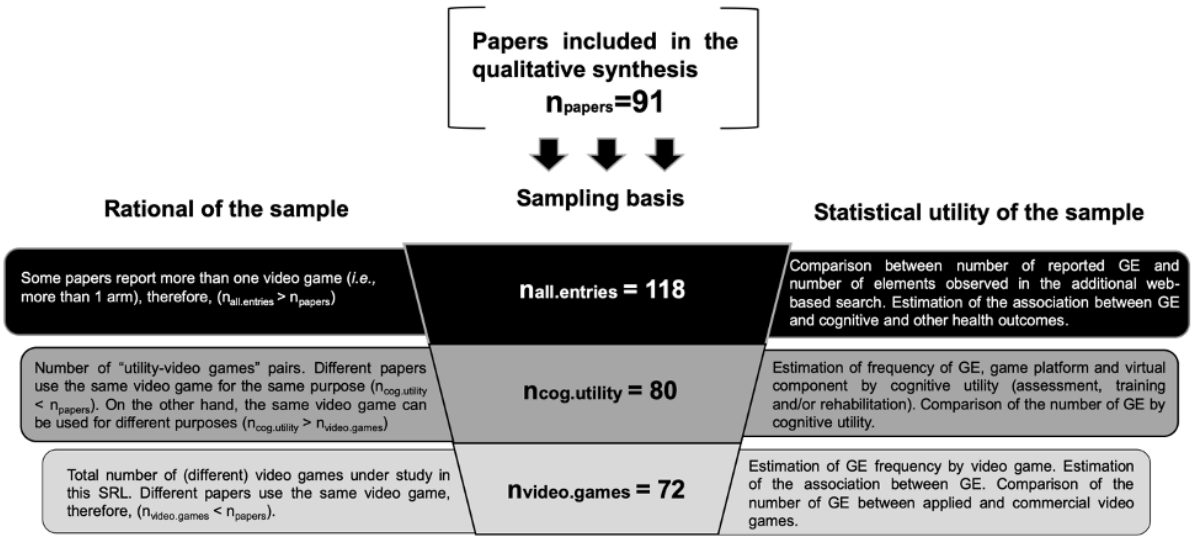


**Fig. 2.** Sampling bases used in statistical analysis.

video games interventions ($n_{all.entries}$ = 118) was considered; this means that all entries were considered regardless of duplication across papers. This decision was based on the fact that some video games were used in different papers to evaluate different cognitive functions.

Data normality was tested by using Kolmogorov-Smirnov test and considering kurtosis and skewness (normality assumed when kurtosis and skewness ranged between -2 and 2) [31]. Results were considered significant for a p-value ≤ .05. Because normality was observed for all variables and for all comparison groups, parametric tests were applied. Paired-samples t-tests were conducted to determine whether the number of GE reported in the papers and those that actually compose video games (as observed in webpages describing the games) differed significantly. This was done for all different video games altogether ($n_{all.entries}$ = 118), and for commercial games (n = 51) and applied games (n = 67). Paired-samples t-tests were also used for assessing if the number of GE reported in the papers and those that actually compose video games differ according to the cognitive utility of the video games (assessment, n = 28; training, n = 67; rehabilitation, n = 23). Differences between commercial and applied games regarding the number of GE as described in video games webpages were tested through independent sample t-test ($n_{video.game}$ = 72). Differences between the cognitive utility of the video games (assessment, training and rehabilitation) regarding the number of GE as described in video games webpages were tested with one-way ANOVA with Bonferroni Post-Hoc test ($n_{cog.utility}$ = 80).

Chi-square tests of independence were applied to study the association between different pairs of GE (with Cramer's V for assessing the strength of the associations); this was also done for testing the independence between each GE and cognitive outcomes (attention, working memory, inhibitory control), cognitive utility of the game (assessment, training, rehabilitation), having or not having health-related outcomes, virtual reality or another virtual component (*e.g.,* brain-computer interfaces), being or not being an exergame, and type of game platform (console, smartphone/tablet, computer). Chi-square tests of homogeneity were applied to check if each GE was more frequently used in applied or commercial video games.

## RESULTS

### *3.1 Study selection*

Overall, 3 456 papers matched the set of inclusion criteria (see Figure 3). Fifty-four papers were added after manual search of additional journals focusing on serious games and/or games for health areas. After removing duplicates, 2593 papers were screened considering title and abstract. Overall, 2 406 papers were excluded on basis of this analysis. From the 187 eligible papers for full-text analysis phase, 53 were included in the current review.

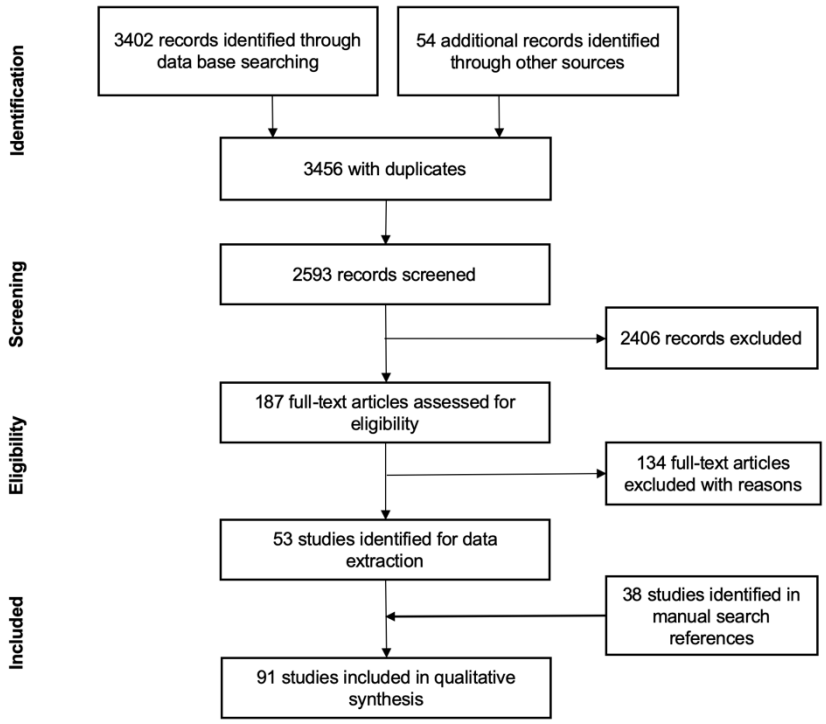


**Fig. 3.** PRISMA flow diagram.

Common reasons for exclusion of papers were: no use of video game (n =17); use of game platforms or more than one video game simultaneously (e.g. at the same study arm; n = 16); attention, working memory and inhibitory control were not assessed as cognitive outcomes (n = 28); literature reviews (n = 28); different scope (n = 17) (e.g., roundtable discussions); full-text was not available, even after e-mail contact with authors (n = 2); and two or more of the aforementioned reasons combined (n = 26). Thirty-eight papers were later added from manual search of the list of references of included papers and literature reviews. A total of

91 papers were included for data extraction, in which 72 different video games were identified.

3.2. Bibliometric characterization of GBI studies

Year of publication of studies ranged from 2006 to 2018, with publication peak at 2013 (n = 15). More than half of the studies were published in journals ranked in the first quartile (54/91). Sixteen studies were published in journals in the second quartile, six studies in the third quartile, and five studies in the fourth quartile. Ten studies were published in journals with no impact factor attributed.

From the 81 papers published in journals with impact factor, 42 were published in journals scoping Health Sciences, 25 Social Sciences, eight Computer Sciences, and six other scientific disciplines. Additional analysis considering quartile of publication by area of expertise showed that from the 54 studies published in the first quartile, 26 were indexed to Health Sciences, 22 to Social Sciences, one to Computer Sciences, and five to the category "other" (see Supplementary Table S3 for details).

3.3. Purpose and cognitive utility of GBI

From the 72 identified video games, 42 are AG and 30 CG. Sixteen video games were used for cognitive assessment (of which 15 are AG and one CG), 46 for cognitive training (of which 18 are AG and 28 CG) and 18 for cognitive rehabilitation purposes (of which 14 AG and 4 CG). The difference between the number of identified video games ($n_{video.games}$ = 72), the number of entries according to cognitive utility ($n_{cog.utility}$ = 80), and the total number of entries ($n_{all.entries}$ = 118) is due to the fact that: (1) eighteen papers reported data regarding more than one video game (one video game per intervention arm) [32–49]; (2) nine CG (Medal of Honor: Allied Assault [42,49]; Medal of Honor: Pacific Assault, EA Games [36,41,50]; Rise of Nations, SEGA [42,51]; Brain Age / Dr. Kawashima's Brain Training, Nintendo [39,40,45,46,52,53]; Tetris [38–40,42,44,49,54]; Modern Combat: Sandstrom, Gameloft [32,47,48]; Big Brain Academy, Nintendo [55,56]; Balance, Atari [36,41]; and The Sims, EA Games [32,35,37]); And (3) 13 AG (Neurofeedback Game [95,96]; VRROOM [116,117]; VRST [81,82]; VRCPAT [75–78,99]; Braingame Brian [86,87,103]; Working memory program, Cogmed Systems [33,107,108]; RoboMemo, Cogmed Systems [109,110]; ClinicaVR: Classroom-CPT [67–73]; VR Setup [114,115]; AULA, Nesplora [59,60,122]; Desktop VR System [91,104]; Space Fortress [97,98,111,123], and Cybercycling [34,90]) were reported in more than one study (see Table 1).

**Table 1.** Description of video games entries identified in the included ($n_{all.entries}$ = 118)

| Purpose and utility of the game | | Game-elements | | | | | | | Cognitive Outcomes | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Game's name<br>Main activity | Study that used the video game | Narrative context | Avatar/ character | Score system | Reward system | Win/lose | Time pressure | Multiplayer | Attention | Working Memory | Inhibitory Control |
| **Applied games for Cognitive Assessment** | | | | | | | | | | | |
| Art Gallery Test (AGT)<br>To identified differences between to images, construct puzzles, and finding the details. | Gamito et al. [57] | Yes | Not clear /sure | Not clear /sure | Not clear /sure | Not clear /sure | No | No | Yes | Yes | Yes |
| Aula Nesplora<br>To respond as quickly as possible to target stimuli while inhibiting any responses to non-target stimuli. | Areces et al. [58] | Yes | Not clear /sure | No | No | Not clear /sure | Yes | No | Yes | Yes | Yes |
| | Iriarte et al. [59] | | | | | | | | Yes | No | No |
| | Díaz-Orueta et al. [60] | | | | | | | | Yes | Yes | No |
| Raiders of the Lost Treasure<br>To collect/find hidden objects. | Silva and Frère [61] | Yes | Yes | Yes | Yes | Not clear /sure | No | Not clear /sure | Yes | No | No |
| Shoe Closet Test<br>To match each pair of shoes with the color's compartments in a virtual closet. | Oliveira et al. [62] | Yes | Not clear /sure | Not clear /sure | No | Not clear /sure | Not clear /sure | No | Yes | No | No |
| Space Matrix<br>To destroy spaceships. | McPherson and Burns [63] | Yes | No | Yes | Yes | Not clear /sure | Yes | Yes | No | Yes | No |
| Tap the little hedgehog<br>To perform different operations on abstract patterns such as copying, reproducing sequences from memory and mirroring patterns. | Verhaegh, Fontijn and Aarts [64] | Yes | No | Yes | Yes | Yes | Yes | No | No | Yes | No |
| Timo's Adventure<br>To collect stars. | Peijnenborgh et al. [65] | Yes | Yes | Yes | Yes | Not clear /sure | Yes | No | Yes | Yes | Yes |

**Table 1.** (Cont.)

| Purpose and utility of the game | | Game-elements | | | | | | | Cognitive Outcomes | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Game's name<br>Main activity | Study that used the video game | Narrative context | Avatar/ character | Score system | Reward system | Win/lose | Time pressure | Multiplayer | Attention | Working Memory | Inhibitory Control |
| Towi Games<br>To make arrangements to travel | Rosetti et al. [66] | Yes | Not clear /sure | Yes | No | Not clear /sure | Not clear /sure | No | Yes | Yes | Yes |
| ClinicaVR: Classroom-CPT<br>To maintain vigilance and react to a specific stimulus within a set of continuously presented distractors. | Parsons et al. [67] | Yes | Not clear /sure | Not clear /sure | Not clear /sure | Not clear /sure | Yes | No | Yes | No | No |
| | Negut, Jurma and David [68] | | | | | | | | Yes | Yes | No |
| | Nolin et al. [69] | | | | | | | | Yes | No | Yes |
| | Gilboa et al. [70] | | | | | | | | Yes | No | No |
| | Moreau et al. [71] | | | | | | | | Yes | No | Yes |
| | Adams et al. [72] | | | | | | | | Yes | No | No |
| | Nolin, Martin and Bouchard [73] | | | | | | | | Yes | No | Yes |
| Virtual Library Task<br>To perform several tasks associated with the day-to-day running of a library. | Renison et al. [74] | Yes | Not clear /sure | Not clear /sure | Not clear /sure | Not clear /sure | Yes | No | No | Yes | Yes |
| Virtual Reality Cognitive Performance Assessment Test (VRCPAT)<br>To select stimuli while drive a car. | Parsons and Rizzo [75] | Yes | Not clear /sure | Yes | Not clear /sure | Not clear /sure | Yes | Not clear /sure | Yes | No | No |
| | Parsons et al. [76] | | | | | | | | Yes | No | No |
| | Parsons et al. [77] | | | | | | | | Yes | No | No |
| | Parsons et al. [78] | | | | | | | | Yes | No | No |

**Table 1.** (Cont.)

| Purpose and utility of the game | | Game-elements | | | | | | | Cognitive Outcomes | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Game's name<br>Main activity | Study that used the video game | Narrative context | Avatar/ character | Score system | Reward system | Win/lose | Time pressure | Multiplayer | Attention | Working Memory | Inhibitory Control |
| ClinicaVR: Apartment Stroop<br>To select target stimuli. | Henry, Joyal and Nolin [79] | Yes | Not clear /sure | Not clear /sure | Not clear /sure | Not clear /sure | Yes | No | Yes | No | Yes |
| VR-Based MET<br>To shop. | Raspelli et al. [80] | Yes | Not clear /sure | Not clear /sure | Not clear /sure | Not clear /sure | Not clear /sure | No | Yes | Yes | No |
| Virtual Reality Stroop Task (VRST)<br>To respond to a Stroop-like condition while driving a car. | Parsons et al. [81] | Yes | Not clear /sure | Not clear /sure | Not clear /sure | Not clear /sure | Not clear /sure | No | Yes | No | Yes |
| | Armstrong et al. [82] | | | | | | | | Yes | No | Yes |
| VR Office Environment<br>To learn 16 target items, depicted among numerous other office distracters. | Matheis et al. [83] | Yes | Not clear /sure | No | No | No | Yes | No | Yes | No | No |
| **Applied games for Cognitive Training** | | | | | | | | | | | |
| 3-D virtual reality kayak program<br>To paddle a Kayak. | Park and Yim [84] | Yes | No | Not clear /sure | Not clear /sure | Not clear /sure | Not clear /sure | Not clear /sure | Yes | No | No |
| Adaptive WM task variant<br>To select target stimuli. | Jaeggi et al. [85] | Yes | No | Yes | Yes | Not clear /sure | Not clear /sure | No | No | Yes | No |
| Braingame Brian<br>To help and befriend the game-worlds inhabitants by creating increasingly elaborate inventions. | van der Oord et al. [86] | Yes | Yes | Yes | Yes | Not clear /sure | Yes | Not clear /sure | No | Yes | Yes |
| | Verbeken et al. [87] | | | | | | | | No | Yes | Yes |

**Table 1.** (Cont.)

| Purpose and utility of the game | | Game-elements | | | | | | | Cognitive Outcomes | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Game's name<br>Main activity | Study that used the video game | Narrative context | Avatar/ character | Score system | Reward system | Win/lose | Time pressure | Multiplayer | Attention | Working Memory | Inhibitory Control |
| Card-pairing memory game<br>To open or close cards on screen. | Lee et al. [88] | Not clear /sure | Not clear /sure | Not clear /sure | Not clear /sure | Not clear /sure | Not clear /sure | No | Yes | No | No |
| City Builder Game<br>To remember and order a set of squares in a specific order. | Boendermaker et al. [89] | Yes | No | Yes | Yes | No | Yes | No | No | Yes | No |
| Cybercycle<br>To cycle. | Anderson-Hanley et al. [90] | Yes | No | Yes | No | No | Yes | No | Yes | No | No |
| Desktop VR System<br>To execute daily life activities. | Gamito et al. [91] | Yes | Not clear /sure | Yes | Not clear /sure | Not clear /sure | Not clear /sure | No | Yes | No | No |
| EVET - Edinburgh Virtual Errands Test<br>To shop. | Logie et al. [92] | Yes | No | Yes | Not clear /sure | No | Yes | No | No | Yes | No |
| Interactive Videogame Technology<br>To collect and deliver the largest amount of contraband items. | Russell and Newton [93] | Yes | Yes | Yes | Not clear /sure | Not clear /sure | Yes | Yes | Yes | No | No |
| Labyrinth<br>To select a set of stimuli while avoiding a snake within a time limit. | Montani, De Grazia and Zorzi [94] | Yes | Yes | Yes | Yes | Yes | Yes | No | Yes | No | No |
| Neurofeedback Game<br>To refill a set of elements. | Thomas et al. [95] | No | No | Yes | Yes | Yes | No | No | Yes | No | No |

**Table 1.** (Cont.)

| Purpose and utility of the game | | Game-elements | | | | | | | Cognitive Outcomes | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Game's name<br>Main activity | Study that used the video game | Narrative context | Avatar/ character | Score system | Reward system | Win/lose | Time pressure | Multiplayer | Attention | Working Memory | Inhibitory Control |
| Neurofeedback Game<br>To refill a set of elements. | Thomas et al. [96] | No | No | Yes | Yes | Yes | No | No | Yes | No | No |
| NeuroRacer<br>To drive the car on a road. | Anguera et al. [16] | Yes | Yes | Yes | Yes | Not clear /sure | Yes | No | Yes | Yes | No |
| Physical exercise plus high cognitive demand<br>To collect different colored coins and corresponding colored dragons. | Barcelos et al. [34] | Yes | No | Yes | Not clear /sure | No | Yes | No | Yes | No | Yes |
| Cybercycle<br>To cycle | | Yes | No | Yes | No | No | Yes | No | Yes | No | Yes |
| Space Fortress<br>To shoot missiles and destroy a space fortress while protecting your spaceship against damage. | Maclin et al. [97] | Yes | Yes | Yes | Yes | Yes | Yes | No | Yes | No | No |
| | Nikolaidis et al. [98] | | | | | | | | Yes | Yes | No |
| Virtual Reality Cognitive Performance Assessment Test (VRCPAT)<br>To select stimuli while drive a car. | Parsons and Rizzo [99] | Yes | Not clear /sure | Yes | Not clear /sure | Not clear /sure | Yes | Not clear /sure | Yes | No | No |
| Working memory program, Cogmed systems<br>To remember both location and order of a number of visual stimuli. | Thorell et al. [33] | No | No | Yes | Yes | Not clear /sure | Yes | No | Yes | Yes | Yes |
| Inhibitory control program, Cogmed systems<br>To respond according to a certain stimulus. | | No | No | Yes | Yes | Not clear /sure | Yes | No | Yes | Yes | Yes |

**Table 1.** (Cont.)

| Purpose and utility of the game | | Game-elements | | | | | | | Cognitive Outcomes | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Game's name<br>Main activity | Study that used the video game | Narrative context | Avatar/ character | Score system | Reward system | Win/lose | Time pressure | Multiplayer | Attention | Working Memory | Inhibitory Control |
| Working memory task with game-elements<br>To memorize a one-digit number (key-digit); to classify a simple arithmetic decision task as either true or false. | Ninaus et al. [100] | Yes | No | Yes | No | Yes | Not clear /sure | Not clear /sure | No | Yes | No |
| **Applied games for Cognitive Rehabilitation** | | | | | | | | | | | |
| 3D classroom environment<br>To select target stimuli. | Ali and Puthusserypady [101] | Yes | Yes | Yes | Not clear /sure | Yes | Not clear /sure | Not clear /sure | Yes | No | No |
| 3D video game rehabilitation training<br>To explore each street with minimal backtracking. | Caglio et al. [102] | Yes | Yes | Not clear /sure | Not clear /sure | Not clear /sure | No | No | No | Yes | No |
| Braingame Brian<br>To help and befriend the game-worlds inhabitants by creating increasingly elaborate inventions. | Dovis et al. [103] | Yes | Yes | Yes | Yes | Not clear /sure | Yes | Not clear /sure | No | Yes | Yes |
| Desktop VR System<br>To execute daily life activities. | Gamito et al. [104] | Yes | Not clear /sure | Yes | Not clear /sure | Not clear /sure | Not clear /sure | No | Yes | No | No |
| Motion Rehab<br>To select target stimuli and ignore distractors. | Martel, Colussi and Marchi [105] | Yes | Yes | Yes | Not clear /sure | Not clear /sure | Not clear /sure | No | Yes | No | No |
| 'Odd Yellow' training<br>To reproduce the location of the odd-one-out and the location of the yellow figure shape. | van der Molen et al. [106] | No | No | Yes | No | Yes | Yes | No | No | Yes | Yes |

**Table 1.** (Cont.)

| Purpose and utility of the game | | Game-elements | | | | | | | Cognitive Outcomes | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Game's name<br>Main activity | Study that used the video game | Narrative context | Avatar/ character | Score system | Reward system | Win/lose | Time pressure | Multiplayer | Attention | Working Memory | Inhibitory Control |
| Working memory program, Cogmed systems<br>To remember both location and order of a number of visual stimuli. | Chacko et al. [107] | No | No | Yes | Yes | Not clear /sure | Yes | No | No | Yes | No |
| | Beck et al. [108] | | | | | | | | No | Yes | No |
| RoboMemo, Cogmed systems<br>To reproduced sequence of stimuli (lights/numbers) in direct or backward order. | Gray et al. [109] | Yes | No | Yes | Yes | Not clear /sure | Yes | No | Yes | Yes | No |
| | Westerberg et al. [110] | | | | | | | | Yes | Yes | Yes |
| Space Fortress<br>To destroy the Space Fortress. | Janssen et al. [111] | Yes | Yes | Yes | Yes | Yes | Yes | No | Yes | Yes | No |
| The Virtual Supermarket<br>To shop. | Carelli et al. [112] | Yes | Not clear /sure | Yes | Not clear /sure | Yes | Not clear /sure | No | Yes | No | No |
| Virtual reality environment<br>To perform quotidian activities. | La Paglia et al. [113] | Yes | Not clear /sure | Not clear /sure | Not clear /sure | Not clear /sure | Not clear /sure | Not clear /sure | Yes | No | No |
| VR Setup<br>To execute daily living activities. | Gamito et al. [114] | Yes | Not clear /sure | Yes | Not clear /sure | Not clear /sure | Not clear /sure | No | Yes | Yes | No |
| | Gamito et al. [115] | | | | | | | | Yes | Yes | No |
| VRROOM - Virtual Reality and Robotic Optical Operations Machine<br>To hold the handle of the robot and move it toward spherical targets. | Larson et al. [116] | No | No | No | Yes | No | Yes | No | Yes | No | No |
| | Dvorkin et al. [117] | | | | | | | | Yes | No | No |
| WM training task with game elements<br>To reproduce sequences of randomly lit-up squares in a 4x4 grid. | Prins et al. [118] | Yes | Yes | Yes | Yes | Yes | No | Not clear /sure | Yes | Yes | No |

**Table 1.** (Cont.)

| Purpose and utility of the game | | Game-elements | | | | | | | Cognitive Outcomes | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Game's name<br>Main activity | Study that used the video game | Narrative context | Avatar/ character | Score system | Reward system | Win/lose | Time pressure | Multiplayer | Attention | Working Memory | Inhibitory Control |
| **Commercial video games for Cognitive Assessment** | | | | | | | | | | | |
| Tetris<br>To form a horizontal line without leaving any gaps. | Lau-Zhu et al. [54] | No | No | Yes | Yes | Yes | Yes | No | No | Yes | No |
| **Commercial video games for Cognitive Training** | | | | | | | | | | | |
| Big Brain Academy, Nintendo<br>To respond as quickly as possible to the different tasks. | McLaughlin et al. [55] | No | Yes | Yes | Yes | No | Yes | Yes, not clear if active | Yes | No | No |
| Mario Kart DS, Nintendo<br>To race. | | Yes | Yes | Yes | Yes | No | Yes | Yes, but not active | | | |
| Brain Age / Dr. Kawashima's Brain Training: How old is your brain, Nintendo<br>To solve mathematical questions and memorize information. | Boot et al. [46] | No | Yes | Yes | No | No | Yes | No | Yes | No | No |
| New Super Mario Bros, Nintendo<br>To rescue the princess. | Lorant-Royer et al. [45] | Yes | Yes | Yes | Yes | No | No | Yes, not clear if active | Yes | Yes | No |
| Brain Age / Dr. Kawashima's Brain Training: How old is your brain, Nintendo<br>To solve mathematical questions and memorize information. | Nouchi et al. [39] | No | Yes | Yes | No | No | Yes | No | Yes | No | No |
| Tetris<br>To form a horizontal line without leaving any gaps. | | No | No | Yes | Yes | Yes | Yes | No | | | |

**Table 1.** (Cont.)

| Purpose and utility of the game | | Game-elements | | | | | | | Cognitive Outcomes | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Game's name<br>Main activity | Study that used the video game | Narrative context | Avatar/ character | Score system | Reward system | Win/lose | Time pressure | Multiplayer | Attention | Working Memory | Inhibitory Control |
| Brain Age / Dr. Kawashima's Brain Training: How old is your brain, Nintendo<br>To solve mathematical questions and memorize information. | Nouchi et al. [40] | No | Yes | Yes | No | No | Yes | No | Yes | Yes | Yes |
| Tetris<br>To form a horizontal line without leaving any gaps. | | No | No | Yes | Yes | Yes | Yes | No | | | |
| Modern Combat: Sandstorm, Gameloft<br>To navigate in hostile enemy territory and to achieve predetermined objectives such as deactivating enemy equipment. | Oei and Patterson [48] | Yes | Yes | Yes | Yes | Yes | No | Yes, not clear if active | Yes | No | No |
| Metal Gear Solid, Konami<br>To kill enemies. | | Yes | Yes | Yes | No | Yes | Yes | No | Yes | No | No |
| Super Sniper, Addicting Games<br>To kill enemies. | | Yes | No | Yes | Not clear /sure | Yes | Yes | No | Yes | No | No |
| Deer Hunter, Atari, Glu Mobile<br>To hunt. | | Yes | No | Yes | Yes | Not clear /sure | No | No | Yes | No | No |
| Computerized Card Game "Belote"<br>To complete a set of missions. | Cujzek and Vranis [43] | No | No | Yes | No | Yes | No | Yes | No | Yes | Yes |
| Computerized Ludo<br>To place all of the figures on the specific fields before other players. | | No | Yes | No | No | Yes | No | Yes | No | Yes | Yes |
| Unreal Tournament 2004<br>To kill enemies and avoid death | Green and Bavelier [38] | Yes | No | Yes | Yes | Yes | Yes | Yes, not clear if active | Yes | No | No |
| Tetris<br>To form a horizontal line without leaving any gaps | | No | No | Yes | Yes | Yes | Yes | No | | | |

**Table 1.** (Cont.)

| Purpose and utility of the game | | Game-elements | | | | | | | Cognitive Outcomes | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Game's name<br>Main activity | Study that used the video game | Narrative context | Avatar/ character | Score system | Reward system | Win/lose | Time pressure | Multiplayer | Narrative context | Avatar/ character | Score system |
| Tetris<br>To form a horizontal line without leaving any gaps | Schubert et al. [49] | No | No | Yes | Yes | Yes | Yes | No | Yes | No | No |
| Medal of Honor: Allied Assault, EAGames<br>To kill enemies and avoid being killed. | Boot et al. [42] | Yes | Yes | Yes | Not clear /sure | Yes | Yes | Yes, not clear if active | Yes | Yes | No |
| Tetris<br>To form a horizontal line without leaving any gaps. | | No | No | Yes | Yes | Yes | Yes | No | Yes | Yes | No |
| Rise of Nations, SEGA<br>To build new cities, to improve city infrastructures and to expand one's national border. | Basak et al. [51] | Yes | No | Yes | Not clear /sure | Yes | No | Yes, not clear if active | Yes<br>Yes | Yes<br>Yes | No<br>Yes |
| Hidden-object game: Expedition-Everest, Big Fish Games<br>To find hidden objects. | Oei and Patterson [32] | Yes | No | Yes | Yes | Yes | Yes | No | Yes | Yes | No |
| Match-3: Bejewelled 2, PopCap Games<br>To line up at least three similar colors either horizontally or diagonally by switching the positions of adjacent square. | | No | No | Yes | Yes | Yes | No | No | Yes | Yes | No |
| Memory matrix 1.0, Tvishi Technologies<br>To reproduce a sequence by touching of each tile. | | No | No | Yes | Not clear /sure | Yes | Not clear /sure | Not clear /sure | Yes | Yes | No |
| The Sims 3, EAGames<br>To accomplish tasks that mimic real-life activities. | | Yes | Yes | Yes | Yes | Not clear /sure | Not clear /sure | No | Yes | Yes | No |
| Modern Combat: Sandstorm, Gameloft<br>To navigate in hostile enemy territory and to achieve predetermined objectives such as deactivating enemy equipment. | | Yes | Yes | Yes | Yes | Yes | Not clear /sure | Yes, not clear if active | Yes | Yes | No |

**Table 1.** (Cont.)

| Purpose and utility of the game | | Game-elements | | | | | | | Cognitive Outcomes | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Game's name<br>Main activity | Study that used the video game | Narrative context | Avatar/ character | Score system | Reward system | Win/lose | Time pressure | Multiplayer | Attention | Working Memory | Inhibitory Control |
| Modern Combat: Sandstorm, Gameloft<br>To navigate in hostile enemy territory and to achieve predetermined objectives such as deactivating enemy equipment. | Oei and Patterson [47] | Yes | Yes | Yes | Yes | Yes | Not clear /sure | Yes, not clear if active | No | No | Yes |
| Starfront Collision, Gameloft<br>To kill an alien bug specie. | | Yes | Yes | Yes | Yes | Yes | Not clear /sure | Yes, not clear if active | No | No | Yes |
| Cut the Rope - Zepto Lab/Chillingo<br>To solve puzzles | | Yes | No | Yes | Yes | Yes | Yes | No | No | No | Yes |
| Fruit Ninja<br>To get the highest score possible. | | Yes | No | Yes | No | Yes | Yes | No | No | No | Yes |
| The Sims 3, EAGames<br>To accomplish tasks that mimic real-life activities. | Blacker et al. [35] | Yes | Yes | Yes | Yes | Not clear /sure | Not clear /sure | No | No | Yes | No |
| Call of Duty, Activision<br>To complete a set of missions. | | Yes | Yes | Yes | Not clear /sure | Yes | Not clear /sure | Yes, but not active | | | |
| Ballance, Atari<br>To steer a ball through a hovering maze of paths | Wu and Spence [41] | Not clear /sure | Yes | Yes | Yes | Yes | No | No | Yes | No | No |
| Need for Speed: Most Wanted, EAGames<br>To drive a car. | | Yes | Yes | Yes | Not clear /sure | Not clear /sure | Yes | Yes | | | |
| Medal of Honor: Pacific Assault, EAGames<br>To collect hidden objects and a achieve 100% accuracy at the shooting range. | Wu et al. [50] | Yes | Yes | Yes | Yes | Yes | Not clear /sure | Yes, not clear if active | Yes | No | No |

**Table 1.** (Cont.)

| Purpose and utility of the game | | Game-elements | | | | | | | Cognitive Outcomes | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Game's name<br>• Main activity | Study that used the video game | Narrative context | Avatar/ character | Score system | Reward system | Win/lose | Time pressure | Multiplayer | Attention | Working Memory | Inhibitory Control |
| Medal of Honor: Rising Sun, EAGames<br>To collect hidden objects and a achieve 100% accuracy at the shooting range. | Belchior et al. [44] | Yes | Yes | Yes | Yes | Yes | Not clear /sure | Yes, not clear if active | Yes | No | No |
| Tetris<br>To form a horizontal line without leaving any gaps. | | No | No | Yes | Yes | Yes | Yes | Yes, not clear if active | Yes | No | No |
| StarCraft, Blizzard Entertainment<br>To create, organize, and command an army against an enemy army in a real-time map-based setting. | Glass, Maddox and Love [37] | Yes | No | Yes | Not clear /sure | Yes | Not clear /sure | Yes, not clear if active | Yes | Yes | Yes |
| The Sims 2, EAGames<br>To accomplish tasks that mimic real-life activities. | | Yes | Yes | Yes | Yes | Not clear /sure | Not clear /sure | No | Yes | Yes | No |
| WoW - World of Warcraft, Blizzard Entertainment<br>To complete quests in a persistent virtual world. | Whitlock, McLaughlin and Allaire [119] | Yes | Yes | Yes | Yes | Yes | Yes | Yes, not clear if active | Yes | No | No |
| Medal of Honor: Pacific Assault, EAGames<br>To collect hidden objects and a achieve 100% accuracy at the shooting range. | Feng, Spence and Pratt [36] | Yes | Yes | Yes | Yes | Yes | Not clear /sure | Yes, not clear if active | Yes | No | No |
| Ballance, Atari<br>To steer a ball through a hovering maze of paths | | Not clear /sure | Yes | Yes | Yes | Yes | No | No | | | |
| **Commercial video games for Cognitive Rehabilitation** | | | | | | | | | | | |
| Big Brain Academy, Nintendo<br>To respond as quickly as possible to the different tasks. | López-Martín et al. [56] | No | Yes | Yes | Yes | No | Yes | Yes, not clear if active | Yes | Yes | No |

**Table 1.** (Cont.)

| Purpose and utility of the game | | Game-elements | | | | | | | Cognitive Outcomes | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Game's name<br>Main activity | Study that used the video game | Narrative context | Avatar/ character | Score system | Reward system | Win/lose | Time pressure | Multiplayer | Attention | Working Memory | Inhibitory Control |
| Brain Age/ Dr. Kawashima's Brain Training: How old is your brain, Nintendo | De Giglio et al. [53] | No | Yes | Yes | No | No | Yes | No | Yes | Yes | Yes |
| To solve mathematical questions and memorize information. | Brem et al. [52] | | | | | | | | No | Yes | No |
| Colin McRea Rally3, CodeMasters<br>To drive a car. | Tahiroglu et al. [120] | Yes | Yes | Yes | Not clear /sure | Not clear /sure | Yes | Yes, but not active | Yes | No | No |
| Tetriminos<br>To manipulate and rotating the blocks to creat a horizontal line without gaps. | Bikic et al. [121] | No | Not clear /sure | Yes | No | Yes | Yes | Yes, not clear if active | Yes | Yes | No |

3.4. Game elements used in GBI

Our results showed a significant difference ($t_{(117)} = 9.67$, $p < .001$) between the number of GE described in the papers (M = 2.17, SD = 1.43) and the number of GE existent in the video games (M = 3.60, SD = 1.53). Statistically significant differences between the number of GE described in papers (M = 1.92, SD = 1.43) and GE really existing (M = 4.49, SD = 1.19) were also observed for CG ($t_{(50)} = 11.82$, $p < .001$) and for AG (GE described: M = 2.36, SD = 1.42; GE really existent: M = 2.93, SD = 1.42; $t_{(66)} = 4.63$, $p < .001$). Similar results were identified in video games used for cognitive assessment (GE described: M = 2.04, SD = 1.26; GE really existent: M = 2.39, SD = 1.13; $t_{(27)} = 2.79$, $p = .010$), training (GE described: M = 2.33, SD = 1.50; GE really existent: M = 4.21, SD = 1.43; $t_{(66)} = 9.14$, $p < .001$) and for rehabilitation (GE described: M = 1.87, SD = 1.42; GE really existent: M = 3.30, SD = 1.30; $t_{(22)} = 4.25$, $p < .001$). In average, CG presented more GE (observed trough websites) than AG ($t_{(70)} = 0.11$, $p < .001$). Considering cognitive utility there was a statistically significant difference between groups as determined by one-way ANOVA ($F_{(2,79)} = 7.34$, $p = .001$). Bonferroni Post Hoc Test revealed that video games used for training (M = 4.17, SD = 1.54) present more GE when compared to video games use for assessment (M = 2.56, SD = 1.41, $p = .001$).

As shown in Table 2, score system and narrative context were the two most used GE (57 out of 72 video games). Score system was the most frequent GE in CG (29/30), in video games used for training (43/46) and for rehabilitation purposes (15/18), whereas narrative context was the most used GE in AG (35/42) and in video games used for cognitive assessment (15/16). Score system was associated with reward system ($X^2_{(1)} = 14.32$, $p < .001$, *Cramer's V* = 0.446), avatar ($X^2_{(1)} = 5.21$, $p = .005$, *Cramer's V* = 0.269), and with win/lose condition ($X^2_{(1)} = 11.00$, $p = .001$, *Cramer's V* = 0.388). Thus, when video games have score systems, they tend to have reward systems (n = 31), win/lose condition (n = 31), and avatars (n = 26). No significant association was found between narrative context and the other GE. Finally, it was more likely to encounter avatar ($X^2_{(1)} = 6.84$, $p = .014$), score systems ($X^2_{(1)} = 9.55$, $p = .002$), win/lose condition ($X^2_{(1)} = 21.63$, $p < .001$), and multiplayer component ($X^2_{(1)} = 22.02$, $p < .001$) in CG than in AG.

**Table 2.** Frequency of use of game-elements in video games ($n_{video.games}$ = 72) and according to cognitive utility ($n_{cog.utility}$ = 80)

| Utility of the game (n) | Purpose of the game | Game-elements n (%) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Narrative Context | Avatar / Character | Score system | Reward system | Win/Lose | Time Pressure | Multiplayer* |
| **All Games ($n_{video.games}$ = 72)** | Applied games (n = 42) | 35 (83.3%) | 11 (26.2%) | 28 (66.7%) | 15 (35.7%) | 9 (21.4%) | 22 (52.4%) | 2 (4.8%) |
| | Commercial games (n = 30) | 22 (73.3%) | 17 (56.7%) | 29 (96.7%) | 16 (53.3%) | 23 (76.7%) | 15 (50.0%) | 16 (53.3%) |
| | **Total** | **57 (79.2%)** | **28 (38.9%)** | **57 (79.2%)** | **31 (43.1%)** | **32 (44.4%)** | **37 (51.4%)** | **18 (25.0%)** |
| **Assessment ($n_{cog.utility}$ = 16)** | Applied games (n = 15) | 15 (100%) | 2 (13.3%) | 6 (40.0%) | 4 (26.7%) | 1 (6.7%) | 9 (60.0%) | -- |
| | Commercial games (n = 1) | -- | -- | 1 (100%) | 1 (100%) | 1 (100%) | 1 (100%) | -- |
| | **Total** | **15 (93.8%)** | **2 (12.5%)** | **7 (43.8%)** | **5 (31.3%)** | **2 (12.5%)** | **10 (62.5%)** | **--** |
| **Training ($n_{cog.utility}$ = 46)** | Applied games (n = 18) | 13 (72.2%) | 5 (27.8%) | 16 (88.9%) | 9 (50.0%) | 4 (22.2%) | 11 (61.1%) | 2 (11.1%) |
| | Commercial games (n = 28) | 21 (75.0%) | 16 (57.1%) | 27 (96.4%) | 16 (57.1%) | 22 (78.6%) | 13 (46.4%) | 15 (53.6%) |
| | **Total** | **34 (73.9%)** | **21 (45.7%)** | **43 (93.5%)** | **25 (54.3%)** | **26 (56.5%)** | **24 (52.2%)** | **17 (37.0%)** |
| **Rehabilitation ($n_{cog.utility}$ = 18)** | Applied games (n = 14) | 11 (78.6%) | 6 (42.9%) | 11 (78.6%) | 5 (35.7%) | 5 (35.7%) | 6 (42.9%) | -- |
| | Commercial games (n = 4) | 1 (25%) | 3 (75%) | 4 (100%) | 1 (25%) | 1 (25%) | 4 (100%) | 2 (50%) |
| | **Total** | **12 (66.7%)** | **9 (50.0%)** | **15 (83.3%)** | **6 (33.3%)** | **6 (33.3%)** | **10 (55.6%)** | **2 (11.1%)** |

*Cases where it was reported that this GE was not available/active during intervention were not included

*3.5. Platform and virtual components*

Computer was the most used platform to run video games (42/72), regardless of cognitive utility (see Figure S1). Game consoles were used to run eight video games in 11 papers [36,37,64,38,47–49,52,53,55,56], while the 12 video games that used touch-based devices correspond to only four studies [32,47,48,104]. Win/lose condition was associated with using a touch-based device ($X^2_{(1)} = 8.95$, $p = .003$), time pressure ($X^2_{(1)} = 4.70$, $p = .030$) and multiplayer component ($X^2_{(1)} = 6.75$, $p = .009$) were frequent in video games that run-in game consoles (87,5%, 87,5%, and 62,5%, respectively).

Twelve video games were categorized as using VR technology, six were exergames and six used specific interfaces such as brain-computer interface [88,101] (see Figure S2). More than half of all AG (24/42) presented some type of virtual component, with VR technology (n=12) being more frequent in these type of video games ($X^2_{(1)} = 10.29$, $p = .001$) than in CG (none of the video games under this category reported VR). Video games used for cognitive assessment ($X^2_{(1)} = 16.74$, $p < 0.001$, *Cramer's V* = 0.457) and video games used for cognitive training ($X^2_{(1)} = 10.53$, $p = .002$, *Cramer's V* = 0.363) were more likely to use VR technology.

*3.6. Outcomes of GBI*

As shown in Table 3, attention (94/118) was the cognitive outcome most frequently targeted in GBI, followed by working memory (54/118) and inhibitory control (30/118). This trend was also observed in video games used for cognitive training and rehabilitation (see Supplementary Table S4 for details). None of the three main cognitive outcomes was associated with any of the GE under study. Other cognitive outcomes (*e.g.,* fine motor skill, reasoning, fluid intelligence) were assessed in 91 out of 118 interventions, and other health outcomes (*e.g.,* mood, ADHD symptoms, health-related quality of life) were analysed in 24 out of 118 interventions.

Near transfer capacity was evaluated in most of the studies (109/118) and far transfer capacity for cognitive and other health outcomes was evaluated in 38/118 and in 13/118 interventions, respectively. User-experience evaluation was performed in 29/118 interventions, with the assessment of usability (15/118) or of hedonic aspects (*e.g.,* fun, enjoyment, immersion) performed in 21/118 interventions. Win/lose condition was associated (rarely occurring) with the evaluation of video game's impact on other health outcomes ($X^2_{(1)} = 18.18$, $p < .001$, *Cramer's V* = 0.396).

Also, win/lose condition was associated (rarely occurring) with far transfer capacity to health outcomes ($X^2_{(1)}$ = 8.48, $p$ = .004, *Cramer's V* = 0.270). Finally, UX assessment was associated (rarely occurring) to video games that present multiplayer component ($X^2_{(1)}$ = 12.89, $p$ < .001, *Cramer's V* = 0.333). Evaluation of hedonic aspects of UX was found to be associated with multiplayer component ($X^2_{(1)}$ = 8.55, $p$ = .002, *Cramer's V* = 0.271): within video games having multiplayer component, no study conducted hedonic aspects of UX. Usability evaluation was associated with all GE except for narrative context (*p-values between* $p \leq .001$ and $p$ = .027; *Cramer's V between* 0.211 and 0.343). Overall, usability evaluation was rarely conducted.

**Table 3.** Frequency of game-elements by cognitive outcomes ($n_{all.entries}$ = 118)

| Game-elements | Cognitive outcomes n (%) | | |
|---|---|---|---|
| | Attention (n = 94) | Working memory (n = 54) | Inhibitory control (n = 30) |
| Score system | 70 (76.1%) | 46 (85.2%) | 19 (65.5%) |
| Narrative Context | 70 (76.1%) | 36 (66.7%) | 20 (69.0%) |
| Time Pressure | 55 (59.8%) | 33 (61.1%) | 19 (65.5%) |
| Reward system | 33 (35.9%) | 25 (46.3%) | 10 (34.5%) |
| Win/Lose | 33 (35.9%) | 22 (40.7%) | 8 (27.6%) |
| Avatar/Character | 37 (40.2%) | 21 (38.9%) | 10 (34.5%) |
| Multiplayer*** | 25 (27.2%) | 10 (18.5%) | 5 (17.2%) |

**The association between each GE and each cognitive outcome was done by cell (chi-square test for independence).

***Cases where it was reported that this GE was not available/active during intervention were not included.

## DISCUSSION

The aim of this study was to identify, integrate and report which GE have been used in GBI for cognitive assessment, training, or rehabilitation. For this purpose, a systematic review of literature following PRISMA guidelines [20] was conducted. Ninety-one papers were included in the qualitative synthesis, covering a total of 72 different video games.

A significant difference between the number of GE described in the studies included and those that compose video games was found. The lack of a detailed description of the video games used constitutes a serious methodological limitation which hinders the analysis and interpretation of GBI results. To our knowledge, this is the first review on GBI where the information extracted from the studies included was compared to the description available

in other sources of public access. Despite unusual, the methodological decision to complete data extraction with information gathered through less traditional sources (webpages describing video games) enabled to uncover this methodological shortcoming, thus contributing to future research and data reporting on GBI.

Score system was most frequently used GE in CG and in video games used for training and rehabilitation purposes. Similar findings have been reported for digital learning environments [124] and health and fitness apps [23]. Numeric feedback systems such as points, levels, and leader boards are considered goal metrics since it establishes a clear link between user's effort and performance [125]. The assumption that users highly value this element contributes to its widespread use (for pointsification perspective review see [126]). However, that assumption is not always verified [23]. In fact, implementation of tangible and predictable rewards, such as those provided by score systems were previously associated with decrease of free-choice behaviour [127] and considered by some as the less exciting and engaging feature of video games [128].

However, since the motivational affordance [129] of each GE, as well as how different GE interact to promote human behaviour is still to determine, no elements should be dismissed at this point without a careful study of its impact. For instance, Mekler and colleagues [125] showed that GE (i.e., points, leader boards, and levels) within the same category (i.e., score system) can impact human behaviour differentially. By using an image annotation task where participants received 100 points for each tag created in a set of 15 abstract paintings, Mekler and colleagues showed that participants who received points for each created tag outperformed participants in the non-gamified version group (no points assigned) but were outperformed by the participants allocated to the group where points were used to classify participants in relation with themselves (i.e., levels of difficult condition) or in relation to other participants (i.e., leader board condition) [125]. It is also plausible to consider that score systems may undermine adherence if associated with a progressive difficult-level system (i.e., getting more points depends on individuals' skills for playing the game) whereas that is less the case if no individuals-skills improvement is required to points-accumulation (namely, if a game narrative is associated).

Narrative context was the most used GE in AG and in video games used for cognitive assessment. Unlike the other GE analysed in this study (e.g., score and reward systems and win/lose condition), narrative context has no association with player's performance [24]. This GE is used primarily to contextualize and to add meaning to game's main activity,

inspiring motivation and long-term willingness towards tasks that may be perceived as boring and repetitive in its non-gamified version [24]. Meaningful storylines, especially if in line with one's personal goals, may improve/maintain patients' long-term motivation and promote skills transference to other (real-life) contexts [130]. Although no significant associations were found between narrative context and purpose, utility or cognitive outcomes, the high frequency of this GE is encouraging, because it suggests a concern for developing GBI with meaningful game narratives that promote participants' long-term adherence.

The possibility to interact with other players is an attractive feature of video games [131] since it provides an opportunity to learn and develop meaningful relationships [132]. However, as our study revealed, multiplayer component was the less used GE. This can be explained by the fact that interacting with other players also means to be exposed to other's judgment. Fear of failure and performance-related frustration are two possible behavioural responses when competing or collaborating with others [133]. Design and implementation complexity, necessity to combine schedules, share game control and relying on other' players skills [134] may also contribute for the low usage of this GE in cognitive therapeutic settings.

Attention, working memory and inhibitory control capacity are essential components of cognitive control [28] and self-regulated behaviour [26]. Attention supports all processes involved in human thought [28], and a non-adequate assessment of attentional deficits may result in diagnosis errors and failure to prescribe suitable cognitive interventions [135]. Hereby, it was not surprising that attention was the most frequently targeted outcome in the included studies, since it plays such a central role in human cognition. Closely related to (and dependent of) attentional resources, working memory capacity and inhibitory control are essential cognitive components for fluid reasoning, comprehension, learning [28][136], as well as crucial skills for our ability to function in the real world [137]. However, in our study no association was found between the assessment of attention, working memory or inhibitory control and any of the GE, nor between the study of those cognitive indicators and utility (assessment, training, rehabilitation) or purpose (commercial/applied) of the game. The lack of association between GE and the study of these cognitive functions may be the result of the absence of a theoretical and empirical framework that guide GE selection for the study of video games impact on human health.

GBI seem to follow the trends of video games industry. In our study, as in ESA annual report [138] computer was the most popular gaming platform. On the other hand, touch-based devices were the less used game platform being reported only in four studies. Touch-based devices such as tablets are particularly suitable in fragile populations such as older adults [139,140]. Intuitive interfaces, direct manipulation [141] and bigger screens (compared to smartphones) are some of the features that contribute to technology adaptation by less familiar users. However, none of the studies that used older adults as study's participants reported tablets as game's platform. Other market trend is VR technology to develop video games. VR through high-detailed three-dimensional (3D) environments and increasingly natural ways of interacting with it [142] promises to be a remarkable improvement in the assessment of the capacity to perform daily living tasks (ecological validity), compared with traditional neuropsychological tools (Sbordone, 1996 cit. by [143]). Taking this into account, it was not surprisingly to find out that this component was primarily present in video games used for assessment purposes, area in which diversity and standardization of stimuli display, as well as performance measurement are fundamental requirements.

### *4.1. Limitations*

The findings of this study should be interpreted in the context of some limitations. First, the strategy used to identify additional journals scoping serious games and games for health may have excluded studies published in scientific journals in which these terms do not appear as part of the title/abstract or scoping interests. Second, electronic data-base selection may have unintentionally excluded work published in conferences or other type of meetings (a popular path to publish work in the engineering and computational science fields). A strong point, nevertheless, regards the fact that the search strategy was based on Cochrane's guidelines for conducting Systematic Reviews of Literature [144], such as consulting three different databases for locating papers, using specialist databases, searching reference lists of the included papers as well as reference lists of literature reviews identified during screening process. Third, the additional web-based search may have contributed to obtain more detailed descriptions of CG vs AG, since more sources of information with detailed descriptions are available to these video games than to AG. The absence of a consensual GE classification system nor a clear definition of what is and is not a video game introduced some degree of subjectivity in eligibility criteria and data extraction. Such bias was minimized by carefully defining search protocol and by developing GE definitions based on

the results obtained in the narrative review, which underwent a process of active discussion within research team and reformulation.

## CONCLUSIONS

This study aimed to identify which GE have been used in GBI for cognitive assessment, training, or rehabilitation. Score system and narrative context were the two most frequently used GE. However, the development of GBI that are based on the implementation of numeric feedback systems may jeopardize the main objective with which this type of interventions has been used: promotion of intrinsic motivation towards long-term goals. Moreover, the lack of any other significant association between GE used and the targeted cognitive outcomes emphasizes the necessity of defining a theoretical framework that supports the strategic selection of GE according to patient/pathology features, as well as according to the features of cognitive constructs that are targeted by specific game-based intervention.

## SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://shre.ink/1ScE


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***Study 2:*** *Are video games effective to promote cognition and everyday functional capacity in MCI/dementia patients? A meta-analysis of randomized controlled trials.*

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## ***Study 3:*** *Photo Realistic Interactive Virtual Environments for Neurorehabilitation in Mild Cognitive Impairment (NeuroVRehab.PT): A Participatory Design and Proof-of-Concept Study.*

**Abstract:**

Mild cognitive impairment (MCI) is characterized by cognitive, psychological, and functional impairments. Digital interventions typically focus on cognitive deficits, neglecting the difficulties that patients experience in instrumental activities of daily living (IADL). The global conjecture created by COVID-19 has highlighted the seminal importance of digital interventions for the provision of healthcare services. Here, we investigated the feasibility and rehabilitation potential of a new design approach for creating highly realistic interactive virtual environments for MCI patients' neurorehabilitation. Through a participatory design protocol, a neurorehabilitation digital platform was developed using images captured from a Portuguese supermarket (NeuroVRehab.PT). NeuroVRehab.PT's main features (*e.g.,* medium-sized supermarket, the use of shopping lists) were established according to a shopping behavior questionnaire filled in by 110 older adults. Seven health professionals used the platform and assessed its rehabilitation potential, clinical applicability, and user experience. Interviews were conducted using the think-aloud method and semi-structured scripts, and four main themes were derived from an inductive semantic thematic analysis. Our findings support NeuroVRehab.PT as an ecologically valid instrument with clinical applicability in MCI neurorehabilitation. Our design approach, together with a comprehensive analysis of the patients' past experiences with IADL, is a promising technique to develop effective digital interventions to promote real-world functioning.

**Keywords:** virtual reality; cognition; transfer capacity; recovery of function; neurorehabilitation

## 1. INTRODUCTION

Mild cognitive impairment (MCI) was initially conceptualized as a clinical entity affecting the cognitive functioning exclusively (i.e., memory capacity) [1]. However, empirical evidence has shown that cognitive and functional impairments co-exist from very early stages of the disease [2], and difficulties in instrumental activities of daily living (IADL) are prevalent among MCI patients [3]. Vascular mild cognitive impairment (VaMCI) is a clinical condition of vascular etiology, in which executive deficits are a prominent feature [4,5] and a strong predictor of functional decline and dementia [6]. Nonetheless, studies conducted in VaMCI patients are scarce, with even fewer studies focused on the development of rehabilitation instruments which target cognitive and functional impairments simultaneously.

Virtual reality (i.e., computer-generated interactive environments) [7] has been recognized as a valuable resource for developing instruments that enable health professionals to accurately predict patients' performance in everyday living activities (i.e., ecologically valid instruments) [8,9], especially in activities that actively engage executive functions [8,10–12]. Several virtual environments (VEs) have been developed targeting IADL, such as preparing meals [13,14], moving within the community [15,16], and cleaning and maintaining the house [17–20].

Shopping for groceries is perhaps one of the most studied IADL, with several studies showing that patients with executive deficits reveal in VEs a similar pattern of impairments to those observed in real-world tasks [21–27]. However, the majority of these VEs are manually designed, time- and human-resource consuming, and do not provide tasks or scenarios of sufficient realism [28]. Additionally, only a few of these VEs are designed for neurorehabilitation purposes [23] in MCI patients [22].

The feeling of "being physically present" in the virtual world, known as presence, is described as the phenomenon of users acting and experiencing emotions as if they were in the real world [29]; this is thought to promote the transfer of trained skills and behaviors from VEs to real-world contexts [8,29]. One design approach that has been used to improve the realism and sense of the presence is image-based rendering VEs. One example of a realistic image-based VE is Google Street View, where users can navigate within 360° photos of the surrounding environment. Previous findings have shown that the use of images of real-world scenarios results in highly visual realistic VEs and, therefore, an increased sense of presence [28]. Furthermore, image-based rendering VEs have shown promising results when applied to

reminiscent therapy [28]. However, in the scarce studies that use this technique, the images are embedded as just a decorative/background element [30] or are non-interactive [15]. Other image-based VE interventions require complex technologic equipment and space availability in order to accommodate the experimental apparatus [28], which limits its widespread use in clinical and neurorehabilitation contexts.

Based on the limitations mentioned above and considering the concept of function-led instruments [8], in which neuropsychological instruments should be as far as possible an accurate representation of real-world functioning, we conducted a qualitative analysis of the rehabilitation potential and clinical applicability of an image-based fully navigable and interactive virtual supermarket, NeuroVRehab.PT to promote cognition and functional capacity in VaMCI patients. This neurorehabilitation platform was developed by ISAMB (Lisbon, Portugal), LASIGE (Lisbon, Portugal), and Nippon Gases Portugal (Vila Franca de Xira, Portugal).

The goals of this study are twofold: (1) to describe the design process of NeuroVRehab.PT and (2) to characterize health professionals' (i.e., neurologists, psychologists, and neuropsychologists) perspectives about the rehabilitation potential and clinical applicability of NeuroVRehab.PT for VaMCI patients' neurorehabilitation.

## 2. Experimental Section

This study was conducted using a participatory design research protocol and reported according to the consolidated criteria for reporting qualitative research checklist (COREQ) guidelines [31] (see Supplementary Files Table S1. COREQ: consolidated criteria for reporting qualitative research checklist). Two groups of stakeholders (i.e., older adults and health professionals) were invited to participate in the design of a virtual supermarket aiming to train the cognitive functions and behavior strategies recruited during a shopping activity.

The present study was performed in compliance with the Declaration of Helsinki and was approved by the following ethics committees: Comissão de Ética do Centro Hospitalar de Lisboa Norte e Centro Académico de Medicina de Lisboa–CAML (reference number 89/19) and Comissão de Ética para Recolha e Proteção de Dados de Ciências (CERPDC) (reference number CERPDC/16/2019) (see Supplementary Files, Doc S1, ethical standards, for a description of the ethical aspects considered during the execution of this project).

*2.1. Participatory Design of NeuroVRehab.PT–Shopping Behaviors Questionnaire with Older Adults (Phase1)*

2.1.1. Sample and Recruitment

Two senior universities of the municipality of Almada, Portugal, were contacted and agreed to participate in the study. Visits were scheduled to a group of classes identified earlier by the executive board of the two institutions. During these visits, one of the co-authors of this paper (FFB) presented the project and explained how the data gathered through the questionnaires would support the research team's decisions regarding the main features of the virtual supermarket, such as the use (or not) of a shopping list, the number of products included in the shopping list, and the type of supermarket (grocery store vs. supermarket vs. hypermarket), among other features. To be eligible, the participants had to be more than 60 years old, be community dwelling, be responsible for grocery shopping, and give written informed consent.

2.1.2. Instruments and Procedure

A questionnaire with 11 multiple-choice questions that aimed to analyze the shopping behaviors and routines of older adults was developed and reviewed by the research team (see Supplementary Files Table S2 for the shopping behaviors questionnaire with older adults). The questionnaire was filled in individually and collected at the end of the senior universities' sessions. Questions included items regarding the type of store they usually go to (i.e., local grocery store, supermarket, or department store), the time spent there, and the frequency they go shopping per week. Other items included the habit of using shopping lists, establishing budgets, shopping for weekly or monthly necessities, and an estimation of the amount of money spent while shopping. The questionnaire was anonymous, and besides age, gender, and professional status (active vs. retired), no other personal information was collected.

2.1.3. Data Analysis

Statistical Package for the Social Sciences (IBM-SPSS, version 24.0; International Business Machines Corp., Armonk, New York, USA) was used to conduct descriptive analyses of the data collected through the shopping behaviors questionnaire with older adults. For nominal variables (e.g., gender, professional status, and questionnaire responses), tables of frequencies were calculated. For continuous variables (e.g., age, time spent shopping), the mean, standard deviation, mode, minimum, and maximum were calculated.

### 2.1.4. Results

A total of 110 participants aged between 61 and 86 years (70.92 ± 5.94 years) filled in the questionnaire. Twenty-eight were men (26.7%) and 77 women (73.3%). Fifty-three participants (53.5%) stated that they usually go to supermarkets as opposed to local grocery (*n* = 8, 8.1%) stores or big department stores (*n* = 38, 38.4%). Fifty-nine (56.2%) claimed that they usually make shopping lists, but only 42 (75%) use it during shopping. Before going shopping, 44 (79.4%) participants claimed that they included items in the shopping list as they remember what they need, and 10 (14.7%) organized the products according to the products' position in the supermarket.

More than half of the participants claimed they go to the supermarket less than once per week (*n* = 56, 52.8%), alone (*n* = 64, 60.4%), and to buy groceries for weekly necessities (*n* = 59, 56.2%). On average, the participants spend 59.24 ± 33.68 min on each visit to the supermarket. Sixty-one participants (58.1%) claimed that they have an estimation of how much they will spend before going to the checkout counter, and 33 (35.9%) stated that, after being informed of the value of the bill, they know precisely how much they should receive in return (see Supplementary Files Table S2 for the shopping behaviors questionnaire in older adults' descriptive data).

### 2.1.5. Main Implications for the Development of the NeuroVRehab.PT

Supermarket was the most frequently visited type of store for food and house products shopping. A relevant percentage of the participants reported that they carry out their weekly shopping alone. The findings also suggested that shopping lists do not tend to be long, although diversified.

The majority of older adults in our sample claimed that they go to the supermarket less than once per week and spend around 60 min on each visit. These data were initially collected to determine an adequate dose exposure to our digital platform. Although there are no guidelines regarding dose exposure in cognitive rehabilitation for MCI patients [32,33], previous studies have shown that interventions composed of few sessions with extended durations were not effective [34]. This implies that clinical trials of cognitive rehabilitation should accommodate the difficulties that VaMCI patients experience in their real-life activities (related or not to cognitive decline), provide sufficient repetition, and manage fatigue and frustration throughout the intervention length [35].

*2.2. Design and Implementation of the NeuroVRehab.PT (Phase 2)*

Based on the shopping behavior survey with older adults, we developed a first prototype of a web-based application called NeuroVRehab.PT. NeuroVRehab.PT allows people suffering from VaMCI to perform typical shopping tasks, such as creating shopping lists, navigating in a supermarket, adding products to the shopping basket, or sticking to a budget. The application was developed using HTML (version 5.2.; https://www.w3.org/TR/html52/), JavaScript (version ECMAScript 2019; https://www.ecma-international.org/ecma-262/10.0/index.html), CSS (version 3; https://www.w3.org/Style/CSS/), and PHP (version 7.4.9; https://www.php.net/). The supermarket was constructed using the Photo Sphere Viewer library (https://photo-sphere-viewer.js.org/) and panoramic photographs of the interior of a typical Portuguese supermarket (captured using the Google Street View app for Android, Google LLC., Mountain View, California, United States); see Supplementary Files document S1, ethical standards, for a description of the ethical aspects considered during the image capture and editing).

The platform is optimized to run on tablets. Tablets provide direct object manipulation (*i.e.,* the person directly interacts with the target object using the fingers) and require less hand–eye coordination [36]. Older adults seem to prefer tablets to more traditional setups such as computers [37]. Previous studies showed that tablets are easier for older adults to use [38], even when they experience technological divide to some extent [39] or already present mild [20] or severe cognitive compromise (i.e., dementia) [40].

2.2.1. Platform Description

NeuroVRehab.PT is a prototype of a web-based digital neurorehabilitation platform composed of three independent game modes—supermarket, recipes, and shopping list. The supermarket is the central part of the platform and the key component of the three game modes.

Supermarket Environment Description

To replicate a real-world scenario, the environment of this system is composed of 49 360° panoramic photographs, together with typical supermarket noises at the background. The background noise can be turned off at any time. Users can only navigate in the supermarket by activating the full-screen mode or touching the start button (which also activates the full-screen mode). This way, users can have a clean screen to prevent distractions, as reported in

previous studies [41]. *Maria*, a virtual shopping assistant, will guide users for the first time and regularly provide information about the game mechanics and behavioral shopping strategies that can be used in real life. Users experience the virtual supermarket from a first-person perspective (*i.e.,* without any intermediating avatar) and can walk through the 19 supermarket sections (*e.g.,* vegetables, fruits, bakery, dairy, frozen food) using the arrows displayed on the screen (Figure 1). Navigation arrows are placed in the screen, at the corridors, and in the exact position where the users want to walk to. If necessary, users may zoom in and out to take a closer look at a product or use the autorotate button to locate themselves in the environment. To select a product, users touch the product and a tag with the product's information (name, photo, category, description, and price) is displayed on the right side of the screen, together with an "add to the basket" button that allows users to add products to the shopping basket (Figure 2a).

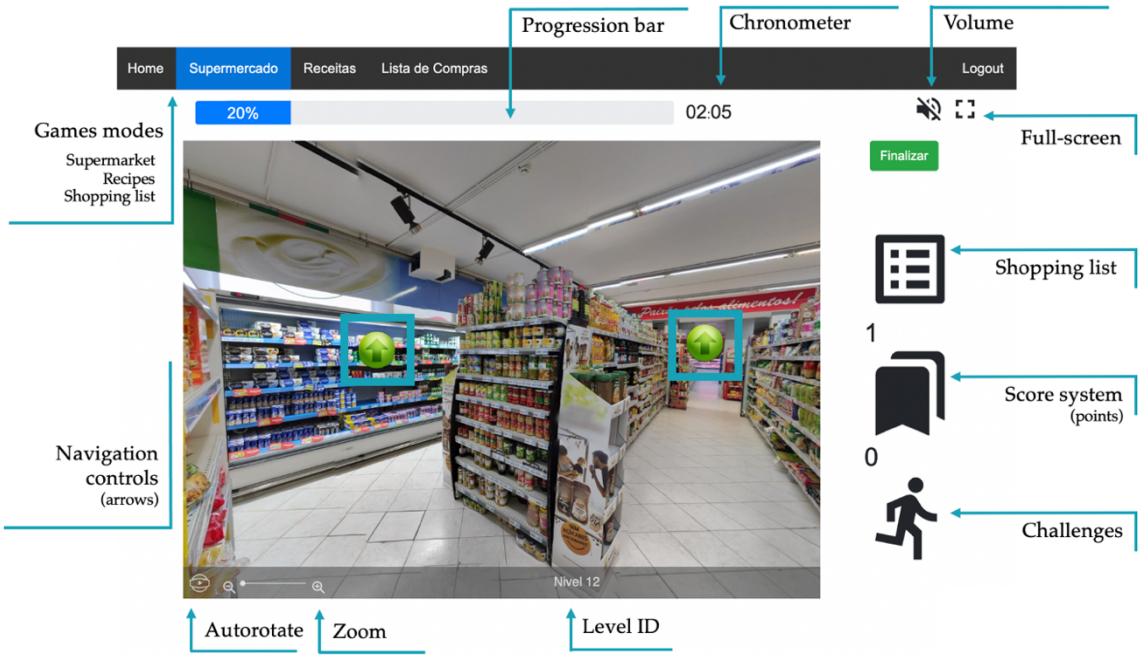


**Figure 1.** Interface elements of the NeuroVRehab.PT neurorehabilitation digital platform.

## Supermarket Game Mode

The system provides fourteen game levels that ask users to go shopping with a predefined shopping list (Figure 2b). Levels have different difficulty levels—easy, medium, and hard—which differ regarding the number of products to buy, the distance between the products, the available time to complete the level, and the presence or absence of background noise. In more advanced levels, there is also a budget to be met. Furthermore, the platform is designed to enable health professionals to create custom levels. Users need to purchase all

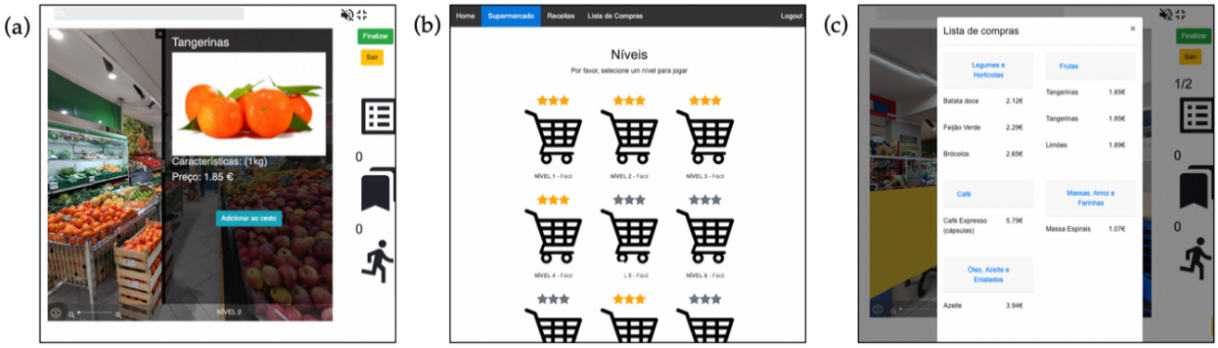


**Figure 2.** (**a**) Tag with product information—name, photo, description/weight, price, and add button; (**b**) view of the screen with the levels of difficulty, three-star classification, level ID, level of difficulty; (**c**) shopping list from a difficult level (medium) with nine products (written in black) under the correspondent category (written in blue).

the items of the shopping list (Figure 2c) to complete the level. If the added product is listed on the shopping list, users will hear a sound of positive feedback and earn points. If users try to add a product that is not on the shopping list, a message together with a sound of negative feedback will appear, and users will keep the same points.

After selecting all the products on the shopping list, users are asked to go to the checkout counter zone and pay the groceries by choosing one of the payment methods (cash or credit card). At the end of each level, a three-star rating is attributed based on the users' performance (time and distance walked).

Recipe Game Mode

The recipe game mode allows users to shop for the ingredients that are required to cook a traditional dish. Users may select among six traditional recipes—one soup, four main courses, and one dessert (Figure 3a). Each recipe is identified by a name and a photo of the dish. As an extra step of difficulty, after selecting one of the recipes the participants are asked to organize the ingredients under the correct category (e.g., apples under fruit) (Figure 3b). Correct and incorrect sorting is identified by turning the ingredients green or red, respectively. The participants need to correctly organize all the ingredients before having access to the virtual supermarket and purchasing the ingredients of the recipe.

Shopping List Game Mode

In this game mode, users can create personalized shopping lists. A list ID is identified by a name customized by users, and they may add products by writing the name of the product in the search field. As they write, a drop-down list appears with products matching the search query (Figure 3c). To select an item, they have to touch it. After finishing their shopping list, the participants are asked to organize the ingredients under the correct category (similar

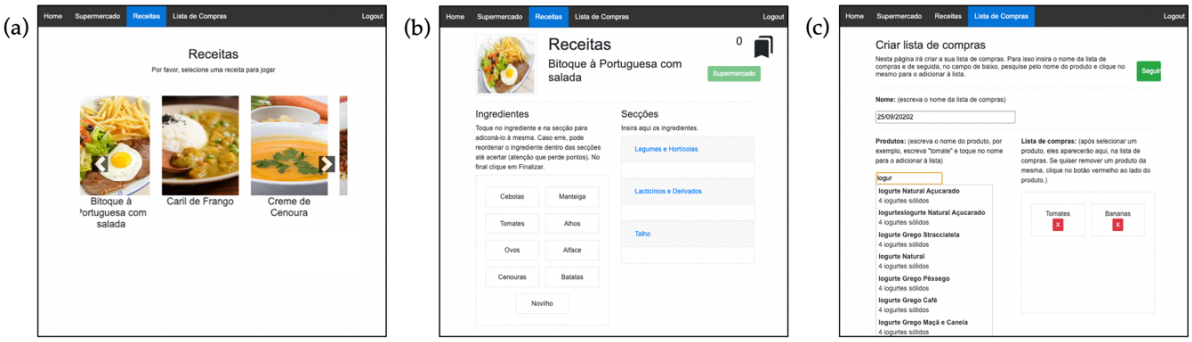


**Figure 3.** (**a**) View of the recipe game mode; (**b**) extra step of difficultly in the recipe game mode, in which users have to organize the ingredients (left side of the screen) under the corresponding category (right side of the screen); (**c**) view of the shopping list game mode with two products included in the list.

to the activity described in the recipe game mode section) before moving on to the virtual supermarket.

### *2.3. Software Evaluation and User Experience (Phase 3)*

#### 2.3.1. Sample and Recruitment

A purposive sample of health professionals (*i.e.,* psychologists, neuropsychologists, and neurologists) identified through professional networking was contacted and invited to participate in the study. Health professionals were identified based on (1) their clinical and scientific experience (≥ 5 years) with ageing, age-related neurological disorders, and cognitive decline; (2) their knowledge of the main theoretical models of human cognition and neurorehabilitation; (3) their familiarity with computerized cognitive training or rehabilitation programs. All the participants who were contacted *(face-to-face)* agreed to participate, and an individual session was booked at the participants' convenience (local and date). All the participants signed the written informed consent.

#### 2.3.2. Instruments and Procedure

Interviews took place in quiet and private rooms and lasted approximately 60 min. The participants sat in front of a desk where a Huawei MediaPad T5 tablet (Android 8) (Huawei Technologies Co. Ltd, Shenzhen, China) was supported horizontally at 25° degrees (approximately) using a tablet stand. The platform was run in the Google Chrome application (version 79.0.3945; Google Inc., Menlo Park, California, United States). A neuropsychologist with previous experience in qualitative research (FFB) conducted the interviews, and a second researcher member (SA, computer scientist and *PhD* student) was also present in five of the seven interviews and ensured that the sessions went on without any technical problems.

Each session was divided into two moments. In the first part of the interview, the participants were encouraged to express their opinions and thoughts verbally—the *think aloud method* (TA) [42]—while using the platform. The interviewer (FFB) demonstrated the TA method to participants while exploring the Gmail website. Then, the participants were encouraged to use it on the NeuroVRehab.PT platform. The participants were free to explore the platform; however, sessions were conducted so that all the participants visited the three game modes (*i.e.,* supermarket, recipes, and shopping list) and played at least two game levels in the supermarket mode. The second part of the session consisted of a semi-structured interview focused on the participants' experience (i.e., user experience; UX) and the perceived clinical applicability and rehabilitation potential of the platform.

#### 2.3.3. Data Analysis

The participants' demographic data were analyzed using IBM-SPSS (version 24.0; International Business Machines Corp., Armonk, New York, United States). Interviews were transcribed for content analysis, and a list of codes was developed on the basis of two interviews (data grounded theory). This initial code system was created independently by two researchers (FFB and SA) and then discussed and merged into a comprehensive list. The remaining interview transcripts were coded independently by two researchers (FFB and SA) using the previously developed list of codes and an interrater reliability index of Cohen's $k = 0.82$ was obtained by calculating the mean of Cohen's kappa indexes per interview (Cohen's $k \geq 0.80$). This kappa index was used as indicative of strong interrater reliability in healthcare research [43]. Blocks of 20 lines were used as the unity of analysis for semantic thematic analysis purposes [44]. When completing the analysis, the code system was reorganized into broad categories (major themes) and respective subcategories (minor themes).

## 3. Results

Seven health professionals aged between 29 and 67 (47.14 ± 13.08 years) and with 17 years of professional experience (range: 5–40 years) were interviewed. Two participants were male and 5 were female, with academic backgrounds in medicine/neurology ($n = 2$) or in neuropsychology ($n = 5$).

Two participants rated themselves as being very confident, four as being confident, and one as a little confident in using technology or new technological devices ($n = 2$, $n = 2$, $n = 3$, respectively). On average, the participants spent 16 ± 7.99 h (range: 7–30 h) browsing

content on the internet and 0.86 ± 1.86 h (range: 0–5 h) playing video games per week. All the participants were familiar with at least one computerized cognitive training or rehabilitation program (*e.g.,* Cogweb®, Rehacom®), and three participants (42.9%) reported that they use brain training games or computerized cognitive training programs (CCTP) in their professional practice (e.g., Fitbrain, Neuronation).

Four major themes (and seven minor themes) emerged from the semantic thematic analysis: experience with NeuroVRehab.PT, rehabilitation potential, potential barriers, and opportunities (see Table 1 for the complete code system, including minor themes). Due to technical problems related to audio recording, the second part of interview 2 was lost (90% of the semi-structured interview). Therefore, only the information collected during the TA phase of interview 2 was included in data analysis. Data saturation was obtained at the 5th interview, with no new codes identified in the last two interviews.

### *3.1. Experience with NeuroVRehab.PT*

#### 3.1.1. Hedonic Experience and Presence

Overall, the participants expressed a positive attitude towards NeuroVRehab.PT and reported having fun and enjoying the platform. Different features of the platform stood out and were considered by the participants as appealing and relevant from a clinical point of view (e.g., the icon used to identify the different game levels (Figure 2b), the label with the product's characteristics (Figure 2a), the zoom-in functionality, and the availability of a shopping list that the participants can check (Figure 1)). However, it was the high realism and visual complexity (and auditory stimuli) of the VE that captured the participants' attention. All the participants but one explicitly mentioned this aspect during the interviews (and some of them more than once).

> *Participant 1:* "I was expecting something more, rudimentary, but not the case, I think it was… the products were clear and colors vivid…"
>
> *Participant 2:* "Well, it is a very appealing image of the supermarket. It makes you want to explore it, doesn't it? It has beautiful fruits."
>
> *Participant 4:* "Ah! How cute (…) it really looks like a supermarket (…), maybe this is really a supermarket (…) The products are real, not drawings [as in 3D-modulated scenarios], I think it is good."

**Table 1.** Code system developed with the semantic analysis of the interviews.

| | |
|---|---|
| ⇒ | Experience with NeuroVRehab.PT |
| | • Hedonic experience and presence |
| | • Usability |
| ⇒ | Rehabilitation potential |
| | • Cognitive stimulation |
| | • Transfer capacity |
| ⇒ | Potential barriers |
| ⇒ | Opportunities |
| | • Clinical and non-clinical contexts |
| | • Friend sourcing |
| | • Other environments |

*Participant 5:* "[While performing a task in NeuroVRehab.PT] Ok, hot chocolate. Hot chocolate, now I have to find…. this is really realistic. In fact, it is real, I did not have this expectation."

*Participant 6:* "It seems very realistic, hyper-realistic (…) The locations, the type of products, yes, yes, I think is quite realistic."

*Participant 7:* "The environment sound is very good; it really puts you inside of a supermarket (…) we know where we are, perfectly."

3.1.2. Usability

The participants identified and played the three game modes without relevant difficulties. However, the navigation controls and the sense of orientation inside NeuroVRehab.PT were identified as two aspects that should be improved in order to provide a more smooth and pleasant experience. For instance, some participants misinterpreted the meaning of the navigation controls and interpreted them as mandatory actions to progress in the game.

*Participant 2:* "The arrow appears, I assume this means I need to follow the arrows."

*Participant 1:* "... the arrow then... means that I need to go back to the fruit section?"

Other participants considered the arrows as hints to the location of the next product in the shopping list.

*Participant 5:* "The arrow helps to orient, doesn't it? I did not understand if the arrow gives you a hint or if … Does it give you a hint?"

Regarding the sense of being oriented within the supermarket, the participants felt that it "… could be useful, for example, before starting (the game levels) that the person visits the whole supermarket, a kind of orientation exercise, to learn (the supermarket) more or less." (Participant 1). Still on this subject, another participant referred to the famous experiment of Willard S. Small [45] to explain the importance of having the opportunity to explore (learning) the environment before starting any specific task*: "*… a person is in that environment; it is like a mouse when it is put on a place, like (…) a maze, something like that, it (the mouse) will explore, the first thing it will do is to explore the surroundings to get a perception. We are a little bit like mice. The first thing a person wants to do is… in fact, surrounded by these fruits, is to see what is around and understand*... "* (Participant 2). In this regard, the participants suggested that the presence of signs with the names of the sections and/or a map of the supermarket would improve the sense of orientation as well as the learning of the VE.

*3.2. Rehabilitation Potential*

The health professionals considered NeuroVRehab.PT a useful and innovative instrument for cognitive stimulation that they would recommend to their MCI patients.

> *Participant 5:* "[regarding another virtual supermarket for IADL rehabilitation] (…) it was prehistoric when compared to this one."
>
> *Participant 2:* "… a good alternative for cognitive stimulation."

3.2.1. Cognitive Stimulation

The participants considered NeuroVRehab.PT "… sufficiently appealing and demanding for MCI patients…" (Participant 5) and comprehensive in terms of the cognitive functions stimulated—namely, executive functions (working memory, planning, decision making), memory, attention, spatial orientation, and math abilities.

> *Participant 5*: "… working memory, of course, always pumping in my head (…) Manifestly, this also trains orientation….". […] From an attentional point of view, it is quite demanding".

In addition, the choice for a shopping activity as the core activity of this digital intervention was considered as "…meeting the necessities of this population." (Participant 1) and "…

important, crucial for [patients] daily-life, if they do not have someone to do the shopping for them, they have to do it themselves…" (Participant 7).

The realism of the scenario was also identified as an asset that could be used to promote patients' motivation to comply with long and emotionally demanding rehabilitation programs.

*Participant 7:* "[regarding other CCTP] I think there is not an effort or an intent to be similar to the person's daily life. Here I notice that effort (…) and that could be more motivating for the person who is doing the training".

3.2.2. Transfer Capacity

NeuroVRehab.PT elicited a sense of presence in some participants; "… I already knew that the milk would be closer to where eggs were, it is similar to other supermarkets where I go, I knew that… even if some fruits are not displayed on the fruit exhibitor, they are right there, it is essentially like… my experience in other [real] supermarkets." (Participant 1).

Participants were divided concerning NeuroVRehab.PT transfer capacity to patients' daily life. Four participants considered that the activities proposed on NeuroVRehab.PT are "… more easily generalized than the paper-and-pencil exercises that we often do." (Participant 5) and "Once the person succeeds in the game, I think..., I would say that it is easy to transfer to real life." (Participant 6). Other participants considered that the transfer of the trained skills could not be assumed only based on the similarities between the virtual and real-world environments. Finally, a third group of participants claimed that the transfer of trained skills is more likely to occur if the activity/exercise is meaningful within the patient's life context.

> *Participant 2:* "It has to make much sense [to the patient] to have any impact or transfer to real life. And even with this software, it is either something that meets what the previous life of the person was, and it has any meaning to him/her, or it ends up [just] being an interesting game...".

Finally, it was also pointed out that, despite being very realistic, our virtual supermarket is still a controlled environment (e.g., being the only customer, the absence of entropy caused by the presence of other buyers, people covering the products) and different from the supermarket frequented by the patient.

*3.3. Potential Barriers*

Among the potential negative psychological side effects that MCI patients might experience associated with the use of our platform, the one most referred to by the participants was frustration (verbalized by six participants), followed by stress ($n = 4$), fatigue ($n = 2$), anxiety ($n = 2$), and irritation ($n = 1$). Feelings of frustration were primarily associated with the process of learning how the platform works. Nonetheless, the participants considered that potential negative psychological side effects could be easily managed if a therapist is present and supports the patient's learning process by explaining game mechanics and controls and helping the patient cope with feelings of frustration.

> *Participant 7:* "I believe they [the patients] will have some doubts (…) I had someone by my side to explain it to me, and they do not have it".
>
> *Participant 3:* "I think in some cases, some patients can easily start to get frustrated. And it is advisable not to continue. And I think there will be some situations like that, which is perfectly normal with this type of activity. Therefore, it is necessary to have resources [as therapists] (…) to be you to finish the activity and help the patient to move on …"

Nausea was also referred to ($n = 1$) as a potential negative side effect as a result of the temporary blurred vision associated with the process of going from one image (sphere) to another. No other physical adverse effects (*e.g.,* falls, dizziness) were foreseen by the participants, although difficulties associated with ageing, such as low visual acuity, were referred to.

*3.4. Opportunities*

Throughout the experimental sections, the participants identified three other possible applications of NeuroVRehab.PT.

3.4.1. Clinical and Non-Clinical Contexts

NeuroVRehab.PT was considered as having applicability in other clinical populations, such as Traumatic Brain Injury (TBI), stroke, and early-stage dementia patients. Some participants also suggested that the platform could be used as a means to increase technology literacy in healthy older adults.

### 3.4.2. Friend Sourcing

Three participants reported they would like to see some degree of interaction between users. One of the suggestions was to provide patients with the possibility of sharing recipes and cooking tips with other NeuroVRehab.PT users (i.e., patients), thus creating a virtual community. The participants also stated that it would be interesting if the therapist could create shopping lists (participant 5) that reflect the patient's diet and/or food restrictions (participant 3). The fact that NeuroVRehab.PT is an online platform was identified by another participant as a way to promote family engagement, especially from younger people. "This (NeuroVRehab.PT) would be much more playful and (...) maybe it could even be more interesting to attract family participation (...) even for grandchildren, it would be much more interesting than sitting next to the grandmother, with a paper and pencil activity" (Participant 7).

### 3.4.3. Other Environments

The possibility of exploring other IADL (*e.g.,* finances, ATMs, housekeeping) as well as real-life scenarios (e.g., the supermarket where they usually go) was noted as being one of most significant opportunities that the design approach presented here could bring to the field of neurorehabilitation. Other proposed activities were to invite patients to cook the recipes available in the recipe game mode, explore public places, and train their capacity to use public transportation.

## 4. DISCUSSION

The use of photo-realistic interactive virtual environments is a promising approach to develop accessible, cost-effective, and ecologically valid instruments for neurorehabilitation in VaMCI patients. The availability of digital instruments has gained even more prominence with the current global health conjecture due to the COVID-19 pandemic, where contact between health professionals and patients is restricted or drastically reduced. In this paper, we described the design and development process of a fully navigable and interactive virtual supermarket built from photos of a typical Portuguese supermarket—the NeuroVRehab.PT. Furthermore, health professionals with extensive clinical and research experience in neurodegenerative and age-related disorders assessed our platform and identified the advantages and challenges associated with its clinical use in VaMCI neurorehabilitation.

The participants considered NeuroVRehab.PT a remarkable improvement in the design of VEs for neurorehabilitation. The use of real-world supermarket photos as a core element of

NeuroVRehab.PT resulted in a highly realistic and ecologically valid VE. In previous studies, the ecological validity of virtual supermarkets for assessment or training purposes was established through the relationships obtained between the participants' performance in the VE and in related measures of executive functions and everyday functional capacity [23,26,46,47]. However, in the present study the ecological validity of NeuroVRehab.PT was established based on the verisimilitude approach [48]. According to this approach, ecological validity can be established based on the degree to which the demands of an experimental task resemble the cognitive demands of that task in the real world [48,49]. In this regard, not only is NeuroVRehab.PT an accurate representation of a typical Portuguese supermarket (face validity), but it was also claimed by the participants that our platform looked like (and felt like) a real supermarket. This was most evident in the statements of participants 1 and 5, when they said that their experience with NeuroVRehab.PT was very similar to shopping in a real-world supermarket; that is, they experienced the same difficulties and resorted to the same problem-solving strategies as they would in a real-world shopping activity. From this perspective, the design approach presented in this paper can also be applied to the development of instruments aiming to assess cognitive functioning, particularly executive functioning.

Moreover, our platform allowed the participants to interact and choose between grocery products that they are familiarized with and use in their daily life. This additional layer of customization (e.g., through the creation of personalized shopping lists that reflect real-life needs) enables coupling between therapeutic exercises and the patients' interests and routines, thus resulting in meaningful exercises with practical (real-life) applications [35]. In other words, NeuroVRehab.PT is therefore a flexible rehabilitation platform to accommodate patients' personal (*e.g.,* food preferences), health (*e.g.,* diet, food allergies and intolerances), cultural/religious (*e.g.,* regional gastronomy), and socioeconomic status (*e.g.,* branded vs. white label products).

Another layer of NeuroVRehab.PT aiming to promote patients' engagement is the use of gamification processes. Gamification (i.e., the use of game elements in non-game contexts) [50,51] has been widely used as a means to promote patients' adherence [52], self-esteem, satisfaction, and positive emotional experience [53] with healthcare interventions. In NeuroVRehab.PT, we implemented two types of game elements: numeric (e.g., points, scores) and visual (e.g., messages, three-star classification) feedback elements and narrative contexts. Although the study of the motivational influences of different game elements is

still in its infancy, preliminary studies suggest that immediate feedback elements are associated with high adherence rates during the initial phases of contact with the platform [54,55]. On the other hand, the storyline in which the main action unfolds is thought to be a crucial feature for long-term adherence [55] (see reference [54] for a description of the rationale underlying the selection of this game element). Although the conclusions that can be drawn from a single moment of contact with our platform are limited, the participants' statements that they had fun with and enjoyed using our platform is indicative that the implementation of these game elements was successful, at least to some degree.

From the semantic thematic analysis, two subthemes emerged regarding the rehabilitation potential of our platform: cognitive stimulation and transfer capacity. Health professionals considered that the activities proposed in NeuroVRehab.PT are feasible by VaMCI patients and target the cognitive functions recruited during a shopping activity (*e.g.,* orientation, planning, decision making, working memory, attention, math abilities). Furthermore, the participants referred to the training provided by our platform as being more easily generalized to the patient's daily life when compared to other forms of cognitive stimulation, such as CCTP and Brain Training Games (BTG). Despite the undeniable social and economic impact of CCTP and BTG, the evidence regarding the efficacy of these programs is still scarce, with few studies showing an impact on other cognitive functions beyond those directly targeted by the cognitive training program, and even fewer studies showing an impact on behavioral outcomes [32,56–58].

It is noteworthy that the theoretical framework used in NeuroVRehab.PT highly contrasts with the one used in CCTP and BTG. While, in CCTP and BTG, individual exercises are developed to target isolated cognitive functions [59–61], in our platform we focused on developing a training exercise that aims to stimulate/train the adequate behavioral patterns/responses to perform one specific IADL successfully. Therefore, in NeuroVRehab.PT we privileged activity segmentation into its basic units (e.g., creating a shopping list, searching for products, checking the shopping) as a means to promote the patient's awareness of where and how errors occur, along with the availability of simple strategies that patients could apply when shopping in the real world (e.g., organizing the shopping list and checking it before leaving each supermarket section). Promoting patients' awareness, training practical strategies to overcome or avoid errors, and the periodical monitorization of action and goals are crucial steps in the Goal Management Training paradigm (GMT) [62]. The GMT has been used in the cognitive rehabilitation of patients

with attention and executive deficits [62], including MCI patients, with positive results on quality of life [63], capacity to identify relevant occupational goals and efficient strategies, and the monitorization of task progression [64].

Nonetheless, not all the participants were sure about the transfer capacity of NeuroVRehab.PT. For instance, participant 3 stated that patients' predisposing characteristics (e.g., previous shopping experiences) rather than the VE characteristics would influence patient adherence and skill transfer. The perspective that different people need and want to (re)learn different things and do this in different ways, using different strategies, is an established fact in the neurorehabilitation field, and programs should be committed to identifying which activities patients perceive as relevant in the actual context of their life [65]. In other words, no matter how well a system is designed or optimized to perform a task, it needs to relate to their users and correspond to their expectations [66]. Shopping for groceries is still a gender-based established activity, at least among older Portuguese generations. This will negatively influence how comfortable some older adults will feel performing a task that they are not used to, or that they might consider as conflicting with his/her role in the family and the social system. Therefore, in future feasibility and efficacy digital health intervention studies, factors such as perceived usefulness, expectations regarding digital interventions, and the perceived social impact of resorting to mental health programs [67] should be taken into account when establishing the participant inclusion criteria.

Although NeuroVRehab.PT has been designed to be used independently by VaMCI patients, health professionals were in agreement regarding the importance of the presence of the therapist during the training sessions (at least, in the first sessions). The therapeutic bond established between the health professional and patient (i.e., therapeutic alliance) is a strong predictor of psychotherapy outcome [68], the decision to start treatment, and patient attrition [69–71]. Feelings of frustration triggered by successive experiences of failure are common among patients with cognitive impairments and, when not managed properly, can lead to feelings of confusion, anxiety, and dropouts [71]. In our study, the need for the therapist's presence was associated with two main roles: to support the learning process of how the platform works, and to help patients cope with failure and frustration. This finding is supported by an extensive body of literature that shows that learning can be fostered when guided by a more experienced agent [72].

Furthermore, we acknowledge that VaMCI patients may also experience other difficulties observed in healthy older adults, such as the fear of failure and peer judgment, anxiety about using computers, and a low assessment of their skills and capacity to learn new things [73]. Therefore, an intermediate phase of user testing with healthy older adults is being planned to analyze age-related usability issues, gender and social variable influences, and the system stability [74], which may compromise the use of NeuroVRehab.PT by VaMCI patients.

## 5. Conclusions

Taken together, our results show that the NeuroVRehab.PT is an engaging, ecologically valid neurorehabilitation digital platform for VaMCI patient neurorehabilitation. Although some interface components such as the navigation controls should be optimized to improve the patients' UX, health professionals considered this platform a significant step forward to the design of efficient and family-inclusive digital interventions for cognitive stimulation and IADL training. The present study also highlighted the impact that the perceived personal and social relevance of the training activities might have on patients' adherence and long-term use and, ultimately, the interventions' efficacy. Finally, our results are elucidative regarding the potential positive impact of the therapeutic bond between the health professional and patient on an intervention's outcomes, and so this should not be dismissed even in interventions supported mostly by digital resources.

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## ***Study 4****: Adherence to health technologies in older adults: challenges and lessons learned.*


### ABSTRACT

The level of computer confidence and self-efficacy can impact an individual's perceived ease of use and usefulness of technology, ultimately determining their adherence to digital healthcare services, especially among older individuals. However, only a few digital cognitive platforms have been tested to determine the impact of non-clinical factors on the efficacy and adherence to digital healthcare services. In this study, we aimed to analyse the role of non-clinical factors (i.e., computer confidence and computer self-efficacy) in the interaction experience (IX) and the feasibility of NeuroVRehab.PT in older community dwellers. Eight individual, audio-recorded interviews were conducted, transcribed, and analysed using an inductive-deductive informed thematic analysis protocol. Three themes (i.e., Interaction Experience, Digital Literacy, and Attitudes toward NeuroVRehab.PT) and eight subthemes were identified. Our findings align with the existing literature, highlighting that individuals with low familiarity with technology and computer anxiety may experience challenges in using technology effectively. Moreover, our results showed that even individuals who reported high confidence in their technology use expressed anxiety and fear of making errors when encountering unexpected situations while using the system. Future studies should consider incorporating a training period to familiarise users with the technology *prior* to the intervention to ensure the successful adoption of digital healthcare services. Additionally, training periods may be more effective if facilitated by someone with whom older adults can relate regarding their past experiences with technology. Neglecting users' digital skills and computer self-confidence will perpetuate inequalities in the access and efficient use of digital healthcare services, deepening the second-level digital divide among populations less familiar with the technology.



**Keywords:** digital divide; digital health; computer confidence; computer self-efficacy; technology adoption

## INTRODUCTION

The global population is ageing, and promoting cognitive functioning and functional capacity in frail populations, particularly older adults with or without cognitive impairments, is a pressing public health priority [1].

Digital healthcare, which refers to the use of digital, mobile, and wireless technologies to achieve health outcomes, has become a mainstream way to deliver healthcare services [2]. To develop effective digital healthcare interventions, evaluating their applicability and feasibility is crucial to meet the needs and characteristics of clinical populations [3–5]. However, the impact of non-clinical variables, such as users' familiarity with technology, psychological factors, and previous experiences with technology, is often overlooked [1]. For instance, digital cognitive platforms typically focus solely on the barriers and requirements created by users' cognitive impairments [6], neglecting other user characteristics that may affect their ability and willingness to use these services.

A growing body of literature has shown that digital/computer literacy, negative emotions associated with previous unsuccessful experiences, computer anxiety, and low perceived computer self-efficacy can impact the adoption and use of digital healthcare interventions in older adults [7–9]. For example, according to the eHealth Literacy model by Norman and Skinner [10], using and adapting to computers and new technologies to solve problems (i.e., digital / computer literacy) is crucial to engage and using digital healthcare services. Moreover, negative emotions associated with previous unsuccessful experiences also determine users' perceived ease of use and technology usefulness. For instance, Portz et al., [11] showed that past negative experiences with technology resulted in computer anxiety (i.e., apprehension or even fear of using technology) and low perceived computer self-efficacy (i.e., confidence in the ability to "figure things out" while using technology), which, in turn, negatively impacted the search for and adoption of digital healthcare services by older adults.

In the present study, we aimed to identify potential barriers to adopting and using a digital neuropsychological rehabilitation platform called NeuroVRehab.PT. This platform was designed to promote cognitive functioning and functional capacity required to perform an Instrumental Activity of Daily Living (IADL), namely shopping for groceries [16]. For this purpose, we invited a group of healthy older adults with different proficiency levels and usage of digital healthcare services to use and assess NeuroVRehab.PT's interaction

experience (IX) [12,13]. By doing so, we aimed to contribute to providing insights into potential barriers to consider when designing digital cognition-based interventions for older adults who may be less familiar with the technology.

## MATERIALS AND METHODS

### *Recruitment and Participants*

To recruit participants, we visited two senior universities and presented the project to attendees in two Information and Communication Technologies (ICT) classes. Eight ICT attendees (Table 1) expressed willingness to participate and were screened for eligibility. Participants had to meet the following criteria: (1) be 60 years or older, (2) be fluent in Portuguese (spoken and written), (3) live in the community, and (4) have basic skills or willingness to learn how to use a tablet.

This study was conducted in compliance with the Declaration of Helsinki, and ethical approval was obtained from the Ethics Committee of the Centro Hospitalar de Lisboa Norte e Centro Académico de Medicina de Lisboa (CAML; ref.546/19) and Comissão de Ética para Recolha e Proteção de Dados de Ciências (ref. CERPDC/16/2019). Furthermore, we also use the Consolidated Criteria for Reporting Qualitative Research (COREQ) guidelines [15] for conducting and reporting the study (see Table S1 in Supplementary Files).

### *Instruments*

The study employed individual audio-recorded interviews lasting approximately 60 minutes with two parts. During the first part, the Think-Aloud Method was used to collect participants' thoughts and feelings regarding their IX with the platform. This method involves the collection of subjects' verbalisations as data, which researchers can analyse [14]. According to Someren et al., [14], this method enables to bring to the surface complicated thinking processes and problem-solving strategies that participants experience while performing a task. In parallel with the Think-Aloud exercise, researchers documented participants' behavioural patterns while interacting with the platform, using field notes from direct observation.

In the second part of the session, a semi-structured interview was conducted based on a script the team members had developed beforehand. The semi-structured interview aimed to ensure that relevant aspects of platform interaction that might be neglected or omitted during the Think-Aloud exercise were collected for analysis. The script comprised open-ended

questions on platform's usability, user-experience, platform inputs and feedback quality, intention to use, and the most and least appreciated/enjoyable platform features. Examples of the questions included: "What difficulties did you experience while using the platform?", "How would you describe your experience with the platform?", "How precise did you find the instructions provided by the platform?", "If available to the public, will you consider using the platform on a daily/weekly basis? Why?" and "What platform features did you enjoy/value most?". We selected these protocols for their capacity to elicit verbal comments and remarks from participants.

**Table 1.** Demographic information, self-reported confidence using technology, self-reported confidence in using new technological devices, weekly time browsing the internet, habits of playing video games or using cognitively stimulating Apps.

| ID | GN | Age | Education | Marital Status | Confidence using technology | Confidence using new devices | Time browsing internet/week | Play video games/other Apps |
|---|---|---|---|---|---|---|---|---|
| **P1** | M | 68 | High school | Married | Confident | Confident | 14 hours | No |
| **P2** | F | 78 | High school | Widow | Little confident | Little confident | 11 hours | Sudoku game and Solitaire Spider Microsoft® |
| **P3** | F | 77 | High school | Married | Little confident | Little confident | 4 hours | No |
| **P4** | F | 67 | Primary education | Married | Confident | Confident | 5 hours | No |
| **P5** | F | 68 | University | Single | Confident | Confident | 5 hours | Facebook® math exercises |
| **P6** | F | 61 | High school | Divorced | Little confident | Little confident | 8 hours | No |
| **P7** | M | 69 | High school | Single | Very confident | Very confident | 10 hours | No |
| **P8** | M | 77 | University | Widower | Confident | Confident | 10 hours | No |
| | | 70.6 ± 6.1 mean age | | | | | 8.38 ± 3.50 mean time | |

*Procedure*

To conduct the study, two senior universities were contacted, and the first author (FFB) introduced the study during visits to two ICT classes. Participants who expressed willingness to participate were included, and sessions were scheduled at a convenient time for each participant. The sessions were conducted in a private room at the senior universities' facilities by a neuropsychologist (FFB) with previous experience in qualitative research, with the second author (SA), a computer scientist and PhD student, present at the first two interviews to ensure that the sessions went smoothly without technical issues.

An informative sheet was provided to each participant, which included the study's objectives and authors' contact information. Participants were encouraged to read both forms and ask any questions they may have. Additionally, demographic information, including age, sex, education level, marital status, digital literacy (self-reported confidence using technology and new technological devices, weekly time browsing the internet), and digital mhealth use (use of cognitive training mobile apps) were collected. All participants provided written

informed consent before the start of the study.

A Huawei MediaPad T5 tablet (Android 8, Huawei Technologies Co. Ltd, Shenzhen, China) was placed horizontally at a 25º degree using a tablet stand on a table in front of participants. Before participants started exploring the platform, the first author (FFB) demonstrated a Think-Aloud exercise using the Gmail website.

*Digital neuropsychological rehabilitation platform*

NeuroVRehab.PT is a photo-realistic virtual supermarket designed to promote cognitive functions and functional/behavioural skills involved in shopping activities. The platform was developed using a participatory design approach by a multidisciplinary team of psychologists, neurologists, and computer engineers in collaboration with health professionals and community dwellers [16]. The activities incorporated gamification elements such as numeric and non-numeric feedback systems and narrative context to increase users' engagement and motivation. These activities were grouped into three game modes: supermarket, recipes, and shopping list (see Fig. 1a, 2a, 3a, 4a, and 5a).

In NeuroVRehab.PT, users are rewarded with points and positive feedback sounds when they perform correct actions such as putting a product on the shopping list into the basket. On the other hand, if users perform an incorrect action, such as selecting an item that is not on the shopping list, they are provided with a negative feedback sound, and no points are awarded. At the end of each level, users are presented with a three-star classification system based on their performance (see Fig 1a). For more details about the platform and game modes, see Ferreira-Brito et al., 2020 [16].

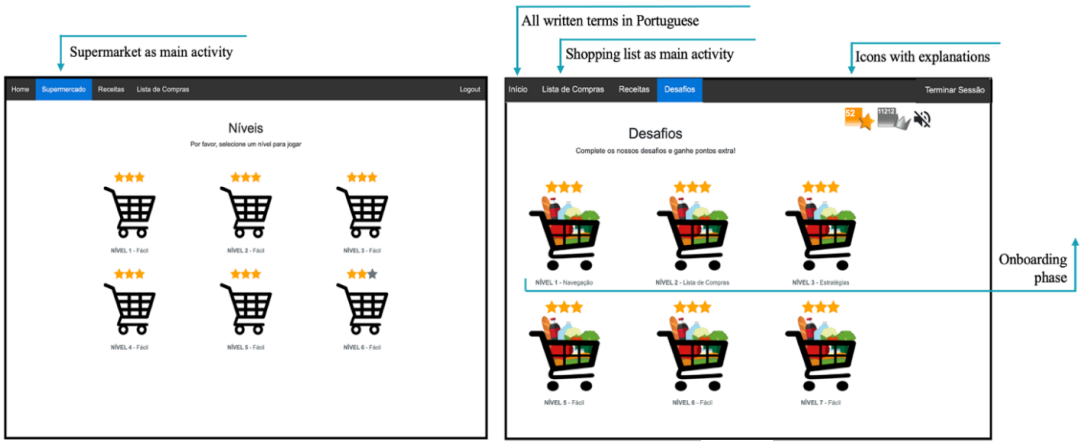
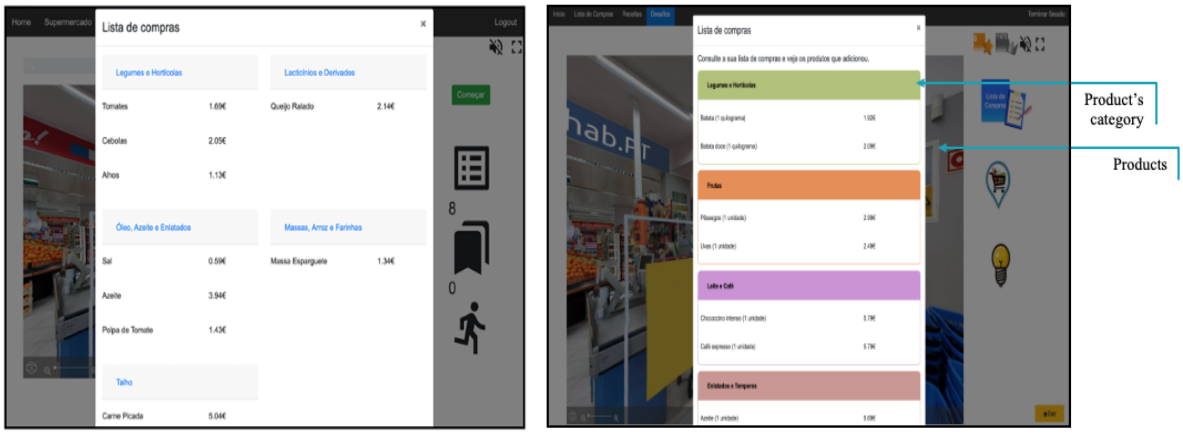
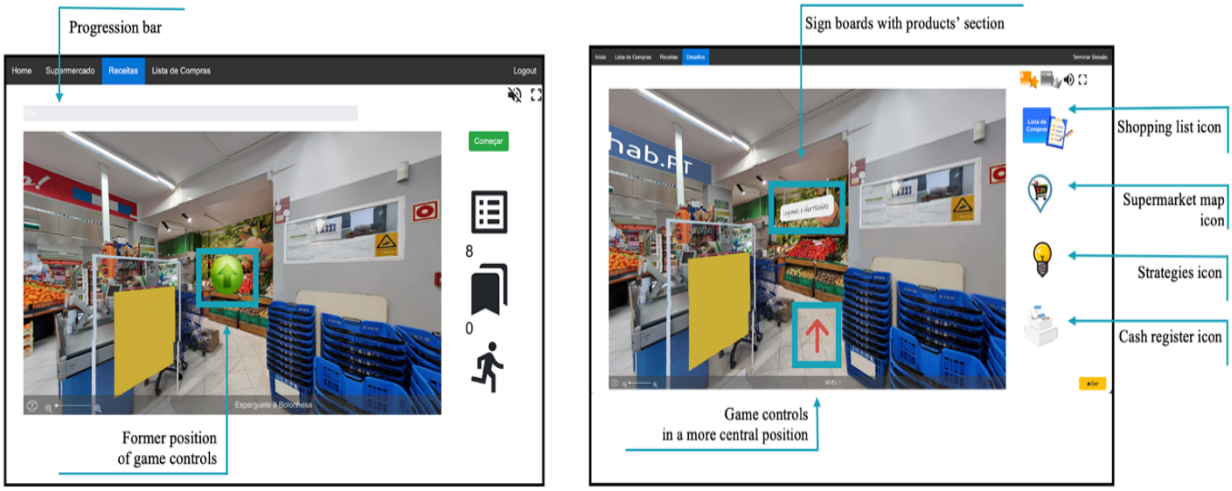



**Figure 1.** (**a**) Former Supermarket game mode interface. The default game mode was the supermarket with different game levels; (**b**) Challenges interface with the new features. In the latest version (after this qualitative study) default game mode is the Shopping list game.



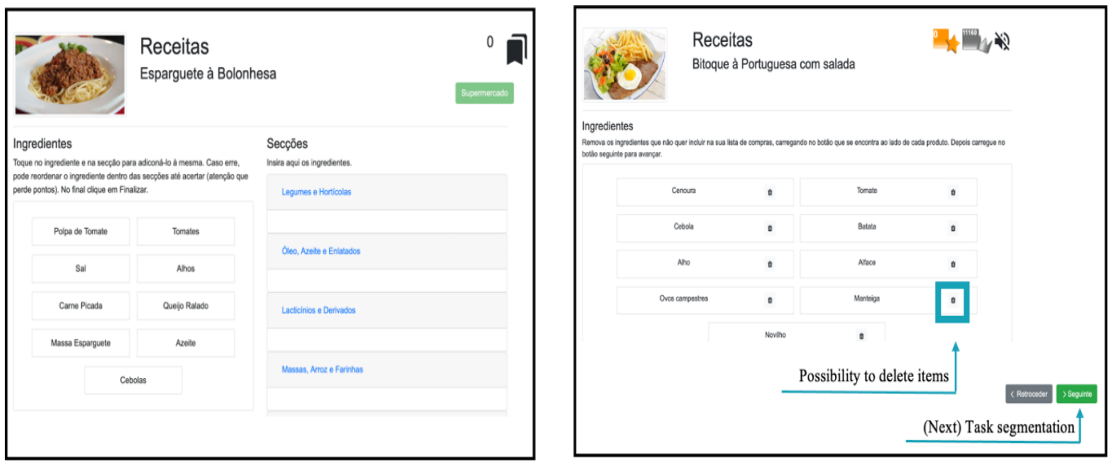

(**a**) (**b**)

**Figure 2.** (**a**) Former Shopping list interface with a 2-columns shopping list; (**b**) New Shopping list interface (after this qualitative study) with 1-column shopping list organised by product's category.




(a) (b)

**Figure 3.** (a) Former Supermarket environment and interface; (b) Supermarket environment and interface with the (new) features identified through this qualitative study.




(**a**) (**b**)

**Figure 4**. (**a**) Former Recipe game mode interface; (**b**) The new Recipe game mode interface where users can skip subtasks (e.g., task segmentation- organisation of the ingredients according to product's category).

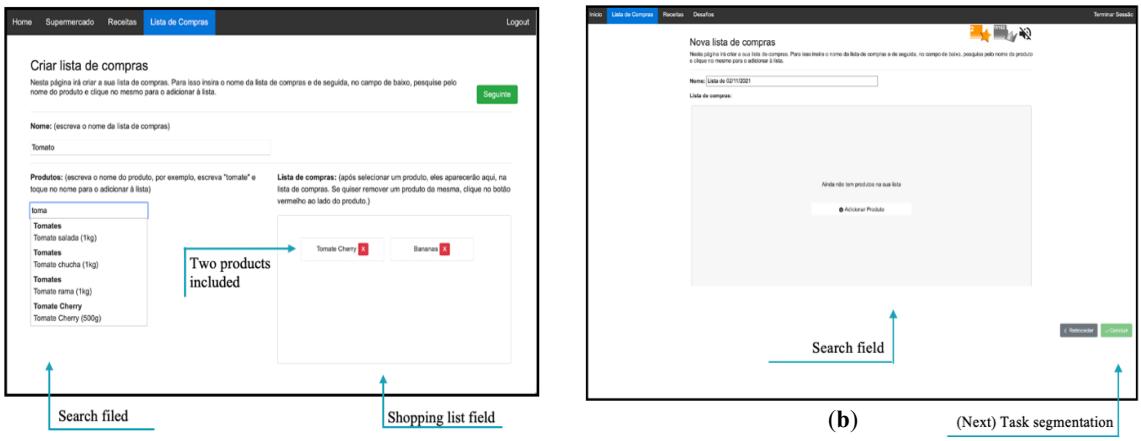



**Figure 5.** (**a**) Former Shopping list game mode; (**b**) Shopping list game mode with the (new) features identified through this qualitative study.

*Data analysis*

The audio recordings of the interviews were transcribed (see Supplementary Material Doc S2) and then cross-checked by the first author (FFB) to ensure accuracy and remove any identifiable information (such as participant names, locations, and brands). An inductive-deductive informed Thematic Analysis (TA) [17] was conducted following the 6-step approach proposed by Braun & Clarke [18].

The first step involved two co-authors (FFB and SA) familiarising themselves with the data by reading and re-reading the transcriptions of two randomly selected interviews. An initial set of codes was deductively informed based on the research question and interview script to identify significant patterns of meaning. Additionally, relevant phrases and recurring ideas were annotated and added to the code list inductively. The unit of analysis was blocks of 20 lines, and codes were modified or added (for all interview transcripts, by revisiting the complete set of interviews) as new codes were identified in the remaining transcriptions. Data saturation was achieved during the content analysis, with no new codes identified in the last three interviews. The research team collated text extracts under each potential theme, and codes were organised to fit into the themes' organising concept. Finally, the research team discussed and refined the final list of themes (and subthemes) and their headings.

## RESULTS

Based on the analysis of the *corpus* of the interviews conducted with eight community-dwellers, three major themes and eight subthemes (Table 2) were identified.

**Table 2.** Themes and subthemes identified based on eight interviews analysed using a TA protocol.

| |
|---|
| **Interaction Experience** |
| • Usability and accessibility |
| • Hedonic experience |
| • Reproduction of daily routines |
| **Digital Literacy** |
| • Computer/tablet skills |
| • Gamification and game elements |
| • Confidence, self-efficacy, and computer anxiety |
| **Attitudes toward NeuroVRehab.PT** |
| • Intention to use |
| • Utility, usefulness, and connectedness |

## *1. Interaction Experience*

### *1.1. Usability and accessibility*

The platform's ability to be learnt and used was determined based on the participants' statements and observed behaviour regarding their capacity to identify the different game modes, follow instructions, and use game controls. All participants could use the platform independently (to some extent) and identify and switch between the three game modes. However, it was not immediately evident to some participants how they could navigate inside the virtual supermarket (i.e., use of game controls). For instance, some participants interpreted the arrows (see Fig. 3a) as mandatory actions or tips for finding a specific product. After being more familiar with the game controls, one participant reported: *"... I will not say confusing. But I must train more*." (Participant 5, line 351). To other participants, game controls were *"... [not difficult at all] ... as I had the arrows, I would press the arrows, and they would take me where I wanted to go."* (Participant 2, line 413).

The instructions presented at the beginning of each game mode and during the activities were considered by participants necessary, important, and easy to follow *"... to those who do not know [the platform], it makes sense (...) I think so."* (Participant 2, line 419). In addition, two participants stressed the importance of the instructions being in Portuguese *"... there were no foreign words at all, it was all in Portuguese."* (Participant 1, line 684), and "… *do not put signboards in English (...) I do not know English*…" (Participant 4, line 754).

### *1.2. Hedonic experience*

Except for one (Participant 5), all participants enjoyed using NeuroVRehab.PT. One of the aspects most valued by participants was the possibility of navigating within a highly realistic virtual supermarket, *"... this is interesting, it shows you the supermarket products, the photos of the objects are great…"* (Participant 8, line 415). Another participant echoed this perspective, stating, "…*it is interesting the possibility of navigating [within the supermarket] because it motivates you to plan your shopping list in your head. It is interesting. And then you see, I need this [product] while walking through the aisles…. I think it is interesting, yes*!" (Participant 6, line 652).

On the other hand, Participant 5 claimed, *"... to be honest, I did not like it…"* (line 385). To this participant, the absence of "people" in the aisles and checkout counters made the environment look very artificial compared to what happens in real life. *"... there is no one [in the aisles], the checkout counters are empty (...) maybe [including non-playable characters] would be confusing for the people who will use the platform. But I considered it too artificial; it looked more like a huge freezer than a supermarket*." (Participant 5, line 340); and then added, *"... usually, when I go to the supermarket, I think about the time of the day [to go during low affluence periods]. But not having anyone at the checkout counter!... [seems implausible]"* (Participant 5, line 420).

### *1.3. Reproduction of daily routines*

Once inside the virtual supermarket, participants' choices and behaviours seemed to be based on their routines (i.e., real-life behaviours and strategies). For instance, one participant asked, "*What am I going to need? Fish, let's follow what I had planned for today [in real life], to buy fish, and then I buy bread…"* (Participant 1, line 36). Other situations where it was possible to observe that participants rely on their usual behaviour patterns to progress in the game were, for instance, when Participant 2 (line 11), as soon as she entered the virtual supermarket, tried to pick one of the shopping baskets (without any instructions in that regard. Another example was when Participant 3 (line 290) was asked how she could check the price of a product, and she instinctively touched the price tag near the product. The similarity between the virtual supermarket and a real-world supermarket also helped participants monitor the task's progression and know what they needed to do next to conclude the activity: "*I finished the shopping list, right? Now I am going to the checkout*

*counter. I am assuming that this is the same [as in a real-world supermarket]."* (Participant 5, line 235).

Furthermore, participants looked puzzled and discontent whenever the system did not allow such freedom of actions and choices (i.e., an accurate reproduction of their shopping-related behaviours) "[referring to the shopping list assigned in one of the levels in the Supermarket game mode] "*But I do not want bananas…. Ah! Do I have to buy bananas? Oh, okay. Oh, I just wanted the mangos*" (Participant 4, line 168). A similar situation occurred when participants realised that the system did not allow them to choose how much of a product they could buy: "*Curry, curry in powder. 50 grams. What if I do not want 50 grams of curry, what if I wanted more or less?"* (Participant 6, line 89) and "*bananas… 450 grams, why? What if I want more…?*" (Participant 6, line 277).

*2. Digital Literacy*

*2.1. Computer/tablet skills*

Although all participants were attending ICT classes, for some of them, the evaluation session was *"… the first time I interacted with a tablet."* (Participant 1, line 626). This raised additional challenges for some participants when specific patterns of interaction with the device were required. For example, when participants had to open and use the keyboard, *"… I am not used to this [tablet], if it were on a computer, maybe I would be quicker."* (Participant 4, line 607). Nevertheless, the lack of technological proficiency was not specific to tablet use. Participants also expressed difficulties logging in, remembering to close the instruction windows to proceed in the game, and exploring the entire screen and not just the virtual supermarket environment area.

*2.2. Gamification and game elements*

Our results showed that some participants were unfamiliar with some elements typically present in video games (i.e., game elements; GEs). For instance, when questioned about the meaning of the three-star score system (see Fig. 1a), one participant said*: "That is not décor, for sure! Now, it can be interpreted in two ways … what if there are five stars and I only got three, this orange colour [of the stars] is not good, for sure…*" (Participant 1, line 349). Other participants, when questioned about how they interpreted the three-star score system, said: *"Three stars is not a lot"* (Participant 5, line 149), or *"It is sufficient"* (Participant 3,

line 400), and *"For me, it is [good], I have never done this before, so it is not bad"* (Participant 2, line 373). The lack of familiarity with GEs was also observed regarding the progress bar (see Fig. 3a), which was rarely or wrongly identified "*… this should mean that I already spent 50% [of the budget]."* (Participant 7, line 81).

On the other hand, the meaning of the colour system used to identify correct and wrong actions was well interpreted by all participants. "*It turned red (…) It is not right. There is something that is not right…."* (Participant 2, line 305), and *"[when asked if the last action was correct] Yes. (….) It turned green…"* (Participant 1, line 533). The auditory feedback system was somewhere in the middle, with some participants identifying them correctly "*It tells you [that the product] is already in the basket.*" (Participant 4, line 131), and "[it tells you] *It is done!"* (Participant 6, line 285). Nonetheless, another participant completely missed it "*It went unnoticed... I will tell you why… because this is the sound of the computer when (...) an email appears, [when you] do something on the computer*." (Participant 7, line 394).

### *2.3. Confidence, self-efficacy, and computer anxiety*

Our results showed that despite using NeuroVRehab.PT and executing all the proposed activities, some participants were tense and anxious while using the platform. Some participants had to be constantly encouraged and ensured that everything was all right and that they were not looking bad or doing something wrong *"… do not be afraid, you are doing great*." (Interviewer speech, Participant 3, line 98) and "*You are doing well, do not worry. You are using something for the first time, and we are all a little like that (...) we are a little unsure, and we have to explore [the platform], we do not know what we are working with, do not worry.*" (Interviewer speech, Participant 1, line 170).

In some cases, this lack of confidence was mixed and aggravated by participants' subjective perception of age-related cognitive decline, fear of memory loss and dementia, *"… the problem is me, regarding my memory. If I had a better memory like I used to have in the old days, I would not have forgotten all the details and would have assimilated it all and go straight [to the point]* (Participant 1, line 626) and "*I do not know; I have already forgotten what was written. I messed it …"* (Participant 5, line 172). Finally, the fact that participants were using someone else's device also contributed to feelings of uneasiness and nervousness, "*[referring to her mobile device] I am not afraid of making mistakes. Okay,*

*that is out, it is not right, let it be (…) I do not cause prejudice to anyone."* (Participant 3, line 433).

### *3. Attitudes toward NeuroVRehab.PT*

#### *3.1. Intention to use*

Overall, participants present an open and positive attitude towards technology and NeuroVRehab.PT. Regarding NeuroVRehab.PT, participants expressed they were *"…curious and want to become more familiarised with it."* (Participant 3, line 494). Another participant stated, "…*this is interesting… because… how can I explain, this makes us want to explore with the finger, try to find [a product], to rummage [the supermarket], for me, it would be good to be here one or two hours exploring the whole supermarket…"* (Participant 4, line 620). Furthermore, the participation in the evaluation session was described as a "*... pleasure…",* and a motivation to seek additional opportunities of contact with technology and "…*willingness to buy one of these things [referring to the tablet] ...*" (Participant 3, line 602).

#### *3.2. Utility, usefulness, and connectedness*

It was apparent that some participants were trying to identify how to use NeuroVRehab.PT could help them to shop more efficiently. Among the potential practical (utilitarian) benefits identified by participants, there was the possibility of completing a pre-existent shopping list, "*It could be useful to visit the [virtual] supermarket, to gather ideas (…) maybe I did not even realise that I needed that product. In this aspect [the platform] is perfect.*" (Participant 8, line 234), and "*Being able to create a shopping list with this [while visiting the virtual supermarket], it seems like a good idea. Sometimes, I am at home, [searching for] what I need [to buy], and maybe…, it would come to me [to my mind] easier.... the products that I need (…) The fact that we can visit the aisles… it helps us to identify what we need*" (Participant 6, line 657). One participant further developed this idea by suggesting that the final shopping list could be sent by e-mail or be printed and then used in a real-life shopping activity: *"… this shopping list goes somewhere out, or can I bring it with me to [my] supermarket?"* (Participant 6, line 119). Another practical aspect identified by participants was the possibility of using the platform to strengthen family bonds, especially with the younger generations "*Yes. I have grandsons that play (…) they enjoy playing these*

*things. Maybe they would like to play this one too, especially the older one who is 11 years old*." (Participant 2, line 441).

## DISCUSSION

The perceived ease of use and usefulness of technology may be negatively affected by a lack of familiarity with technology and computer anxiety, which could hamper the intention to use digital healthcare services [11,19,20]. In the present study, we conducted a qualitative study to examine the role of non-clinical factors, such as computer confidence and computer self-efficacy, on IX and the feasibility of a digital neuropsychological rehabilitation platform – NeuroVRehab.PT. Our sample comprised eight old community dwellers ($\overline{x}$ = 70.6 ± 6.1 years old), and we identified three major themes (and eight subthemes) following a thematic analysis protocol.

Our study revealed that NeuroVRehab.PT is feasible among older adults with varying computer confidence and computer self-efficacy levels. Most participants enjoyed using the platform, and despite some difficulties regarding the use of game controls, evaluation sessions went without any significant difficulties. However, our findings suggest that participants' computer confidence and computer self-efficacy (as observed during the evaluation session) might determine adherence to NeuroVRehab.PT in older adults. For instance, it was apparent in our study that participants' perceptions regarding their (low) computer skills and the fear of doing something wrong reduced their capacity to initiate/conclude an action without validation from the researcher. As a result, some participants required continuous encouragement to explore and interact with the platform, despite demonstrating the skills and knowledge to do it independently. These results are consistent with Bandura's Theory of Behavioral Change [21], which states that individuals who perceive themselves as less competent in a particular domain are less engaged and more likely to give up when encountering difficulties. Based on our results, we can assume that addressing anxiety or stress caused by uncertainty about the correctness of actions taken could improve adherence to digital healthcare services among older adults.

It is noteworthy that even participants who perceived themself as confident / very confident in their ability to use technology and new technological devices encountered difficulties when using some features/functions of our platform. These findings suggest that, in addition to perceived computer confidence and computer self-efficacy, participants' observable

capacity to adapt and utilise new digital healthcare services should be evaluated on a case-by-case basis for each new intervention/platform. Moreover, providing an adequate learning support mechanism is essential, especially for interventions delivered on platforms with which participants need to become more familiar (e.g., tablets).

Another relevant insight from our study was identifying a utilitarian use of technology. Specifically, participants were primarily focused on identifying the potential advantages and real-world impact/benefits of using a digital neuropsychological platform like NeuroVRehab.PT. For example, participants associated the use of NeuroVRehab.PT with the possibility to optimise shopping activities by making or completing their shopping lists before going to a real-world supermarket. Additionally, they identified another advantage of using our platform as an opportunity to strengthen family bonds by playing NeuroVRehab.PT with younger generations, such as their grandchildren. These findings are consistent with previous ones that have shown that older adults do value (and more easily adhere to) technology when it enables them to improve and support daily-life activities [22] or tighten family bonds [23].

In addition, our study highlights two important aspects of designing and implementing digital cognition-based interventions for older adults. First, some of the GEs used in NeuroVRehab.PT were not intelligible to all participants despite being previously identified in digital neuropsychological instruments [24]. For example, the three-star system and the progress bar were confusing to some participants. Although the familiarity with video game culture is increasing among older generations [25,26], and scientific evidence has shown that older adults can benefit from gamified applications to improve cognitive and other health-related outcomes [27], many studies focus solely on the cognitive efficacy of the platform without taking into account users' characteristics, including their familiarity with GEs and gamification. From this perspective, our study's results reinforce the need for a thorough analysis of the impact of gamification processes on health-related outcomes in frail populations [28,29]. Furthermore, there is a need to develop design solutions that make GEs more intuitive to individuals less familiar with gamified environments and assess GEs' individual impact (i.e., motivational affordance) on health-related outcomes [28,29].

Second, we found that participants relied on the virtual environment (VE) realism to guide their behaviour and progress in the game. According to Maran & Glavin [30], a VE is more realistic as it can simulate both the physical characteristics (i.e., engineering fidelity) and the

critical elements that demand specific behaviours to complete the task (i.e., psychological fidelity). Based on the reports gathered, we can conclude that NeuroVRehab.PT has a high engineering fidelity since some participants were compelled to execute specific actions just by being exposed to a stimulus that, although virtual, was sufficiently familiar/natural to trigger the usual behaviour (e.g., pick up a basket or check the price of a product by clicking on the tag price). On the other hand, we consider that the psychological fidelity of our platform could be enhanced by implementing features that allow participants to determine the number and quantity of products included in the shopping list and the possibility of adding new items to the shopping basket while inside the virtual supermarket.

*Platform improvements*

The previous section discussed insights and suggestions provided by participants, which were used to improve NeuroVRehab.PT (see Figures 1b, 2b, 3b, 4b, and 5b). The changes implemented were selected based on their potential capacity to enhance the overall IX with the platform (see Table S2 in the Supplementary Files for details). The changes were categorised into those resulting from participants' direct suggestions (i.e., verbally expressed) and those resulting from observations of users' behaviour (e.g., difficulties identified from users' observed behaviour) that highlighted areas for improvement.

## IMPLICATIONS FOR THE FIELD

In an era where digital applications rapidly expand and become a mainstream medium for delivering healthcare services [31,32], our study has three significant contributions. Firstly, it is one of the few studies that examined the feasibility of a gamified platform in promoting health-related outcomes among older adults, which is in stark contrast to the growing body of literature that focuses on the impact of gamified platforms on younger populations [27]. Secondly, we provide additional data on the role of non-clinical factors (i.e., perceived computer confidence and computer self-efficacy) in using and adhering to digital healthcare services [33]. Conducting feasibility studies that consider participants' digital literacy and computer confidence, as well as providing a training period that ensures effective platform usage, is crucial.

## LIMITATIONS

The results of this study provide valuable insights into the impact of noncognitive factors on the IX and feasibility of NeuroVRehab.PT in community-dwelling. However, some limitations need to be considered when interpreting the findings. First, the participants recruited for this study were all attendees of ICT classes, which may have resulted in a biased sample of individuals who were more motivated and capable of exploring and interacting with the platform. Second, for most participants, this was their first experience using a tablet, making it difficult to determine whether their motivation was due to the platform's IX or simply the novelty of interacting with a new mobile device. Third, this study only involved a single session of platform use, limiting the ability to draw conclusions about long-term adherence and satisfaction with NeuroVRehab.PT.

## CONCLUSIONS

The study shows that NeuroVRehab.PT is feasible among community dwellers with different levels of computer confidence and self-efficacy, but the proficiency of some participants was affected by low computer confidence. Non-clinical factors, such as computer confidence and self-efficacy, should be considered in the design of digital healthcare services to address the second-level digital divide [34]. Providing computer/platform training to patients and research participants before using digital healthcare interventions might help increase adherence. Furthermore, conducting feasibility studies that include the analysis of non-clinical factors might allow researchers to distinguish limitations related to interface flaws from those associated with the clinical condition or low digital literacy.

**SUPPLEMENTARY MATERIAL:** The Supplementary Material for this article can be found online at: https://shre.ink/1ScE

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## ***Study 5:*** *Neuropsychological rehabilitation in vascular mild cognitive impairment: a feasibility study of NeuroVRehab.PT*

This chapter is currently submitted to a non-Open Access Journal, and acceptance may entail restrictions on its dissemination.

# CHAPTER IV. GENERAL DISCUSSION

## 4.1 Main Results and Contributions to the Field

The main objective of the present thesis was to contribute to scientific knowledge by exploring an innovative approach to develop ecologically valid platforms for neuropsychological rehabilitation in VaMCI patients. To achieve this goal, we developed an AG that simulated a real-world supermarket for IADL training (i.e., a shopping activity) and tested it with different stakeholders through a multi-step feasibility protocol.

The main contributions of this project can be grouped into three categories. First, we deepened our understanding of using AGs and gamified platforms in the neuropsychological field. By conducting a systematic review of the literature (study 1), we mapped the most frequently used GEs in neuropsychological GBI, providing a theoretical basis for the debate on the motivational affordance and adequacy of GEs in the study and training of cognitive-related outcomes. Additionally, we presented the first scientific evidence regarding the positive impact of VGs on general cognition (i.e., MMSE scores) in patients with MCI/dementia (study 2).

Additionally, we identified a new methodological shortcoming introduced by using AGs and gamified applications to deliver digital neuropsychological interventions. For instance, we found a statistically significant difference between the GEs described in the studies and those composing the digital interventions analysed (study 1). Notably, identifying this limitation was only possible by combining an established literature review method with a web-based search that included universities, research groups, video-sharing platforms (e.g., YouTube), and VGs' official websites. The combination of full-paper analysis and web-based searches conducted in study 1 can be considered a methodological innovation worth including in future reviews of the impact of gamified digital interventions on cognitive and other health-related outcomes.

Second, we developed an innovative, affordable, and accessible AG called NeuroVRehab.PT for neuropsychological rehabilitation in VaMCI patients. Unlike previous image-based digital platforms, NeuroVRehab.PT offers patients a full-navigable, photo-realistic, and interactive VE to train cognitive functions and behavioural skills required during shopping. Participants from the three recruited groups highlighted the striking similarity between our VE and a real-world supermarket.

Scientific literature has demonstrated the high correlation between the realism of VEs and the perceived sense of presence (i.e., the subjective experience of being physically present in the VE; SoP), with SoP mediating the transfer of the skills trained [129]. In our study, some participants reported using the same strategies in the VE as they would in the real world. Although preliminary, the data collected thus far suggest photo-realistic and full-interactive VEs like NeuroVRehab.PT offer a relevant approach to exploring the impact of VEs on patients' real-world functioning. This perspective is supported by the insights and opinions of health professionals who recognise the high level of realism of NeuroVRehab.PT as a significant improvement over current VEs used for IADL training.

Furthermore, the realistic VE developed enables researchers to investigate how patients adapt to real-life challenges without the limitations and constraints associated with constructing life-size mock-ups or the ethical concerns related to exposing patients to unforeseeable and uncontrollable situations in real-world environments. Additionally, NeuroVRehab.PT's capacity to simulate real-world scenarios only requires a tablet and an internet connection, resulting in an affordable tool for neuropsychological rehabilitation. The low-resource requirements, coupled with future studies that provide strong scientific evidence of its beneficial impact, might establish the groundwork for a novel approach to developing affordable, tailored, and personalised digital neuropsychological rehabilitation interventions.

Third, we conducted a thorough participatory design and feasibility evaluation of NeuroVRehab.PT, to accommodate the skills and limitations of VaMCI patients. We explored the platform's feasibility for the cognitive, functional, and technological profile of VaMCI patients from three different perspectives. First, we obtained insights from health professionals, including neurologists and neuropsychologists, who confirmed the activities available on NeuroVRehab.PT are a valuable addition to the neuropsychological rehabilitation of VaMCI patients, as it focuses on an IADL often reported as being impaired in these patients. Moreover, the cognitive workload of the activities presented in NeuroVRehab.PT was found to match the patients' cognitive skills, striking the desired balance between skill and challenge required in rehabilitation tasks.

Second, we followed WHO recommendation [77] and conducted a study of the platform's feasibility, taking into consideration the impact of technological-related variables (i.e., computer confidence and computer self-efficacy) on platform use and long-term adoption (i.e., adherence). In study 4, we identified that participants perceived low ICT skills and fear

of doing something wrong, which decreased their ability to initiate and conclude actions in NeuroVRehab.PT without validation and encouragement provided by the researcher. If not controlled, users' low computer confidence and self-efficacy might determine participants' drop-out, which can undermine the intention-to-use of NeuroVRehab.PT and other digital healthcare services in less technologically savvy populations.

The relevance of conducting a feasibility study focused on other variables besides patients' cognitive status was also reinforced by the results obtained in study 1. In this study, we identified that the usability and the hedonic experience associated with playing/using game-based neuropsychological platforms were rarely assessed (15 out of 118 interventions, 12.7%; and 21 out of 118 interventions, 17.8%, respectively). In addition, analysing how individuals with similar ICT profile to our end-users interact with the platform enabled us to improve its accessibility and identify other variables that might undermine its use, such as the lack of therapist's assistance and support.

Third, in study 5, we confirmed that the NeuroVRehab.PT met VaMCI patients' needs and limitations. Despite facing more challenges than the group of community dwellers, VaMCI patients were able to learn and interact with the platform with increasing autonomy. We believe that the observed improvement in patients' autonomy was due to the implementation of the suggestions gathered from the first two feasibility studies, which led to an enhanced IX. Additionally, these suggestions helped us increase the number and variety of activities available, making the platform more adaptable to different lifestyles and health constraints. The results of study 5 also demonstrated that our platform enables the training of an IADL according to the principles of neuropsychological rehabilitation, such as goal identification, task prioritisation, sequential action execution, and outcome comparison with the initial objective. These principles are the basis of other validated cognitive and functional rehabilitation programs, such as Goal Management Training (for an example, see [130]).

Furthermore, during the use of NeuroVRehab.PT, it was possible to observe impaired behaviour patterns common in VaMCI patients, including a high propensity to distraction, loss of task goals, and decreased information processing capacity. These findings also provide evidence of the therapeutic value and adequacy of NeuroVRehab.PT for VaMCI neuropsychological rehabilitation. As an effort to buck the trend of applying *ipsis verbis* to digital healthcare services, a "recipe" coming from VG's industry, the extensive participatory design work reported in this project provides an example of how the jointed work of a multidisciplinary team (i.e., neuropsychologists, neurologists, computer scientists)

with different stakeholders by the intertwining of the knowledge coming from different fields of expertise, can help to develop digital health services that are based on and support the clinical practice.

## 4.2. Future Directions

A detailed description of interventions' components is essential to studying the motivational affordance and impact of individual GEs on health-related outcomes. Only by carefully studying the effects of individual GEs on human behaviour can we move towards an evidence-based use of GEs in digital healthcare services and digital neuropsychological rehabilitation platforms. Further research is needed to explore the individual impact and adequacy of GEs on VaMCI patients, as well as in other populations with low familiarity with technology.

In addition, to fully explore the clinical and practical advantages of NeuroVRehab.PT for VaMCI patients, it is essential to conduct future studies on the impact of the platform on cognitive and functional capacity outcomes. A randomised controlled trial (RCT) would be particularly valuable in establishing the efficacy of NeuroVRehab.PT and identifying causal relationships between platform exposure and cognitive functioning and functional capacity improvements among VaMCI patients. Therefore, a second step could be the conduction of a multicentre RCT according to the CONSORT-SPI guidelines [131,132], which includes detailed eligibility criteria regarding VaMCI diagnostic, participants' ICT user profile, and information regarding how important it is to participants to relearn/acquire the capacity to shop independently in their current daily-life routines and lifestyle. Moreover, a training period should be included before participants enrol in the intervention to ensure they have the necessary digital skills and competencies to interact with the platform.

Finally, another interesting line of research could be the use of NeuroVRehab.PT to monitor disease progression based on the identification of digital biomarkers. The use of machine learning/artificial intelligence models could be complemented by including biometric measures such as eye-tracking, skin conductance, and electroencephalography, which is a promising approach to disease monitoring. This would allow for early intervention and development of personalised and adaptive neuropsychological rehabilitation programs.

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# Game-based interventions for neuropsychological assessment, training and rehabilitation: Which game-elements to use? A systematic review

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ABSTRACT

Game-based interventions (GBI) have been used to promote health-related outcomes, including cognitive functions. Criteria for game-elements (GE) selection are insufficiently characterized in terms of their adequacy to patients' clinical conditions or targeted cognitive outcomes. This study aimed to identify GE applied in GBI for cognitive assessment, training or rehabilitation. A systematic review of literature was conducted. Papers involving video games were included if: (1) presenting empirical and original data; (2) using video games for cognitive intervention; and (3) considering attention, working memory or inhibitory control as outcomes of interest. Ninety-one papers were included. A significant difference between the number of GE reported in the assessed papers and those composing video games was found ($p < .001$). The two most frequently used GE were: score system (79.2% of the interventions using video games; for assessment, 43.8%; for training, 93.5%; and for rehabilitation, 83.3%) and narrative context (79.2% of interventions; for assessment, 93.8%; for training, 73.9% and for rehabilitation, 66.7%). Usability assessment was significantly associated with six of the seven GE analyzed (*p-values between* $p \leq 0.001$ and $p. = 027$). The use of GE that act as extrinsic motivation promotors (*e.g.,* numeric feedback system) may jeopardize patients' long-term adherence to interventions, mainly if associated with progressive difficulty-increase of gaming experience. Lack of precise description of GE and absence of a theoretical framework supporting GE selection are important limitations of the available clinical literature.

## 1. Introduction

Game-based interventions (GBI) are built on the assumption that specific human skills and behaviors can be more easily promoted when the required training is conducted within a playful and entertaining context, such as the ones entailed by video games [1]. Gamification processes [2], serious games [3] and applied games [4] are, currently, relevant and innovative approaches in the study of human behavior change through the use of video games.

Game-based interventions have been used in clinical contexts to promote adherence and cognitive capacity among both healthy and clinical populations. Directly inspired on traditional games, game-elements (GE) can be defined as a set of video games components which include patterns, objects, principles, models or methods [2,5]. Points, levels of difficulty, badges, storyline and plot, progression based on success or failure to achieve the game's goals and multiplayer component are just a few examples of GE typically present in video games.

The use of GE to promote learning and motivation finds support on traditional psychological theories [6]. According to the Self-Determination Theory [7], intrinsic-motivated behavior (or at least more

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autonomous motivated behavior) is developed when the person achieves a sense of competence towards the activity and when it is allied with an internal perceived locus of control of the task. In video games, some GE, such as positive feedback messages, can promote a sense of competence while playing the game. Also, internal perceived locus of control is promoted with tooltips or help buttons that show to the player what he or she did wrong and how to correct the action [7].

Another possible example is the implementation of tutorials and other on-boarding tools to introduce game mechanics that are initially beyond the newbie's capacity. The acquisition and development of new skills, supported by such "external" help or by a more experienced agent, finds theoretical support in Vygotsky's concept of zone of proximal development [8], as well as in the concept of scaffolding proposed by Wood and colleagues [9]. Within these two conceptual views, learning and problem solving are depicted as constructive processes that can be fostered if guided by more capable peers. This is also the case in Massively Multiplayer Online Games, where interaction and collaboration with more skilled players are not only available but highly sought through participation in both in- and out-game activities, such as raids, parties, chats and discussion forums.

The study of the impact of video games on human cognition and behavior has been heavily focused on the downsides of such playing. Notwithstanding, existing results are conflicting. On one side, excessive exposure to video games, especially to those with violent content [10], has been associated with increased aggressiveness (at behavioral, cognitive or emotional levels), and decreased prosocial behavior, empathy, and sensitiveness to aggression [11]. On the other side, there are studies were these results were not replicated [12]. A recent study proposed that the increase of aggressive behavior associated with playing video games is mainly the result of a priming effect (which increases accessibility to aggressive/violent thoughts) and, so, the effects are short-lived, occurring only immediately after video game exposure (no more than 15 min) [12]. Przybylski and Weinstein [13], on the other hand, propose that the aggressiveness that might be associated with video games may be better explained by background-factors present in specific cohorts (*e.g.,* technology use and material deprivation). Additionally, the authors highlighted the high methodological flexibility present in aggression behavior and violent gaming measures that contributes to selective reporting of results [13].

The scientific community has recently been also interested on the beneficial impact that video games may have in human behavior. For instance, in a recent meta-analysis about the efficacy of serious games to reduce cognitive decline among psychiatric patients, a moderate effect size of this ludic-therapeutic approach was found ($g = 0.79$ (95% CI 0.36 – 1.21); $p < 0.05$) [14]. In another systematic review of literature, where the impact of video games was compared to other computer-based interventions, Kueider and colleagues concluded that video games constitute an effective intervention for global cognition stimulation ($d = 0.69$), with relevant results also on reaction time ($d = 0.77$), processing speed ($d = 0.72$), executive function ($d = 0.25$), and attention ($d = 0.21$) [15]. Anguera et al. [16] showed a significant reduction in multitasking cognitive cost in a group of older adults after playing NeuroRacer – a 3D multitasking training video game designed to improve cognitive control – when compared to an active control (single-task training) and to a non-contact group. Furthermore, improvements identified in Anguera's experiment persisted after six months without boosting sessions, with benefits being transferred to other cognitive domains than those directly targeted by the video game (*i.e.,* sustained attention and working memory).

Nonetheless, important methodological shortcomings (*e.g.,* lack of concise terms or of standardized methods to develop and assess GBI) and ethical concerns (*e.g.,* unfamiliarity or technophobia, unrealistic expectations of improvement and skill generalization, the possibility of physical harm, addiction, or social isolation) have been reported [5,17,18].

From a clinical point-of-view, it is of great concern the absence of a conceptual or clinical rationale supporting GE selection depending on patient's clinical conditions and/or on targeted cognitive outcomes. One rare exception can be found in the work of Lumsden et al. [17], where the authors clearly stated that GE such as rewards and feedback seem to be particularly suitable for persons with Attention Deficit Hyperactivity Disorder (ADHD), who are especially responsive to immediate reinforcement, feedback and clear definition of goals and objectives. On the other hand, the subjective and somehow arbitrary use of GE in vulnerable populations [18] can impair the successful clinical usage of GBI and can introduce deleterious effects on users' performance [19] or psychological/emotional health. Take as example a life bar (score system element) in a serious game for cancer survivors, where patients lose points every time they do not achieve the game's goal.

To the authors knowledge, this research represents a first effort to overcome the aforementioned limitations, namely the lack of a theoretical framework supporting GE selection in interventions focused on cognitive promotion. For this purpose, a systematic review of literature (following PRISMA guidelines [20]) was conducted to identify which GE were most frequently present in GBI used for cognitive assessment, training or rehabilitation. Furthermore, considerations were made regarding the capacity of those GE to promote patient's adherence to the cognitive intervention, reflecting on the adequacy of such GE to the study of the targeted cognitive outcomes.

## 2. Materials and methods

### 2.1. Search strategy

Search-terms related to "game-based interventions" and "cognitive outcomes" were identified on basis of an exploratory narrative review and discussion between members of the research team. Medical Subject Headings (MeSH) terms were used whenever possible. A total of 46 "game-based interventions" terms were combined listwise with 14 search-terms related with "cognitive outcomes" (*i.e.,* each search-term of the first category was individually combined with each term of the second category) (see Supplementary Table S1 for details on the search strategy). This keyword combination allowed us to minimize the exclusion of potential entries that could be masked by the use of less common terms, which is not unusual in recent research fields.

### 2.2. Information sources and search

Electronic database search was conducted on 24 January 2017 and then updated on 22 March 2019. PubMed, SciELO, and EBSCO – Psychology and Behavioral Sciences Collection were searched, with a restriction to the following inclusion criteria: (1) publication date (PubMed: 24 January of 2006 to 21 March of 2019, SciELO: 2007–2019; EBSCO: 1 January of 2006 to 21 March of 2019); (2) full text in English (PubMed and EBSCO); and (3) search field (title and abstract). Furthermore, search was restricted to peer-reviewed papers (EBSCO database) and studies with humans as study's subjects (PubMed). Book chapters were excluded.

### 2.3. Additional sources of information

Eighteen journals with editorial interests on serious games and games for health were identified and manually searched to locate additional studies of interest published between 2012 and 2019 (see Supplementary Table S1 for details). Additionally, reference lists of (1) each paper included for data extraction and (2) the literature reviews (narrative or systematic ones) identified during the screening process were also hand-searched for identification of additional relevant papers. Literature reviews were considered only as potential source to identify empirical papers (*i.e.* for reference search purposes; not for data extraction).

which were excluded.

- *Working memory:* system that enables the temporary storage and manipulation of information necessary to adequately respond to environmental demands [28]. Working memory outcomes were always considered when presented as a single expression ("working memory") in the analyzed paper.
- *Inhibitory control*: capacity to inhibit a dominant and automatic response in order to (deliberately) select a more adequate one regarding environment or task's characteristics [29]. Inhibitory control or inhibitory capacity were both accepted and considered as equivalent terms.

The presence of other cognitive or health-related outcomes was also registered. Finally, information on near transfer capacity (impact on related cognitive functions targeted by the video game), far transfer capacity (impact on non-related cognitive or health outcomes targeted by the video game) [30], user-experience (UX) evaluation (user's perceptions on software usability, hedonic experience), and sample characteristics were also extracted.

### 2.6. Statistical analysis

Analysis of data was done using the program Statistical Package for the Social Science (IBM-SPSS), version 24.0. Studies that presented more than one intervention arm, with a different video game per arm, provided different entries in the database. This was done because the sample unit for data analysis was the video game, not the paper. Important to highlight that this was done only when each intervention arm included only one game (as explained in the screening and eligibility section, studies which entailed more than one video game for the same intervention arm were excluded). Overall, 118 interventions with video games were identified in the 91 papers included in the qualitative analysis.

Three sampling bases were considered for data analysis (see Fig. 2). For GE frequency analysis, video games reported in different papers were considered only once ($n_{video.games} = 72$); this is, therefore, the total number of video games without duplication across papers. For GE frequency analysis by cognitive utility of the games (*i.e.,* assessment, training or rehabilitation), video games reported in different papers targeting the same cognitive utility were considered only once ($n_{cog.utility} = 80$). For instance, if one video game was reported in two or more papers for assessment purposes, the video game was counted only once; but if the same video game was reported for assessing cognitive functions in one paper and for training cognitive functions in another paper, then the video game was considered twice.

Finally, for two types of analyses (comparing the number of GE described in the papers and the number of GE really existent in the video games; and characterizing the association between GE really existent in the video games and cognitive outcomes), the total sample of video games interventions ($n_{all.entries} = 118$) was considered; this means that all entries were considered regardless of duplication across papers. This decision was based on the fact that some video games were used in different papers to evaluate different cognitive functions.

Data normality was tested by using Kolmogorov-Smirnov test and considering kurtosis and skewness (normality assumed when kurtosis and skewness ranged between −2 and 2) [31]. Results were considered significant for a $p$-value $\leq 0.05$. Because normality was observed for all variables and for all comparison groups, parametric tests were applied. Paired-samples t-tests were conducted to determine whether the number of GE reported in the papers and those that actually compose video games (as observed in webpages describing the games) differed significantly. This was done for all different video games altogether ($n_{all.entries} = 118$), and for commercial games (n = 51) and applied games (n = 67). Paired-samples t-tests were also used for assessing if the number of GE reported in the papers and those that actually compose video games differ according to the cognitive utility of the video games (assessment, n = 28; training, n = 67; rehabilitation, n = 23). Differences between commercial and applied games regarding the number of GE as described in video games webpages were tested through independent sample $t$-test ($n_{video.game} = 72$). Differences between the cognitive utility of the video games (assessment, training and rehabilitation) regarding the number of GE as described in video games webpages were tested with one-way ANOVA with Bonferroni Post-Hoc test ($n_{cog.utility} = 80$).

Chi-square tests of independence were applied to study the association between different pairs of GE (with Cramer's V for assessing the strength of the associations); this was also done for testing the independence between each GE and cognitive outcomes (attention, working memory, inhibitory control), cognitive utility of the game (assessment, training, rehabilitation), having health-related outcomes or not, virtual reality or another virtual component (*e.g.,* brain-computer interfaces); being an exergame, or not; and type of game platform (console, smartphone/tablet, computer). Chi-square tests of homogeneity were applied to check if each GE was more frequently used in applied or commercial video games.

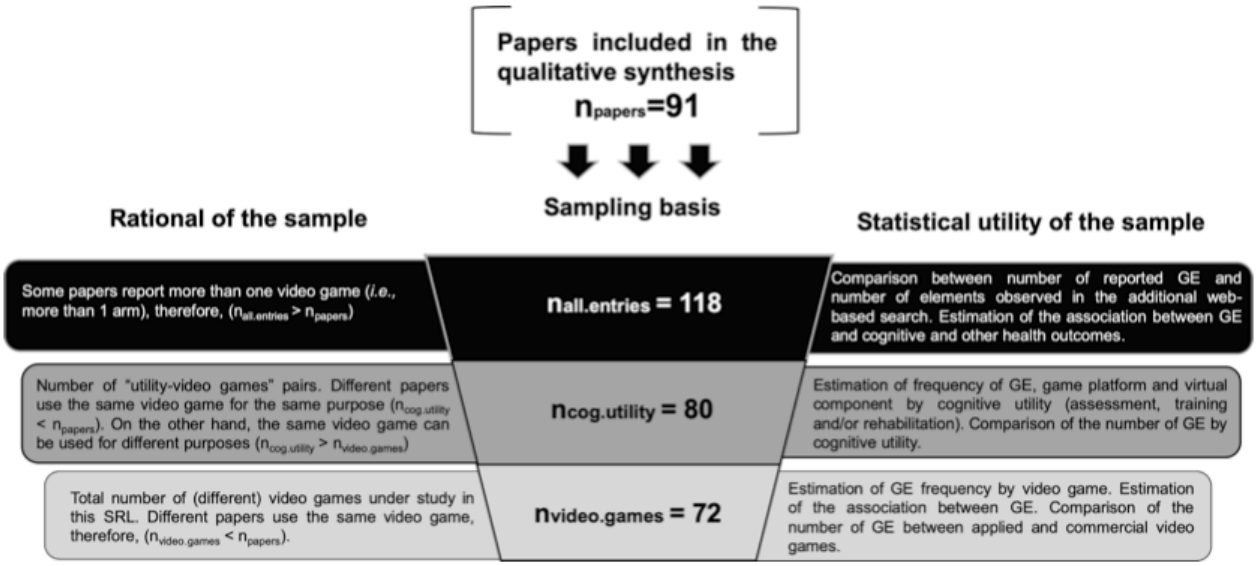


**Fig. 2.** Sampling bases used in statistical analysis.

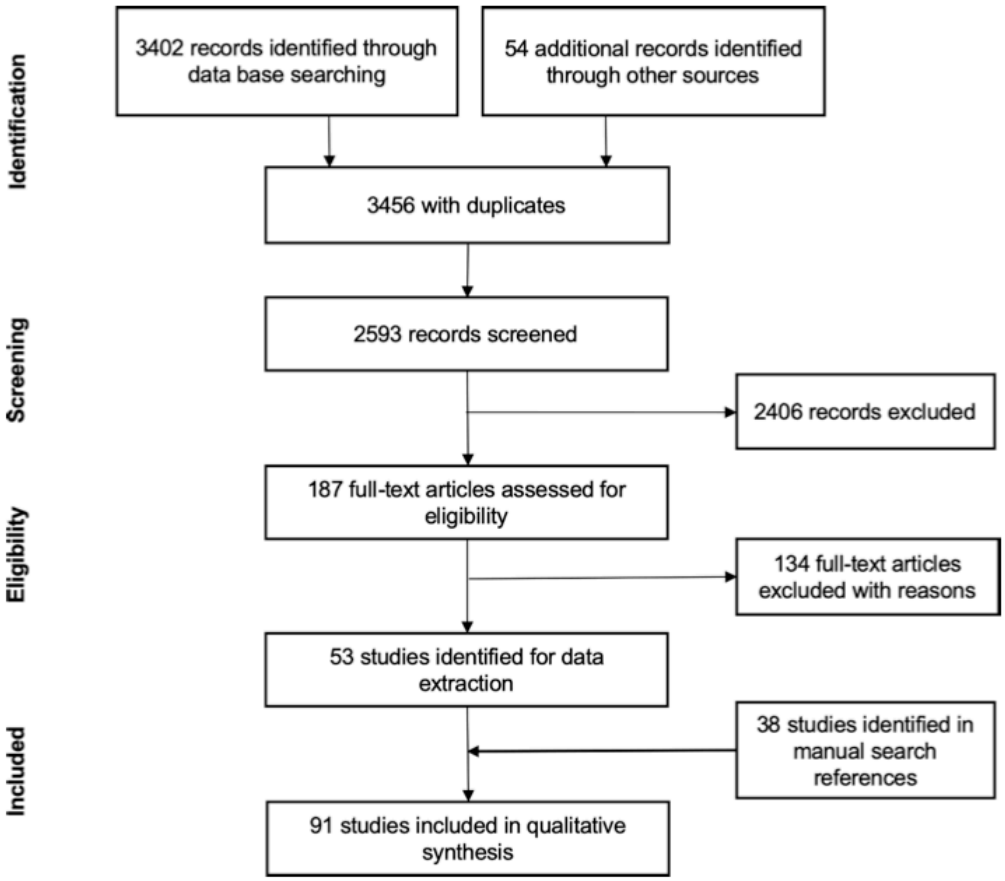


**Fig. 3.** PRISMA flow diagram.

## 3. Results

### 3.1. Study selection

Overall, 3456 papers matched the set of inclusion criteria (see Fig. 3). Fifty-four papers were added after manual search of additional journals focusing on serious games and/or games for health areas. After removing duplicates, 2593 papers were screened considering title and abstract. Overall, 2406 papers were excluded on basis of this analysis. From the 187 eligible papers for full-text analysis phase, 53 were included in the current review. Common reasons for exclusion of papers were: no use of video game (n = 17); use of game platforms or more than one video game simultaneously in the same study arm (n = 16); attention, working memory and inhibitory control were not assessed as cognitive outcomes (n = 28); literature reviews (n = 28); different scope (n = 17) (*e.g.*, roundtable discussions); full-text was not available, even after e-mail contact with authors (n = 2); and two or more of the aforementioned reasons combined (n = 26). Thirty-eight papers were later added from manual search of the list of references of included papers and literature reviews. A total of 91 papers were included for data extraction, in which 72 different video games were identified.

### 3.2. Bibliometric characterization of GBI studies

Year of publication of studies ranged from 2006 to 2018, with publication peak at 2013 (n = 15). More than half of the studies were published in journals ranked in the first quartile (54/91). Sixteen studies were published in journals in the second quartile, six studies in the third quartile and five studies in the fourth quartile. Ten studies were published in journals with no impact factor attributed.

From the 81 papers published in journals with impact factor, 42 were published in journals scoping Health Sciences, 25 Social Sciences, eight Computer Sciences, and six other scientific disciplines. Additional analysis considering quartile of publication by area of expertise showed that from the 54 studies published in the first quartile, 26 were indexed to Health Sciences, 22 to Social Sciences, one to Computer Sciences, and five to the category "other" (see Supplementary Table S3 for details).

### 3.3. Purpose and cognitive utility of GBI

From the 72 identified video games, 42 are AG and 30 CG. Sixteen video games were used for cognitive assessment (of which 15 are AG and one CG), 46 for cognitive training (of which 18 are AG and 28 CG) and 18 for cognitive rehabilitation purposes (of which 14 AG and 4 CG). The difference between the number of identified video games ($n_{video.games}$ = 72), the number of entries according to cognitive utility ($n_{cog.utility}$ = 80), and the total number of entries ($n_{all.entries}$ = 118) is due to the fact that: (1) eighteen papers reported data regarding more than one video game (one video game per intervention arm) [32–49]; (2) nine CG (Medal of Honor: Allied Assault [34,41]; Medal of Honor: Pacific Assault, EA Games [44,49,50]; Rise of Nations, SEGA [34,51]; Brain Age / Dr. Kawashima's Brain Training, Nintendo [37,38,47,48,52,53]; Tetris [34,36,41,46–48,54]; Modern Combat: Sandstrom, Gameloft [32,39,40]; Big Brain Academy, Nintendo [55,56]; Ballance, Atari [44,49]; and The Sims, EA Games [32,43,45]); and (3) 13 AG (Neurofeedback Game [95,96]; VRROOM [116,117]; VRST [81,82]; VRCPAT [75–78,99]; Braingame Brian [86,87,103]; Working memory program, Cogmed Systems [33,107,108];

**Table 1**
Description of video games entries identified in the included ($n_{all.entries}$ = 118).

| Purpose and utility of the game | | Game-elements | | | | | | | Cognitive Outcomes | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Game's name main activity | Study that used the video game | Narrative context | Avatar/ character | Score system | Reward system | Win/lose | Time pressure | Multiplayer | Attention | Working memory | Inhibitory control |
| *Applied games for cognitive assessment* | | | | | | | | | | | |
| Art Gallery Test (AGT) – To identify differences between two images, construct puzzles and finding the details. | Gamito et al. [57] | Yes | Not clear /sure | Not clear /sure | Not clear /sure | Not clear /sure | No | No | Yes | Yes | Yes |
| Aula Nesplora – To respond as quickly as possible to target stimuli while inhibiting any responses to non-target stimuli. | Areces et al. [58] | Yes | Not clear /sure | No | No | Not clear /sure | Yes | No | Yes | Yes | Yes |
| | Iriarte et al. [59] | | | | | | | | Yes | No | No |
| | Díaz-Orueta et al. [60] | | | | | | | | Yes | Yes | No |
| Raiders of the Lost Treasure – To collect/find hidden objects. | Silva and Frère [61] | Yes | Yes | Yes | Yes | Not clear /sure | No | Not clear /sure | Yes | No | No |
| Shoe Closet Test – To match each pair of shoes with the color's compartments in a virtual closet. | Oliveira et al. [62] | Yes | Not clear /sure | Not clear /sure | No | Not clear /sure | Not clear /sure | No | Yes | No | No |
| Space Matrix – To destroy spaceships. | McPherson and Burns [63] | Yes | No | Yes | Yes | Not clear /sure | Yes | Yes | No | Yes | No |
| Tap the little hedgehog – To perform different operations on abstract patterns such as copying, reproducing sequences from memory and mirroring patterns. | Verhaegh, Fontijn and Aarts [64] | Yes | No | Yes | Yes | Yes | Yes | No | No | Yes | No |
| Timo's Adventure – To collect stars. | Peijnenborgh et al. [65] | Yes | Yes | Yes | Yes | Not clear /sure | Yes | No | Yes | Yes | Yes |
| Towi Games – To make arrangements to travel | Rosetti et al. [66] | Yes | Not clear /sure | Yes | No | Not clear /sure | Not clear /sure | No | Yes | Yes | Yes |
| ClinicaVR: Classroom-CPT – To maintain vigilance and react to a specific stimulus within a set of continuously presented distractors. | Parsons et al. [67] | Yes | Not clear /sure | Not clear /sure | Not clear /sure | Not clear /sure | Yes | No | Yes | No | No |
| | Negut, Jurma and David [68] | | | | | | | | Yes | Yes | No |
| | Nolin et al. [69] | | | | | | | | Yes | No | Yes |
| | Gilboa et al. [70] | | | | | | | | Yes | No | No |
| | Moreau et al. [71] | | | | | | | | Yes | No | Yes |
| | Adams et al. [72] | | | | | | | | Yes | No | No |
| | Nolin, Martin and Bouchard [73] | | | | | | | | Yes | No | Yes |
| Virtual Library Task – To perform several tasks associated with the day-to-day running of a library. | Renison et al. [74] | Yes | Not clear /sure | Not clear /sure | Not clear /sure | Not clear /sure | Yes | No | No | Yes | Yes |
| Virtual Reality Cognitive Performance Assessment Test (VRCPAT) – To select stimuli while driving a car. | Parsons and Rizzo [75] | Yes | Not clear /sure | Yes | Not clear /sure | Not clear /sure | Yes | Not clear /sure | Yes | No | No |
| | Parsons et al. [76] | | | | | | | | Yes | No | No |
| | Parsons et al. [77] | | | | | | | | Yes | No | No |
| | Parsons et al. [78] | | | | | | | | Yes | No | No |
| ClinicaVR: Apartment Stroop – To select target stimuli. | Henry, Joyal and Nolin [79] | Yes | Not clear /sure | Not clear /sure | Not clear /sure | Not clear /sure | Yes | No | Yes | No | Yes |
| VR-Based MET – To shop. | Raspelli et al. [80] | Yes | Not clear /sure | Not clear /sure | Not clear /sure | Not clear /sure | Not clear /sure | No | Yes | Yes | No |
| Virtual Reality Stroop Task (VRST) – To respond to a Stroop-like condition while driving a car. | Parsons et al. [81] | Yes | Not clear /sure | Not clear /sure | Not clear /sure | Not clear /sure | Not clear /sure | No | Yes | No | Yes |
| | Armstrong et al. [82] | | | | | | | | Yes | No | Yes |
| VR Office Environment – To learn 16 target items, depicted among numerous other office distractors. | Matheis et al. [83] | Yes | Not clear /sure | No | No | No | Yes | No | Yes | No | No |
| *Applied games for cognitive training* | | | | | | | | | | | |
| 3-D virtual reality kayak program – To paddle a Kayak. | Park and Yim [84] | Yes | No | Not clear /sure | Not clear /sure | Not clear /sure | Not clear /sure | Not clear /sure | Yes | No | No |
| Adaptive WM task variant – To select target stimuli. | Jaeggi et al. [85] | Yes | No | Yes | Yes | Not clear /sure | Not clear /sure | No | No | Yes | No |
| Braingame Brian – To help and befriend the game-worlds inhabitants by creating increasingly elaborate inventions. | van der Oord et al. [86] | Yes | Yes | Yes | Yes | Not clear /sure | Yes | Not clear /sure | No | Yes | Yes |
| | Verbeken et al. [87] | | | | | | | | No | Yes | Yes |

(*continued on next page*)

**Table 1** (*continued*)

| Purpose and utility of the game | | Game-elements | | | | | | | Cognitive Outcomes | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Game's name main activity | Study that used the video game | Narrative context | Avatar/ character | Score system | Reward system | Win/lose | Time pressure | Multiplayer | Attention | Working memory | Inhibitory control |
| Card-pairing memory game – To open or close cards on screen. | Lee et al. [88] | Not clear /sure | Not clear /sure | Not clear /sure | Not clear /sure | Not clear /sure | Not clear /sure | No | Yes | No | No |
| City Builder Game – To remember and order a set of squares in a specific order. | Boendermaker et al. [89] | Yes | No | Yes | Yes | No | Yes | No | No | Yes | No |
| Cybercycle – To cycle. | Anderson-Hanley et al. [90] | Yes | No | Yes | No | No | Yes | No | Yes | No | No |
| Desktop VR System – To execute daily life activities. | Gamito et al. [91] | Yes | Not clear /sure | Yes | Not clear /sure | Not clear /sure | Not clear /sure | No | Yes | No | No |
| EVET - Edinburgh Virtual Errands Test – To shop. | Logie et al. [92] | Yes | No | Yes | Not clear /sure | No | Yes | No | No | Yes | No |
| Interactive Videogame Technology – To collect and deliver the largest amount of contraband items. | Russell and Newton [93] | Yes | Yes | Yes | Not clear /sure | Not clear /sure | Yes | Yes | Yes | No | No |
| Labyrinth – To select a set of stimuli while avoiding a snake within a time limit. | Montani, De Grazia and Zorzi [94] | Yes | Yes | Yes | Yes | Yes | Yes | No | Yes | No | No |
| Neurofeedback Game – To refill a set of elements. | Thomas et al. [95] | No | No | Yes | Yes | Yes | No | No | Yes | No | No |
| Neurofeedback Game – To refill a set of elements. | Thomas et al. [96] | No | No | Yes | Yes | Yes | No | No | Yes | No | No |
| NeuroRacer – To drive the car on a road. | Anguera et al. [16] | Yes | Yes | Yes | Yes | Not clear /sure | Yes | No | Yes | Yes | No |
| Physical exercise plus high cognitive demand – To collect different colored coins and corresponding colored dragons. | Barcelos et al. [42] | Yes | No | Yes | Not clear /sure | No | Yes | No | Yes | No | Yes |
| Cybercycle – To cycle | | Yes | No | Yes | No | No | Yes | No | Yes | No | Yes |
| Space Fortress – To shoot missiles and destroy a space fortress while protecting your spaceship against damage. | Maclin et al. [97]<br>Nikolaidis et al. [98] | Yes | Yes | Yes | Yes | Yes | Yes | No | Yes<br>Yes | No<br>Yes | No<br>No |
| Virtual Reality Cognitive Performance Assessment Test (VRCPAT) – To select stimuli while driving a car. | Parsons and Rizzo [99] | Yes | Not clear /sure | Yes | Not clear /sure | Not clear /sure | Yes | Not clear /sure | Yes | No | No |
| Working memory program, Cogmed systems – To remember both location and order of a number of visual stimuli. | Thorell et al. [33] | No | No | Yes | Yes | Not clear /sure | Yes | No | Yes | Yes | Yes |
| Inhibitory control program, Cogmed systems – To respond according to a certain stimulus. | | No | No | Yes | Yes | Not clear /sure | Yes | No | Yes | Yes | Yes |
| Working memory task with game-elements – To memorize a one-digit number (key-digit); to classify a simple arithmetic decision task as either true or false. | Ninaus et al. [100] | Yes | No | Yes | No | Yes | Not clear /sure | Not clear /sure | No | Yes | No |
| *Applied games for cognitive rehabilitation* | | | | | | | | | | | |
| 3D classroom environment – To select target stimuli. | Ali and Puthusserypady [101] | Yes | Yes | Yes | Not clear /sure | Yes | Not clear /sure | Not clear /sure | Yes | No | No |
| 3D video game rehabilitation training – To explore each street with minimal backtracking. | Caglio et al. [102] | Yes | Yes | Not clear /sure | Not clear /sure | Not clear /sure | No | No | No | Yes | No |
| Braingame Brian – To help and befriend the game-worlds inhabitants by creating increasingly elaborate inventions. | Dovis et al. [103] | Yes | Yes | Yes | Yes | Not clear /sure | Yes | Not clear /sure | No | Yes | Yes |
| Desktop VR System – To execute daily life activities. | Gamito et al. [104] | Yes | Not clear /sure | Yes | Not clear /sure | Not clear /sure | Not clear /sure | No | Yes | No | No |
| Motion Rehab – To select target stimuli and ignore distractors. | Martel, Colussi and Marchi [105] | Yes | Yes | Yes | Not clear /sure | Not clear /sure | Not clear /sure | No | Yes | No | No |
| 'Odd Yellow' training – To reproduce the location of the odd-one-out and the location of the yellow figure shape. | van der Molen et al. [106] | No | No | Yes | No | Yes | Yes | No | No | Yes | Yes |
| Working memory program, Cogmed systems – To remember both location and order of a number of visual stimuli. | Chacko et al. [107]<br>Beck et al. [108] | No | No | Yes | Yes | Not clear /sure | Yes | No | No<br>No | Yes<br>Yes | No<br>No |
| RoboMemo, Cogmed systems – To reproduced sequence of stimuli (lights/numbers) in direct or backward order. | Gray et al. [109]<br>Westerberg et al. [110] | Yes | No | Yes | Yes | Not clear /sure | Yes | No | Yes<br>Yes | Yes<br>Yes | No<br>Yes |

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**Table 1** (*continued*)

| Purpose and utility of the game | | Game-elements | | | | | | | Cognitive Outcomes | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Game's name main activity | Study that used the video game | Narrative context | Avatar/ character | Score system | Reward system | Win/lose | Time pressure | Multiplayer | Attention | Working memory | Inhibitory control |
| Space Fortress – To destroy the Space Fortress. | Janssen et al. [111] | Yes | Yes | Yes | Yes | Yes | Yes | No | Yes | Yes | No |
| The Virtual Supermarket – To shop. | Carelli et al. [112] | Yes | Not clear /sure | Yes | Not clear /sure | Yes | Not clear /sure | No | Yes | No | No |
| Virtual reality environment – To perform quotidian activities. | La Paglia et al. [113] | Yes | Not clear /sure | Not clear /sure | Not clear /sure | Not clear /sure | Not clear /sure | Not clear /sure | Yes | No | No |
| VR Setup – To execute daily living activities. | Gamito et al. [114] | Yes | Not clear /sure | Yes | Not clear /sure | Not clear /sure | Not clear /sure | No | Yes | Yes | No |
| | Gamito et al. [115] | | | | | | | | Yes | Yes | No |
| VRROOM - Virtual Reality and Robotic Optical Operations Machine – To hold the handle of the robot and move it toward spherical targets. | Larson et al. [116] | No | No | No | Yes | No | Yes | No | Yes | No | No |
| | Dvorkin et al. [117] | | | | | | | | Yes | No | No |
| WM training task with game elements – To reproduce sequences of randomly lit-up squares in a 4x4 grid. | Prins et al. [118] | Yes | Yes | Yes | Yes | Yes | No | Not clear /sure | Yes | Yes | No |
| *Commercial video games for cognitive assessment* | | | | | | | | | | | |
| Tetris – To form a horizontal line without leaving any gaps. | Lau-Zhu et al. [54] | No | No | Yes | Yes | Yes | Yes | No | No | Yes | No |
| *Commercial video games for cognitive training* | | | | | | | | | | | |
| Big Brain Academy, Nintendo – To respond as quickly as possible to the different tasks. | McLaughlin et al. [55] | No | Yes | Yes | Yes | No | Yes | Yes, not clear if active | Yes | No | No |
| Mario Kart DS, Nintendo – To race. | Boot et al. [38] | Yes | Yes | Yes | Yes | No | Yes | Yes, but not active | Yes | No | No |
| Brain Age / Dr. Kawashima's Brain Training: How old is your brain, Nintendo – To solve mathematical questions and memorize information. | | No | Yes | Yes | No | No | Yes | No | | | |
| New Super Mario Bros, Nintendo – To rescue the princess. | Lorant-Royer et al. [37] | Yes | Yes | Yes | Yes | No | No | Yes, not clear if active | Yes | Yes | No |
| Brain Age / Dr. Kawashima's Brain Training: How old is your brain, Nintendo – To solve mathematical questions and memorize information. | Nouchi et al. [47] | No | Yes | Yes | No | No | Yes | No | Yes | No | No |
| Tetris – To form a horizontal line without leaving any gaps. | | No | No | Yes | Yes | Yes | Yes | No | | | |
| Brain Age / Dr. Kawashima's Brain Training: How old is your brain, Nintendo – To solve mathematical questions and memorize information. | Nouchi et al. [48] | No | Yes | Yes | No | No | Yes | No | Yes | Yes | Yes |
| Tetris – To form a horizontal line without leaving any gaps. | | No | No | Yes | Yes | Yes | Yes | No | | | |
| Modern Combat: Sandstorm, Gameloft – To navigate in hostile enemy territory and to achieve predetermined objectives such as deactivating enemy equipment. | Oei and Patterson [40] | Yes | Yes | Yes | Yes | Yes | No | Yes, not clear if active | Yes | No | No |
| Metal Gear Solid, Konami – To kill enemies. | | Yes | Yes | Yes | No | Yes | Yes | No | Yes | No | No |
| Super Sniper, Addicting Games – To kill enemies. | | Yes | No | Yes | Not clear /sure | Yes | Yes | No | Yes | No | No |
| Deer Hunter, Atari, Glu Mobile – To hunt. | | Yes | No | Yes | Yes | Not clear /sure | No | No | Yes | No | No |
| Computerized Card Game "Belote" – To complete a set of missions. | Cujzek and Vranis [35] | No | No | Yes | No | Yes | No | Yes | No | Yes | Yes |
| Computerized Ludo – To place all of the figures on the specific fields before other players. | | No | Yes | No | No | Yes | No | Yes | No | Yes | Yes |
| Unreal Tournament 2004 – To kill enemies and avoid death. | Green and Bavelier [46] | Yes | No | Yes | Yes | Yes | Yes | Yes, not clear if active | Yes | No | No |
| Tetris – To form a horizontal line without leaving any gaps. | | No | No | Yes | Yes | Yes | Yes | No | | | |

(*continued on next page*)

**Table 1** (*continued*)

| Purpose and utility of the game | | Game-elements | | | | | | | Cognitive Outcomes | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Game's name main activity | Study that used the video game | Narrative context | Avatar/ character | Score system | Reward system | Win/lose | Time pressure | Multiplayer | Attention | Working memory | Inhibitory control |
| Tetris – To form a horizontal line without leaving any gaps. | Schubert et al. [41] | No | No | Yes | Yes | Yes | Yes | No | Yes | No | No |
| Medal of Honor: Allied Assault, EAGames – To kill enemies and avoid being killed. | Boot et al. [34] | Yes | Yes | Yes | Not clear /sure | Yes | Yes | Yes, not clear if active | Yes | Yes | No |
| Tetris – To form a horizontal line without leaving any gaps. | | No | No | Yes | Yes | Yes | Yes | No | Yes | Yes | No |
| Rise of Nations, SEGA – To build new cities, to improve city infrastructures and to expand one's national border. | Basak et al. [51] | Yes | No | Yes | Not clear /sure | Yes | No | Yes, not clear if active | Yes<br>Yes | Yes<br>Yes | No<br>Yes |
| Hidden-object game: Expedition-Everest, Big Fish Games – To find hidden objects. | Oei and Patterson [32] | Yes | No | Yes | Yes | Yes | Yes | No | Yes | Yes | No |
| Match-3: Bejewelled 2, PopCap Games – To line up at least three similar colors either horizontally or diagonally by switching the positions of adjacent square. | | No | No | Yes | Yes | Yes | No | No | Yes | Yes | No |
| Memory matrix 1.0, Tvishi Technologies – To reproduce a sequence by touching each tile. | | No | No | Yes | Not clear /sure | Yes | Not clear /sure | Not clear /sure | Yes | Yes | No |
| The Sims 3, EAGames – To accomplish tasks that mimic real-life activities. | | Yes | Yes | Yes | Yes | Not clear /sure | Not clear /sure | No | Yes | Yes | No |
| Modern Combat: Sandstorm, Gameloft – To navigate in hostile enemy territory and to achieve predetermined objectives such as deactivating enemy equipment. | | Yes | Yes | Yes | Yes | Yes | Not clear /sure | Yes, not clear if active | Yes | Yes | No |
| Modern Combat: Sandstorm, Gameloft – To navigate in hostile enemy territory and to achieve predetermined objectives such as deactivating enemy equipment. | Oei and Patterson [39] | Yes | Yes | Yes | Yes | Yes | Not clear /sure | Yes, not clear if active | No | No | Yes |
| Starfront Collision, Gameloft – To kill an alien bug specie. | | Yes | Yes | Yes | Yes | Yes | Not clear /sure | Yes, not clear if active | No | No | Yes |
| Cut the Rope - Zepto Lab/Chillingo – To solve puzzles | | Yes | No | Yes | Yes | Yes | Yes | No | No | No | Yes |
| Fruit Ninja – To get the highest score possible. | | Yes | No | Yes | No | Yes | Yes | No | No | No | Yes |
| The Sims 3, EAGames – To accomplish tasks that mimic real-life activities. | Blacker et al. [43] | Yes | Yes | Yes | Yes | Not clear /sure | Not clear /sure | No | No | Yes | No |
| Call of Duty, Activision – To complete a set of missions. | | Yes | Yes | Yes | Not clear /sure | Yes | Not clear /sure | Yes, but not active | | | |
| Ballance, Atari – To steer a ball through a hovering maze of paths | Wu and Spence [49] | Not clear /sure | Yes | Yes | Yes | Yes | No | No | Yes | No | No |
| Need for Speed: Most Wanted, EAGames – To drive a car. | | Yes | Yes | Yes | Not clear /sure | Not clear /sure | Yes | Yes | | | |
| Medal of Honor: Pacific Assault, EAGames – To collect hidden objects and achieve 100% accuracy at the shooting range. | Wu et al. [50] | Yes | Yes | Yes | Yes | Yes | Not clear /sure | Yes, not clear if active | Yes | No | No |
| Medal of Honor: Rising Sun, EAGames – To collect hidden objects and achieve 100% accuracy at the shooting range. | Belchior et al. [36] | Yes | Yes | Yes | Yes | Yes | Not clear /sure | Yes, not clear if active | Yes | No | No |
| Tetris – To form a horizontal line without leaving any gaps. | | No | No | Yes | Yes | Yes | Yes | Yes, not clear if active | Yes | No | No |
| StarCraft, Blizzard Entertainment – To create, organize, and command an army against an enemy army in a real-time map-based setting. | Glass, Maddox and Love [45] | Yes | No | Yes | Not clear /sure | Yes | Not clear /sure | Yes, not clear if active | Yes | Yes | Yes |
| The Sims 2, EAGames – To accomplish tasks that mimic real-life activities. | | Yes | Yes | Yes | Yes | Not clear /sure | Not clear /sure | No | Yes | Yes | No |
| WoW - World of Warcraft, Blizzard Entertainment – To complete quests in a persistent virtual world. | Whitlock, McLaughlin and Allaire [119] | Yes | Yes | Yes | Yes | Yes | Yes | Yes, not clear if active | Yes | No | No |

(*continued on next page*)

**Table 1** (*continued*)

| Purpose and utility of the game | | Game-elements | | | | | | | Cognitive Outcomes | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Game's name main activity | Study that used the video game | Narrative context | Avatar/ character | Score system | Reward system | Win/lose | Time pressure | Multiplayer | Attention | Working memory | Inhibitory control |
| Medal of Honor: Pacific Assault, EAGames – To collect hidden objects and achieve 100% accuracy at the shooting range. | Feng, Spence and Pratt [44] | Yes | Yes | Yes | Yes | Yes | Not clear /sure | Yes, not clear if active | Yes | No | No |
| Ballance, Atari – To steer a ball through a hovering maze of paths | | Not clear /sure | Yes | Yes | Yes | Yes | No | No | | | |
| *Commercial video games for cognitive rehabilitation* | | | | | | | | | | | |
| Big Brain Academy, Nintendo – To respond as quickly as possible to the different tasks. | López-Martín et al. [56] | No | Yes | Yes | Yes | No | Yes | Yes, not clear if active | Yes | Yes | No |
| Brain Age/ Dr. Kawashima's Brain Training: How old is your brain, Nintendo – To solve mathematical questions and memorize information. | De Giglio et al. [53]<br>Brem et al. [52] | No | Yes | Yes | No | No | Yes | No | Yes<br>No | Yes<br>Yes | Yes<br>No |
| Colin McRea Rally3, CodeMasters – To drive a car. | Tahiroglu et al. [120] | Yes | Yes | Yes | Not clear /sure | Not clear /sure | Yes | Yes, but not active | Yes | No | No |
| Tetriminos – To manipulate and rotate the blocks to create a horizontal line without gaps. | Bikic et al. [121] | No | Not clear/ sure | Yes | No | Yes | Yes | Yes, not clear if active | Yes | Yes | No |

RoboMemo, Cogmed Systems [109,110]; ClinicaVR: Classroom-CPT [67-73]; VR Setup [114,115]; AULA, Nesplora [59,60,122]; Desktop VR System [91,104]; Space Fortress [97,98,111,123]; and Cybercycling [42,90]) were reported in more than one study (see Table 1).

### 3.4. Game-elements used in GBI

Our results showed a significant difference ($t_{(1\,17)} = 9.67$, $p < .001$) between the number of GE described in the papers ($M = 2.17$, $SD = 1.43$) and the number of GE really existent in the video games ($M = 3.60$, $SD = 1.53$). Statistically significant differences between the number of GE described in papers ($M = 1.92$, $SD = 1.43$) and GE really existing ($M = 4.49$, $SD = 1.19$) were also observed for CG ($t_{(50)} = 11.82$, $p < .001$) and for AG (GE described: $M = 2.36$, $SD = 1.42$; GE really existent: $M = 2.93$, $SD = 1.42$; $t_{(66)} = 4.63$, $p < .001$). Similar results were identified in video games used for cognitive assessment (GE described: $M = 2.04$, $SD = 1.26$; GE really existent: $M = 2.39$, $SD = 1.13$; $t_{(27)} = 2.79$, $p = .010$), training (GE described: $M = 2.33$, $SD = 1.50$; GE really existent: $M = 4.21$, $SD = 1.43$; $t_{(66)} = 9.14$, $p < .001$) and for rehabilitation (GE described: $M = 1.87$, $SD = 1.42$; GE really existent: $M = 3.30$, $SD = 1.30$; $t_{(22)} = 4.25$, $p < .001$). In average, CG presented more GE (observed through websites) than AG ($t_{(70)} = 0.11$, $p < .001$). Considering cognitive utility, there was a statistically significant difference between groups as determined by one-way ANOVA ($F_{(2,79)} = 7.34$, $p = .001$). Bonferroni Post Hoc Test revealed that video games used for training ($M = 4.17$, $SD = 1.54$) present more GE when compared to video games use for assessment ($M = 2.56$, $SD = 1.41$, $p = .001$).

As shown in Table 2, score system and narrative context were the two most used GE (57 out of 72 video games). Score system was the most frequent GE in CG (29/30), in video games used for training (43/46) and for rehabilitation purposes (15/18), whereas narrative context was the most used GE in AG (35/42) and in video games used for cognitive assessment (15/16). Score system was associated with reward system ($\chi^2_{(1)} = 14.32$, $p < .001$, *Cramer's* $V = 0.446$), avatar ($\chi^2_{(1)} = 5.21$, $p = .005$, *Cramer's* $V = 0.269$), and with win/lose condition ($\chi^2_{(1)} = 11.00$, $p = .001$, *Cramer's* $V = 0.388$). Thus, when video games have score systems, they tend to have reward systems (n = 31), win/lose condition (n = 31), and avatars (n = 26). No significant association was found between narrative context and the other GE. Finally, it was more likely to encounter avatar ($\chi^2_{(1)} = 6.84$, $p = .014$), score systems ($\chi^2_{(1)} = 9.55$, $p = .002$), win/lose condition ($\chi 2(1) = 21.63$, $p < .001$), and multiplayer component ($\chi 2(1) = 22.02$, $p < .001$) in CG than in AG.

### 3.5. Platform and virtual components

Computer was the most used platform to run video games (42/72), regardless of cognitive utility (see Figure S1). Game consoles were used to run eight video games in 11 papers [36–38,47–49,52,53,55,56,64], while the 12 video games that used touch-based devices correspond to only four studies [32,39,40,104]. Win/lose condition was associated with using a touch-based device ($\chi^2_{(1)} = 7.35$, $p = .007$), with 81.8% of video games running in touch-based devices having win/lose conditions. Avatar ($\chi^2_{(1)} = 8.95$, $p = .003$), time pressure ($\chi^2_{(1)} = 4.70$, $p = .030$) and multiplayer component ($\chi^2_{(1)} = 6.75$, $p = .009$) were frequent in video games that run in game consoles (87.5%, 87.5%, and 62.5%, respectively).

Twelve video games were categorized as using VR technology, six were exergames and six used specific interfaces such as brain-computer interface [88,101] (see Figure S2). More than half of all AG (24/42) presented some type of virtual component, with VR technology (n = 12) being more frequent in these type of video games ($\chi^2_{(1)} = 10.29$, $p = .001$) than in CG (none of the video games under this category reported VR). Video games used for cognitive assessment ($\chi^2_{(1)} = 16.74$, $p < 0.001$, *Cramer's* $V = 0.457$) and video games used

**Table 2**
Frequency of use of game-elements in video games ($n_{video.games}$ = 72) and according to cognitive utility ($n_{cog.utility}$ = 80).

| Utility of the game (n) | Purpose of the game | Game-elements n (%) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Narrative context | Avatar/ character | Score system | Reward system | Win/lose | Time pressure | Multiplayer* |
| All games ($n_{video.games}$ = 72) | Applied games (n = 42) | 35 (83.3%) | 11 (26.2%) | 28 (66.7%) | 15 (35.7%) | 9 (21.4%) | 22 (52.4%) | 2 (4.8%) |
| | Commercial games (n = 30) | 22 (73.3%) | 17 (56.7%) | 29 (96.7%) | 16 (53.3%) | 23 (76.7%) | 15 (50.0%) | 16 (53.3%) |
| | **Total** | **57 (79.2%)** | **28 (38.9%)** | **57 (79.2%)** | **31 (43.1%)** | **32 (44.4%)** | **37 (51.4%)** | **18 (25.0%)** |
| Assessment ($n_{cog.utility}$ = 16) | Applied games (n = 15) | 15 (100%) | 2 (13.3%) | 6 (40.0%) | 4 (26.7%) | 1 (6.7%) | 9 (60.0%) | – |
| | Commercial games (n = 1) | – | – | 1 (100.0%) | 1 (100.0%) | 1 (100.0%) | 1 (100.0%) | – |
| | **Total** | **15 (93.8%)** | **2 (12.5%)** | **7 (43.8%)** | **5 (31.3%)** | **2 (12.5%)** | **10 (62.5%)** | **–** |
| Training ($n_{cog.utility}$ = 46) | Applied games (n = 18) | 13 (72.2%) | 5 (27.8%) | 16 (88.9%) | 9 (50.0%) | 4 (22.2%) | 11 (61.1%) | 2 (11.1%) |
| | Commercial games (n = 28) | 21 (75.0%) | 16 (57.1%) | 27 (96.4%) | 16 (57.1%) | 22 (78.6%) | 13 (46.4%) | 15 (53.6%) |
| | **Total** | **34 (73.9%)** | **21 (45.7%)** | **43 (93.5%)** | **25 (54.3%)** | **26 (56.5%)** | **24 (52.2%)** | **17 (37.0%)** |
| Rehabilitation ($n_{cog.utility}$ = 18) | Applied games (n = 14) | 11 (78.6%) | 6 (42.9%) | 11 (78.6%) | 5 (35.7%) | 5 (35.7%) | 6 (42.9%) | – |
| | Commercial games (n = 4) | 1 (25%) | 3 (75.0%) | 4 (100.0%) | 1 (25.0%) | 1 (25.0%) | 4 (100.0%) | 2 (50.0%) |
| | **Total** | **12 (66.7%)** | **9 (50.0%)** | **15 (83.3%)** | **6 (33.3%)** | **6 (33.3%)** | **10 (55.6%)** | **2 (11.1%)** |

* Cases where it was reported that this GE was not available/active during intervention were not included.

for cognitive training ($\chi^2_{(1)} = 10.53$, $p = .002$, *Cramer's* $V = 0.363$) were more likely to use VR technology.

### 3.6. Outcomes of GBI

As shown in Table 3, attention was the cognitive outcome most frequently targeted in GBI (94/118), followed by working memory (54/118) and inhibitory control (30/118). This trend was also observed in video games used for cognitive training and rehabilitation (see Supplementary Table S4 for details). None of the three main cognitive outcomes was associated with any of the GE under study. Other cognitive outcomes (*e.g.,* fine motor skills, reasoning, fluid intelligence) were assessed in 91 out of 118 interventions, and other health outcomes (*e.g.,* mood, ADHD symptoms, health-related quality of life) were analyzed in 24 out of 118 interventions.

Near transfer capacity was evaluated in most of the studies (109/118) and far transfer capacity for cognitive and other health outcomes was evaluated in 38/118 and in 13/118 interventions, respectively. User-experience evaluation was performed in 29/118 interventions, with the assessment of usability (15/118) or of hedonic aspects (*e.g.,* fun, enjoyment, immersion) performed in 21/118 interventions. Win/lose condition was associated (rarely occurring) with the evaluation of video game's impact on other health outcomes ($\chi^2_{(1)} = 18.18$, $p < .001$, *Cramer's* $V = 0.396$). Also, win/lose condition was associated (rarely occurring) with far transfer capacity to health outcomes ($\chi^2_{(1)} = 8.48$, $p = .004$, *Cramer's* $V = 0.270$). Finally, UX assessment was associated (rarely occurring) with video games that present multiplayer component ($\chi^2_{(1)} = 12.89$, $p < .001$, *Cramer's* $V = 0.333$). Evaluation of hedonic aspects of UX was found to be associated with multiplayer component ($\chi^2_{(1)} = 8.55$, $p = .002$, *Cramer's* $V = 0.271$). Usability evaluation was associated with all GE except for narrative context (*p-values between* $p \leq 0.001$ and $p = .027$; *Cramer's V between* 0.211 and 0.343). Overall, usability evaluation was rarely conducted.

**Table 3**
Frequency of game-elements by cognitive outcomes ($n_{all.entries}$ = 118).

| Game-elements | Cognitive outcomes n (%) | | |
|---|---|---|---|
| | Attention (n = 94) | Working memory (n = 54) | Inhibitory control (n = 30) |
| Score system | 70 (76.1%) | 46 (85.2%) | 19 (65.5%) |
| Narrative context | 70 (76.1%) | 36 (66.7%) | 20 (69.0%) |
| Time pressure | 55 (59.8%) | 33 (61.1%) | 19 (65.5%) |
| Reward system | 33 (35.9%) | 25 (46.3%) | 10 (34.5%) |
| Win/lose | 33 (35.9%) | 22 (40.7%) | 8 (27.6%) |
| Avatar/character | 37 (40.2%) | 21 (38.9%) | 10 (34.5%) |
| Multiplayer*** | 25 (27.2%) | 10 (18.5%) | 5 (17.2%) |

**The association between each GE and each cognitive outcome was done by cell (chi-square test for independence).

*** Cases where it was reported that this GE was not available/active during intervention were not included.

## 4. Discussion

The aim of this study was to identify, integrate and report which GE have been used in GBI for cognitive assessment, training or rehabilitation. For this purpose, a systematic review of literature following PRISMA guidelines [20] was conducted. Ninety-one papers were included in the qualitative synthesis, covering a total of 72 different video games.

A significant difference between the number of GE described in the studies included and those that actually compose video games was found. The lack of a detailed description of the video games used constitutes a serious methodological limitation which hinders the analysis and interpretation of GBI results. To our knowledge, this is the first review on GBI where the information extracted from the studies included was compared to the description available in other sources of public access. Despite unusual, the methodological decision to complete data extraction with information gathered through less traditional sources (webpages describing video games) enabled to uncover this methodological shortcoming, thus contributing to future research and data reporting on GBI.

Score system was the most frequently used GE in CG and in video games used for training and rehabilitation purposes. Similar findings have been reported for digital learning environments [124] and health and fitness apps [23]. Numeric feedback systems such as points, levels and leaderboards are considered goal metrics, since they establish a clear link between user's effort and performance [125]. The assumption that users highly value this element contributes to its widespread use (for *pointsification* perspective review see [126]). However, that assumption is not always verified [23]. In fact, implementation of tangible and predictable rewards, such as those provided by score systems, were previously associated with a decrease of free-choice behavior [127] and considered by some as the less exciting and engaging feature of video games [128].

However, since the motivational affordance [129] of each GE, as well as how different GE interact to promote human behavior, is still to determine, no elements should be dismissed at this point without a

careful study of its impact. For instance, Mekler and colleagues [125] showed that GE (*i.e.,* points, leaderboards and levels) within the same category (*i.e.,* score system) can impact human behavior differentially. By using an image annotation task where participants received 100 points for each tag created in a set of 15 abstract paintings, Mekler and colleagues showed that participants who received points for each created tag outperformed participants in the non-gamified version group (no points assigned) but were outperformed by the participants allocated to the group where points were used to classify participants in relation with themselves (*i.e.*, levels of difficult condition) or in relation to other participants (*i.e.*, leaderboard condition) [125]. It is also plausible to consider that score systems may undermine adherence if associated with a progressive difficult-level system (*i.e.,* getting more points depends on individuals' skills for playing the game) whereas that is less the case if no individuals-skills improvement is required for points-accumulation (namely, if a game narrative is associated).

Narrative context was the most used GE in AG and in video games used for cognitive assessment. Unlike the other GE analyzed in this study (*e.g.,* score and reward systems and win/lose condition), narrative context has no association with player's performance [24]. This GE is used primarily to contextualize and to add meaning to game's main activity, inspiring motivation and long-term willingness towards tasks that may be perceived as boring and repetitive in its non-gamified version [24]. Meaningful storylines, especially if in line with one's personal goals, may improve/maintain patients' long-term motivation and promote skills transference to other (real-life) contexts [130]. Although no significant associations were found between narrative context and purpose, utility or cognitive outcomes, the high frequency of this GE is encouraging, because it suggests a concern for developing GBI with meaningful game narratives that promote participants' long-term adherence.

The possibility to interact with other players is an attractive feature of video games [131] since it provides an opportunity to learn and develop meaningful relationships [132]. However, as our study revealed, multiplayer component was the less used GE. This can be explained by the fact that interacting with other players also means to be exposed to other's judgment. Fear of failure and performance-related frustration are two possible behavioral responses when competing or collaborating with others [133]. Design and implementation complexity, necessity to combine schedules, share game control and relying on other' players skills [134] may also contribute for the low usage of this GE in cognitive therapeutic settings.

Attention, working memory and inhibitory control capacity are essential components of cognitive control [28] and self-regulated behavior [26]. Attention supports all processes involved in human thought [28], and a non-adequate assessment of attentional deficits may result in diagnostic errors and failure to prescribe suitable cognitive interventions [135]. Hereby, it was not surprising that attention was the most frequently targeted outcome in the included studies, since it plays such a central role in human cognition. Closely related to (and dependent of) attentional resources, working memory capacity and inhibitory control are essential cognitive components for fluid reasoning, comprehension and learning [28,136], as well as crucial skills for our ability to function in the real world [137]. However, in our study no association was found between the assessment of attention, working memory or inhibitory control and any of the GE, nor between the study of those cognitive indicators and utility (assessment, training, rehabilitation) or purpose (commercial/applied) of the game. The lack of association between GE and the study of these cognitive functions may be the result of the absence of a theoretical and empirical framework that guides GE selection for the study of video games impact on human health.

Game-based interventions seem to follow the trends of video games industry. In our study, as in ESA annual report [138] computer was the most popular gaming platform. On the other hand, touch-based devices were the less used game platform being reported only in four studies. Touch-based devices, such as tablets, are particularly suitable in fragile populations such as older adults [139,140]. Intuitive interfaces, direct manipulation [141] and bigger screens (compared to smartphones) are some of the features that contribute to technology adaptation by less familiar users. However, none of the studies that used older adults as participants reported tablets as game's platform. Other market trend is VR technology to develop video games. VR through high-detailed three dimensional (3D) environments, and increasingly natural ways of interact with it [142], promises to be a remarkable improvement in the assessment of the capacity to perform daily living tasks (ecological validity), compared with traditional neuropsychological tools (Sbordone, 1996 cit. by [143]). Taking this into account, it was not surprisingly to find out that this component was primarily present in video games used for assessment purposes, area in which diversity and standardization of stimuli display, as well as performance measurement, are fundamental requirements.

### 4.1. Limitations

The findings of this study should be interpreted in the context of some limitations. First, the strategy used to identify additional journals scoping serious games and games for health may have excluded studies published in scientific journals in which these terms do not appear as part of the title/abstract or scoping interests. Second, electronic database selection may have unintentionally excluded work published in conferences or other type of meetings (a popular path to publish work in the engineering and computational science fields). A strong point, nevertheless, regards the fact that the search strategy was based on Cochrane's guidelines for conducting Systematic Reviews of Literature [144], such as consulting three different databases for locating papers, using specialist databases, searching reference lists of the included papers as well as reference lists of literature reviews identified during screening process. Third, the additional web-based search may have contributed to obtain more detailed descriptions of CG vs AG, since more sources of information with detailed descriptions are available to these video games than to AG. The absence of both a consensual GE classification system and a clear definition of what is and is not a video game introduced some degree of subjectivity in eligibility criteria and data extraction. Such bias was minimized by carefully defining the search protocol and by developing GE definitions based on the results obtained in the narrative review, which underwent a process of active discussion and reformulation, within the research team.

## 5. Conclusions

This study aimed to identify which GE have been used in GBI for cognitive assessment, training or rehabilitation. Score system and narrative context were the two most frequently used GE. However, the development of GBI that are based on the implementation of numeric feedback systems may jeopardize the main objective with which this type of interventions has been used: promotion of intrinsic motivation towards long-term goals. Moreover, the lack of any other significant association between GE used and the targeted cognitive outcomes emphasizes the necessity of defining a theoretical framework that supports the strategic selection of GE according to patient/pathology features, as well as according to the features of cognitive constructs that are targeted by specific game-based intervention.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jbi.2019.103287.

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# Photo-Realistic Interactive Virtual Environments for Neurorehabilitation in Mild Cognitive Impairment (NeuroVRehab.PT): A Participatory Design and Proof-of-Concept Study

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**Abstract:** Mild cognitive impairment (MCI) is characterized by cognitive, psychological, and functional impairments. Digital interventions typically focus on cognitive deficits, neglecting the difficulties that patients experience in instrumental activities of daily living (IADL). The global conjecture created by COVID-19 has highlighted the seminal importance of digital interventions for the provision of healthcare services. Here, we investigated the feasibility and rehabilitation potential of a new design approach for creating highly realistic interactive virtual environments for MCI patients' neurorehabilitation. Through a participatory design protocol, a neurorehabilitation digital platform was developed using images captured from a Portuguese supermarket (NeuroVRehab.PT). NeuroVRehab.PT's main features (e.g., medium-sized supermarket, the use of shopping lists) were established according to a shopping behavior questionnaire filled in by 110 older adults. Seven health professionals used the platform and assessed its rehabilitation potential, clinical applicability, and user experience. Interviews were conducted using the think-aloud method and semi-structured scripts, and four main themes were derived from an inductive semantic thematic analysis. Our findings support NeuroVRehab.PT as an ecologically valid instrument with clinical applicability in MCI neurorehabilitation. Our design approach, together with a comprehensive analysis of the patients' past experiences with IADL, is a promising technique to develop effective digital interventions to promote real-world functioning.

**Keywords:** virtual reality; cognition; transfer capacity; recovery of function; neurorehabilitation

## 1. Introduction

Mild cognitive impairment (MCI) was initially conceptualized as a clinical entity affecting the cognitive functioning exclusively (i.e., memory capacity) [1]. However, empirical evidence has shown that

cognitive and functional impairments co-exist from very early stages of the disease [2], and difficulties in instrumental activities of daily living (IADL) are prevalent among MCI patients [3]. Vascular mild cognitive impairment (VaMCI) is a clinical condition of vascular etiology, in which executive deficits are a prominent feature [4,5] and a strong predictor of functional decline and dementia [6]. Nonetheless, studies conducted in VaMCI patients are scarce, with even fewer studies focused on the development of rehabilitation instruments which target cognitive and functional impairments simultaneously.

Virtual reality (i.e., computer-generated interactive environments) [7] has been recognized as a valuable resource for developing instruments that enable health professionals to accurately predict patients' performance in everyday living activities (i.e., ecologically valid instruments) [8,9], especially in activities that actively engage executive functions [8,10–12]. Several virtual environments (VEs) have been developed targeting IADL, such as preparing meals [13,14], moving within the community [15,16], and cleaning and maintaining the house [17–20].

Shopping for groceries is perhaps one of the most studied IADL, with several studies showing that patients with executive deficits reveal in VEs a similar pattern of impairments to those observed in real-world tasks [21–27]. However, the majority of these VEs are manually designed, time- and human-resource consuming, and do not provide tasks or scenarios of sufficient realism [28]. Additionally, only a few of these VEs are designed for neurorehabilitation purposes [23] in MCI patients [22].

The feeling of "being physically present" in the virtual world, known as presence, is described as the phenomenon of users acting and experiencing emotions as if they were in the real world [29]; this is thought to promote the transfer of trained skills and behaviors from VEs to real-world contexts [8,29]. One design approach that has been used to improve the realism and sense of the presence is image-based rendering VEs. One example of a realistic image-based VE is Google Street View, where users can navigate within 360° photos of the surrounding environment. Previous findings have shown that the use of images of real-world scenarios results in highly visual realistic VEs and, therefore, an increased sense of presence [28]. Furthermore, image-based rendering VEs have shown promising results when applied to reminiscent therapy [28]. However, in the scarce studies that use this technique, the images are embedded as just a decorative/background element [30] or are non-interactive [15]. Other image-based VE interventions require complex technologic equipment and space availability in order to accommodate the experimental apparatus [28], which limits its widespread use in clinical and neurorehabilitation contexts.

Based on the limitations mentioned above and considering the concept of function-led instruments [8], in which neuropsychological instruments should be as far as possible an accurate representation of real-world functioning, we conducted a qualitative analysis of the rehabilitation potential and clinical applicability of an image-based fully navigable and interactive virtual supermarket, NeuroVRehab.PT to promote cognition and functional capacity in VaMCI patients. This neurorehabilitation platform was developed by ISAMB (Lisbon, Portugal), LASIGE (Lisbon, Portugal), and Nippon Gases Portugal (Vila Franca de Xira, Portugal).

The goals of this study are twofold: (1) to describe the design process of NeuroVRehab.PT and (2) to characterize health professionals' (i.e., neurologists, psychologists, and neuropsychologists) perspectives about the rehabilitation potential and clinical applicability of NeuroVRehab.PT for VaMCI patients' neurorehabilitation.

## 2. Experimental Section

This study was conducted using a participatory design research protocol and reported according to the consolidated criteria for reporting qualitative research checklist (COREQ) guidelines [31] (see Supplementary Materials Table S1. COREQ: consolidated criteria for reporting qualitative research checklist). Two groups of stakeholders (i.e., older adults and health professionals) were invited to participate in the design of a virtual supermarket aiming to train the cognitive functions and behavior strategies recruited during a shopping activity.

The present study was performed in compliance with the Declaration of Helsinki and was approved by the following ethics committees: Comissão de Ética do Centro Hospitalar de Lisboa Norte e Centro Académico de Medicina de Lisboa–CAML (reference number 89/19) and Comissão de Ética para Recolha e Proteção de Dados de Ciências (CERPDC) (reference number CERPDC/16/2019) (see Supplementary Materials Doc S1, ethical standards, for a description of the ethical aspects considered during the execution of this project).

### *2.1. Participatory Design of NeuroVRehab.PT–Shopping Behaviors Questionnaire with Older Adults (Phase 1)*

#### 2.1.1. Sample and Recruitment

Two senior universities of the municipality of Almada, Portugal, were contacted and agreed to participate in the study. Visits were scheduled to a group of classes identified earlier by the executive board of the two institutions. During these visits, one of the co-authors of this paper (FFB) presented the project and explained how the data gathered through the questionnaires would support the research team's decisions regarding the main features of the virtual supermarket, such as the use (or not) of a shopping list, the number of products included in the shopping list, and the type of supermarket (grocery store vs. supermarket vs. hypermarket), among other features. To be eligible, the participants had to be more than 60 years old, be community dwelling, be responsible for grocery shopping, and give written informed consent.

#### 2.1.2. Instruments and Procedure

A questionnaire with 11 multiple-choice questions that aimed to analyze the shopping behaviors and routines of older adults was developed and reviewed by the research team (see Supplementary Materials Table S2 for the shopping behaviors questionnaire with older adults). The questionnaire was filled in individually and collected at the end of the senior universities' sessions. Questions included items regarding the type of store they usually go to (i.e., local grocery store, supermarket, or department store), the time spent there, and the frequency they go shopping per week. Other items included the habit of using shopping lists, establishing budgets, shopping for weekly or monthly necessities, and an estimation of the amount of money spent while shopping. The questionnaire was anonymous, and besides age, gender, and professional status (active vs. retired), no other personal information was collected.

#### 2.1.3. Data Analysis

Statistical Package for the Social Sciences (IBM-SPSS, version 24.0; International Business Machines Corp., Armonk, New York, NY, USA) was used to conduct descriptive analyses of the data collected through the shopping behaviors questionnaire with older adults. For nominal variables (e.g., gender, professional status, and questionnaire responses), tables of frequencies were calculated. For continuous variables (e.g., age, time spent shopping), the mean, standard deviation, mode, minimum, and maximum were calculated.

#### 2.1.4. Results

A total of 110 participants aged between 61 and 86 years (70.92 ± 5.94 years) filled in the questionnaire. Twenty-eight were men (26.7%) and 77 women (73.3%). Fifty-three participants (53.5%) stated that they usually go to supermarkets as opposed to local grocery ($n$ = 8, 8.1%) stores or big department stores ($n$ = 38, 38.4%). Fifty-nine (56.2%) claimed that they usually make shopping lists, but only 42 (75%) use it during shopping. Before going shopping, 44 (79.4%) participants claimed that they included items in the shopping list as they remember what they need, and 10 (14.7%) organized the products according to the products' position in the supermarket.

More than half of the participants claimed they go to the supermarket less than once per week ($n$ = 56, 52.8%), alone ($n$ = 64, 60.4%), and to buy groceries for weekly necessities ($n$ = 59, 56.2%). On average,

the participants spend 59.24 ± 33.68 min on each visit to the supermarket. Sixty-one participants (58.1%) claimed that they have an estimation of how much they will spend before going to the checkout counter, and 33 (35.9%) stated that, after being informed of the value of the bill, they know precisely how much they should receive in return (see Supplementary Materials Table S2 for the shopping behaviors questionnaire in older adults descriptive data).

#### 2.1.5. Main Implications for the Development of the NeuroVRehab.PT

Supermarket was the most frequently visited type of store for food and house products shopping. A relevant percentage of the participants reported that they carry out their weekly shopping alone. The findings also suggested that shopping lists do not tend to be long, although diversified.

The majority of older adults in our sample claimed that they go to the supermarket less than once per week and spend around 60 min on each visit. These data were initially collected to determine an adequate dose exposure to our digital platform. Although there are no guidelines regarding dose exposure in cognitive rehabilitation for MCI patients [32,33], previous studies have shown that interventions composed of few sessions with extended durations were not effective [34]. This implies that clinical trials of cognitive rehabilitation should accommodate the difficulties that VaMCI patients experience in their real-life activities (related or not to cognitive decline), provide sufficient repetition, and manage fatigue and frustration throughout the intervention length [35].

### 2.2. *Design and Implementation of the NeuroVRehab.PT (Phase 2)*

Based on the shopping behavior survey with older adults, we developed a first prototype of a web-based application called NeuroVRehab.PT. NeuroVRehab.PT allows people suffering from VaMCI to perform typical shopping tasks, such as creating shopping lists, navigating in a supermarket, adding products to the shopping basket, or sticking to a budget. The application was developed using HTML version 5.2. [36], JavaScript version ECMAScript 2019 [37], CSS version 3 [38], and PHP version 7.4.9 [39]. The supermarket was constructed using the Photo Sphere Viewer library [40] and panoramic photographs of the interior of a typical Portuguese supermarket (captured using the Google Street View app for Android, Google LLC., Mountain View, CA, USA); see Supplementary Materials Doc S1, ethical standards, for a description of the ethical aspects considered during the image capture and editing).

The platform is optimized to run on tablets. Tablets provide direct object manipulation (i.e., the person directly interacts with the target object using the fingers) and require less hand–eye coordination [41]. Older adults seem to prefer tablets to more traditional setups such as computers [42]. Previous studies showed that tablets are easier for older adults to use [43], even when they experience technological divide to some extent [44] or already present mild [20] or severe cognitive compromise (i.e., dementia) [45].

#### 2.2.1. Platform Description

NeuroVRehab.PT is a prototype of a web-based digital neurorehabilitation platform composed of three independent game modes—supermarket, recipes, and shopping list. The supermarket is the central part of the platform and the key component of the three game modes.

##### Supermarket Environment Description

To replicate a real-world scenario, the environment of this system is composed of 49 360° panoramic photographs, together with typical supermarket noises at the background. The background noise can be turned off at any time. Users can only navigate in the supermarket by activating the full-screen mode or touching the start button (which also activates the full-screen mode). This way, users can have a clean screen to prevent distractions, as reported in previous studies [46]. *Maria*, a virtual shopping assistant, will guide users for the first time and regularly provide information about the game mechanics and behavioral shopping strategies that can be used in real life. Users experience the virtual supermarket from a first-person perspective (i.e., without any intermediating avatar) and can walk through the 19 supermarket sections (e.g., vegetables, fruits, bakery, dairy, frozen food) using the

arrows displayed on the screen (Figure 1). Navigation arrows are placed in the screen, at the corridors, and in the exact position where the users want to walk to. If necessary, users may zoom in and out to take a closer look at a product or use the autorotate button to locate themselves in the environment. To select a product, users touch the product and a tag with the product's information (name, photo, category, description, and price) is displayed on the right side of the screen, together with an "add to the basket" button that allows users to add products to the shopping basket (Figure 2a).

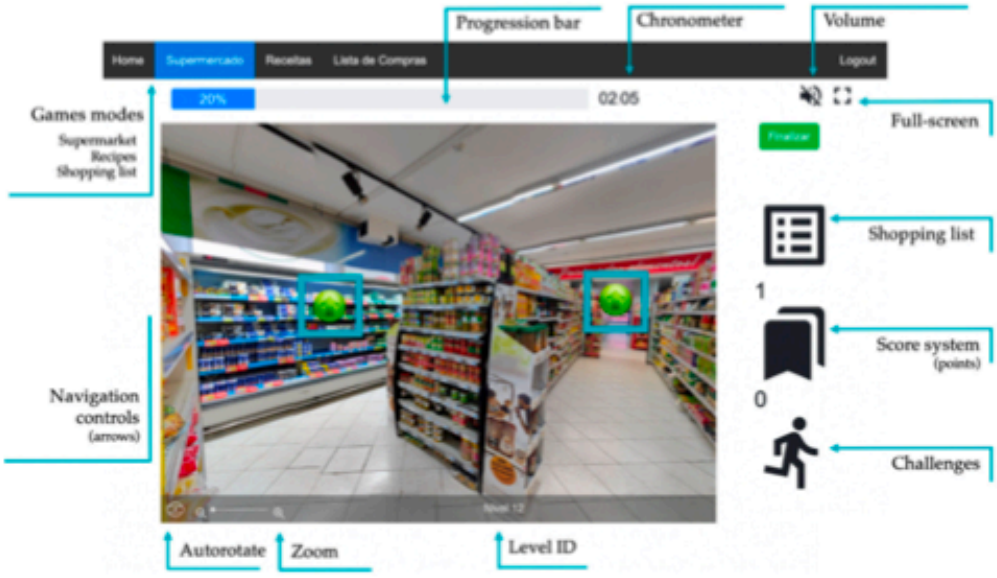


**Figure 1.** Interface elements of the NeuroVRehab.PT neurorehabilitation digital platform.


**Figure 2.** (**a**) Tag with product information—name, photo, description/weight, price, and add button; (**b**) view of the screen with the levels of difficulty, three-star classification, level ID, level of difficulty; (**c**) shopping list from a difficult level (medium) with nine products (written in black) under the correspondent category (written in blue).

### Supermarket Game Mode

The system provides fourteen game levels that ask users to go shopping with a predefined shopping list (Figure 2b). Levels have different difficulty levels—easy, medium, and hard—which differ regarding the number of products to buy, the distance between the products, the available time to complete the level, and the presence or absence of background noise. In more advanced levels, there is also a budget to be met. Furthermore, the platform is designed to enable health professionals to create custom levels. Users need to purchase all the items of the shopping list (Figure 2c) to complete the level. If the added product is listed on the shopping list, users will hear a sound of positive feedback and earn points. If users try to add a product that is not on the shopping list, a message together with a sound of negative feedback will appear, and users will keep the same points.

After selecting all the products on the shopping list, users are asked to go to the checkout counter zone and pay the groceries by choosing one of the payment methods (cash or credit card). At the end of each level, a three-star rating is attributed based on the users' performance (time and distance walked).

Recipe Game Mode

The recipe game mode allows users to shop for the ingredients that are required to cook a traditional dish. Users may select among six traditional recipes—one soup, four main courses, and one dessert (Figure 3a). Each recipe is identified by a name and a photo of the dish. As an extra step of difficulty, after selecting one of the recipes the participants are asked to organize the ingredients under the correct category (e.g., apples under fruit) (Figure 3b). Correct and incorrect sorting is identified by turning the ingredients green or red, respectively. The participants need to correctly organize all the ingredients before having access to the virtual supermarket and purchasing the ingredients of the recipe.


**Figure 3.** (**a**) View of the recipe game mode; (**b**) extra step of difficultly in the recipe game mode, in which users have to organize the ingredients (left side of the screen) under the corresponding category (right side of the screen); (**c**) view of the shopping list game mode with two products included in the list.

Shopping List Game Mode

In this game mode, users can create personalized shopping lists. A list ID is identified by a name customized by users, and they may add products by writing the name of the product in the search field. As they write, a drop-down list appears with products matching the search query (Figure 3c). To select an item, they have to touch it. After finishing their shopping list, the participants are asked to organize the ingredients under the correct category (similar to the activity described in the recipe game mode section) before moving on to the virtual supermarket.

### 2.3. *Software Evaluation and User Experience (Phase 3)*

#### 2.3.1. Sample and Recruitment

A purposive sample of health professionals (i.e., psychologists, neuropsychologists, and neurologists) identified through professional networking was contacted and invited to participate in the study. Health professionals were identified based on (1) their clinical and scientific experience (≥5 years) with ageing, age-related neurological disorders, and cognitive decline; (2) their knowledge of the main theoretical models of human cognition and neurorehabilitation; (3) their familiarity with computerized cognitive training or rehabilitation programs. All the participants who were contacted (face-to-face) agreed to participate, and an individual session was booked at the participants' convenience (local and date). All the participants signed the written informed consent.

#### 2.3.2. Instruments and Procedure

Interviews took place in quiet and private rooms and lasted approximately 60 min. The participants sat in front of a desk where a Huawei MediaPad T5 tablet (Android 8) (Huawei Technologies Co. Ltd,

Shenzhen, China) was supported horizontally at 25° degrees (approximately) using a tablet stand. The platform was run in the Google Chrome application (version 79.0.3945; Google Inc., Menlo Park, CA, USA). A neuropsychologist with previous experience in qualitative research (FFB) conducted the interviews, and a second researcher member (SA, computer scientist and PhD student) was also present in five of the seven interviews and ensured that the sessions went on without any technical problems.

Each session was divided into two moments. In the first part of the interview, the participants were encouraged to express their opinions and thoughts verbally—the think aloud method (TA) [47]—while using the platform. The interviewer (FFB) demonstrated the TA method to participants while exploring the Gmail website. Then, the participants were encouraged to use it on the NeuroVRehab.PT platform. The participants were free to explore the platform; however, sessions were conducted so that all the participants visited the three game modes (i.e., supermarket, recipes, and shopping list) and played at least two game levels in the supermarket mode. The second part of the session consisted of a semi-structured interview focused on the participants' experience (i.e., user experience; UX) and the perceived clinical applicability and rehabilitation potential of the platform.

#### 2.3.3. Data Analysis

The participants' demographic data were analyzed using IBM-SPSS (version 24.0; International Business Machines Corp., Armonk, New York, United States). Interviews were transcribed for content analysis, and a list of codes was developed on the basis of two interviews (data grounded theory). This initial code system was created independently by two researchers (FFB and SA) and then discussed and merged into a comprehensive list. The remaining interview transcripts were coded independently by two researchers (FFB and SA) using the previously developed list of codes and an interrater reliability index of Cohen's $k = 0.82$ was obtained by calculating the mean of Cohen's kappa indexes per interview (Cohen's $k \geq 0.80$). This kappa index was used as indicative of strong interrater reliability in healthcare research [48]. Blocks of 20 lines were used as the unity of analysis for semantic thematic analysis purposes [49]. When completing the analysis, the code system was reorganized into broad categories (major themes) and respective subcategories (minor themes).

## 3. Results

Seven health professionals aged between 29 and 67 (47.14 ± 13.08 years) and with 17 years of professional experience (range: 5–40 years) were interviewed. Two participants were male and 5 were female, with academic backgrounds in medicine/neurology ($n = 2$) or in neuropsychology ($n = 5$).

Two participants rated themselves as being very confident, four as being confident, and one as a little confident in using technology or new technological devices ($n = 2$, $n = 2$, $n = 3$, respectively). On average, the participants spent 16 ± 7.99 h (range: 7–30 h) browsing content on the internet and 0.86 ± 1.86 h (range: 0–5 h) playing video games per week. All the participants were familiar with at least one computerized cognitive training or rehabilitation program (e.g., Cogweb®, Rehacom®), and three participants (42.9%) reported that they use brain training games or computerized cognitive training programs (CCTP) in their professional practice (e.g., Fitbrain, Neuronation).

Four major themes (and seven minor themes) emerged from the semantic thematic analysis: experience with NeuroVRehab.PT, rehabilitation potential, potential barriers, and opportunities (see Table 1 for the complete code system, including minor themes). Due to technical problems related to audio recording, the second part of interview 2 was lost (90% of the semi-structured interview). Therefore, only the information collected during the TA phase of interview 2 was included in data analysis. Data saturation was obtained at the 5th interview, with no new codes identified in the last two interviews.

**Table 1.** Code system developed with the semantic analysis of the interviews.

| | |
|---|---|
| ⇒ | Experience with NeuroVRehab.PT |
| | • Hedonic experience and presence |
| | • Usability |
| ⇒ | Rehabilitation potential |
| | • Cognitive stimulation |
| | • Transfer capacity |
| ⇒ | Potential barriers |
| ⇒ | Opportunities |
| | • Clinical and non-clinical contexts |
| | • Friend sourcing |
| | • Other environments |

### 3.1. *Experience with NeuroVRehab.PT*

#### 3.1.1. Hedonic Experience and Presence

Overall, the participants expressed a positive attitude towards NeuroVRehab.PT and reported having fun and enjoying the platform. Different features of the platform stood out and were considered by the participants as appealing and relevant from a clinical point of view (e.g., the icon used to identify the different game levels (Figure 2b), the label with the product's characteristics (Figure 2a), the zoom-in functionality, and the availability of a shopping list that the participants can check (Figure 1)). However, it was the high realism and visual complexity (and auditory stimuli) of the VE that captured the participants' attention. All the participants but one explicitly mentioned this aspect during the interviews (and some of them more than once).

> Participant 1: "I was expecting something more, rudimentary, but not the case, I think it was ... the products were clear and colors vivid ... "
>
> Participant 2: "Well, it is a very appealing image of the supermarket. It makes you want to explore it, doesn't it? It has beautiful fruits."
>
> Participant 4: "Ah! How cute ( ... ) it really looks like a supermarket ( ... ), maybe this is really a supermarket ( ... ) The products are real, not drawings [as in 3D-modulated scenarios], I think it is good."
>
> Participant 5: "[While performing a task in NeuroVRehab.PT] Ok, hot chocolate. Hot chocolate, now I have to find ... . this is really realistic. In fact, it is real, I did not have this expectation."
>
> Participant 6: "It seems very realistic, hyper-realistic." (line 51) "The locations, the type of products, yes, yes, I think is quite realistic."
>
> Participant 7: "The environment sound is very good; it really puts you inside of a supermarket ( ... ) we know where we are, perfectly."

#### 3.1.2. Usability

The participants identified and played the three game modes without relevant difficulties. However, the navigation controls and the sense of orientation inside NeuroVRehab.PT were identified as two aspects that should be improved in order to provide a more smooth and pleasant experience. For instance, some participants misinterpreted the meaning of the navigation controls and interpreted them as mandatory actions to progress in the game.

Participant 2: "The arrow appears, I assume this means I need to follow the arrows."

Participant 1: " ... the arrow then ... means that I need to go back to the fruit section?"

Other participants considered the arrows as hints to the location of the next product in the shopping list.

Participant 5: "The arrow helps to orient, doesn't it? I did not understand if the arrow gives you a hint or if ... Does it give you a hint?"

Regarding the sense of being oriented within the supermarket, the participants felt that it " ... could be useful, for example, before starting (the game levels) that the person visits the whole supermarket, a kind of orientation exercise, to learn (the supermarket) more or less." (Participant 1). Still on this subject, another participant referred to the famous experiment of Willard S. Small [50] to explain the importance of having the opportunity to explore (learning) the environment before starting any specific task: " ... a person is in that environment; it is like a mouse when it is put on a place, like ( ... ) a maze, something like that, it (the mouse) will explore, the first thing it will do is to explore the surroundings to get a perception. We are a little bit like mice. The first thing a person wants to do is ... in fact, surrounded by these fruits, is to see what is around and understand ... " (Participant 2). In this regard, the participants suggested that the presence of signs with the names of the sections and/or a map of the supermarket would improve the sense of orientation as well as the learning of the VE.

### 3.2. Rehabilitation Potential

The health professionals considered NeuroVRehab.PT a useful and innovative instrument for cognitive stimulation that they would recommend to their MCI patients.

Participant 5: "[regarding another virtual supermarket for IADL rehabilitation] ( ... ) it was prehistoric when compared to this one."

Participant 2 " ... a good alternative for cognitive stimulation."

#### 3.2.1. Cognitive Stimulation

The participants considered NeuroVRehab.PT " ... sufficiently appealing and demanding for MCI patients ... " (Participant 5) and comprehensive in terms of the cognitive functions stimulated—namely, executive functions (working memory, planning, decision making), memory, attention, spatial orientation, and math abilities.

Participant 5 " ... working memory, of course, always pumping in my head ( ... ) Manifestly, this also trains orientation ... .". [ ... ] From an attentional point of view, it is quite demanding".

In addition, the choice for a shopping activity as the core activity of this digital intervention was considered as " ... meeting the necessities of this population." (Participant 1) and " ... important, crucial for [patients] daily-life, if they do not have someone to do the shopping for them, they have to do it themselves ... " (Participant 7).

The realism of the scenario was also identified as an asset that could be used to promote patients' motivation to comply with long and emotionally demanding rehabilitation programs.

Participant 7: "[regarding other CCTP] I think there is not an effort or an intent to be similar to the person's daily life. Here I notice that effort ( ... ) and that could be more motivating for the person who is doing the training".

#### 3.2.2. Transfer Capacity

NeuroVRehab.PT elicited a sense of presence in some participants; " ... I already knew that the milk would be closer to where eggs were, it is similar to other supermarkets where I go, I knew that ... even if some fruits are not displayed on the fruit exhibitor, they are right there, it is essentially like ... my experience in other [real] supermarkets." (Participant 1).

Participants were divided concerning NeuroVRehab.PT transfer capacity to patients' daily life. Four participants considered that the activities proposed on NeuroVRehab.PT are " ... more easily generalized than the paper-and-pencil exercises that we often do." (Participant 5) and "Once the person succeeds in the game, I think ... , I would say that it is easy to transfer to real life." (Participant 6). Other participants considered that the transfer of the trained skills could not be assumed only based on the similarities between the virtual and real-world environments. Finally, a third group of participants claimed that the transfer of trained skills is more likely to occur if the activity/exercise is meaningful within the patient's life context.

> Participant 2: "It has to make much sense [to the patient] to have any impact or transfer to real life. And even with this software, it is either something that meets what the previous life of the person was, and it has any meaning to him/her, or it ends up [just] being an interesting game ... ".

Finally, it was also pointed out that, despite being very realistic, our virtual supermarket is still a controlled environment (e.g., being the only customer, the absence of entropy caused by the presence of other buyers, people covering the products) and different from the supermarket frequented by the patient.

### 3.3. *Potential Barriers*

Among the potential negative psychological side effects that MCI patients might experience associated with the use of our platform, the one most referred to by the participants was frustration (verbalized by six participants), followed by stress ($n = 4$), fatigue ($n = 2$), anxiety ($n = 2$), and irritation ($n = 1$). Feelings of frustration were primarily associated with the process of learning how the platform works. Nonetheless, the participants considered that potential negative psychological side effects could be easily managed if a therapist is present and supports the patient's learning process by explaining game mechanics and controls and helping the patient cope with feelings of frustration.

> Participant 7: "I believe they [the patients] will have some doubts ( ... ) I had someone by my side to explain it to me, and they do not have it".
>
> Participant 3: "I think in some cases, some patients can easily start to get frustrated. And it is advisable not to continue. And I think there will be some situations like that, which is perfectly normal with this type of activity. Therefore, it is necessary to have resources [as therapists] ( ... ) to be you to finish the activity and help the patient to move on ... "

Nausea was also referred to ($n = 1$) as a potential negative side effect as a result of the temporary blurred vision associated with the process of going from one image (sphere) to another. No other physical adverse effects (e.g., falls, dizziness) were foreseen by the participants, although difficulties associated with ageing, such as low visual acuity, were referred to.

### 3.4. *Opportunities*

Throughout the experimental sections, the participants identified three other possible applications of NeuroVRehab.PT.

#### 3.4.1. Clinical and Non-Clinical Contexts

NeuroVRehab.PT was considered as having applicability in other clinical populations, such as Traumatic Brain Injury (TBI), stroke, and early-stage dementia patients. Some participants also suggested that the platform could be used as a means to increase technology literacy in healthy older adults.

#### 3.4.2. Friend Sourcing

Three participants reported they would like to see some degree of interaction between users. One of the suggestions was to provide patients with the possibility of sharing recipes and cooking tips with other NeuroVRehab.PT users (i.e., patients), thus creating a virtual community. The participants also stated that it would be interesting if the therapist could create shopping lists (participant 5) that reflect the patient's diet and/or food restrictions (participant 3). The fact that NeuroVRehab.PT is an online platform was identified by another participant as a way to promote family engagement, especially from younger people. "This (NeuroVRehab.PT) would be much more playful and ( ... ) maybe it could even be more interesting to attract family participation ( ... ) even for grandchildren, it would be much more interesting than sitting next to the grandmother, with a paper and pencil activity" (Participant 7).

#### 3.4.3. Other Environments

The possibility of exploring other IADL (e.g., finances, ATMs, housekeeping) as well as real-life scenarios (e.g., the supermarket where they usually go) was noted as being one of most significant opportunities that the design approach presented here could bring to the field of neurorehabilitation. Other proposed activities were to invite patients to cook the recipes available in the recipe game mode, explore public places, and train their capacity to use public transportation.

## 4. Discussion

The use of photo-realistic interactive virtual environments is a promising approach to develop accessible, cost-effective, and ecologically valid instruments for neurorehabilitation in VaMCI patients. The availability of digital instruments has gained even more prominence with the current global health conjecture due to the COVID-19 pandemic, where contact between health professionals and patients is restricted or drastically reduced. In this paper, we described the design and development process of a fully navigable and interactive virtual supermarket built from photos of a typical Portuguese supermarket—the NeuroVRehab.PT. Furthermore, health professionals with extensive clinical and research experience in neurodegenerative and age-related disorders assessed our platform and identified the advantages and challenges associated with its clinical use in VaMCI neurorehabilitation.

The participants considered NeuroVRehab.PT a remarkable improvement in the design of VEs for neurorehabilitation. The use of real-world supermarket photos as a core element of NeuroVRehab.PT resulted in a highly realistic and ecologically valid VE. In previous studies, the ecological validity of virtual supermarkets for assessment or training purposes was established through the relationships obtained between the participants' performance in the VE and in related measures of executive functions and everyday functional capacity [23,26,51,52]. However, in the present study the ecological validity of NeuroVRehab.PT was established based on the verisimilitude approach [53]. According to this approach, ecological validity can be established based on the degree to which the demands of an experimental task resemble the cognitive demands of that task in the real world [53,54]. In this regard, not only is NeuroVRehab.PT an accurate representation of a typical Portuguese supermarket (face validity), but it was also claimed by the participants that our platform looked like (and felt like) a real supermarket. This was most evident in the statements of participants 1 and 5, when they said that their experience with NeuroVRehab.PT was very similar to shopping in a real-world supermarket; that is, they experienced the same difficulties and resorted to the same problem-solving strategies as

they would in a real-world shopping activity. From this perspective, the design approach presented in this paper can also be applied to the development of instruments aiming to assess cognitive functioning, particularly executive functioning.

Moreover, our platform allowed the participants to interact and choose between grocery products that they are familiarized with and use in their daily life. This additional layer of customization (e.g., through the creation of personalized shopping lists that reflect real-life needs) enables coupling between therapeutic exercises and the patients' interests and routines, thus resulting in meaningful exercises with practical (real-life) applications [35]. In other words, NeuroVRehab.PT is therefore a flexible rehabilitation platform to accommodate patients' personal (e.g., food preferences), health (e.g., diet, food allergies and intolerances), cultural/religious (e.g., regional gastronomy), and socioeconomic status (e.g., branded vs. white label products).

Another layer of NeuroVRehab.PT aiming to promote patients' engagement is the use of gamification processes. Gamification (i.e., the use of game elements in non-game contexts) [55,56] has been widely used as a means to promote patients' adherence [57], self-esteem, satisfaction, and positive emotional experience [58] with healthcare interventions. In NeuroVRehab.PT, we implemented two types of game elements: numeric (e.g., points, scores) and visual (e.g., messages, three-star classification) feedback elements and narrative contexts. Although the study of the motivational influences of different game elements is still in its infancy, preliminary studies suggest that immediate feedback elements are associated with high adherence rates during the initial phases of contact with the platform [59,60]. On the other hand, the storyline in which the main action unfolds is thought to be a crucial feature for long-term adherence [60] (see reference [59] for a description of the rationale underlying the selection of this game element). Although the conclusions that can be drawn from a single moment of contact with our platform are limited, the participants' statements that they had fun with and enjoyed using our platform is indicative that the implementation of these game-elements was successful, at least to some degree.

From the semantic thematic analysis, two subthemes emerged regarding the rehabilitation potential of our platform: cognitive stimulation and transfer capacity. Health professionals considered that the activities proposed in NeuroVRehab.PT are feasible by VaMCI patients and target the cognitive functions recruited during a shopping activity (e.g., orientation, planning, decision making, working memory, attention, math abilities). Furthermore, the participants referred to the training provided by our platform as being more easily generalized to the patient's daily life when compared to other forms of cognitive stimulation, such as CCTP and Brain Training Games (BTG). Despite the undeniable social and economic impact of CCTP and BTG, the evidence regarding the efficacy of these programs is still scarce, with few studies showing an impact on other cognitive functions beyond those directly targeted by the cognitive training program, and even fewer studies showing an impact on behavioral outcomes [32,61–63].

It is noteworthy that the theoretical framework used in NeuroVRehab.PT highly contrasts with the one used in CCTP and BTG. While, in CCTP and BTG, individual exercises are developed to target isolated cognitive functions [64–66], in our platform we focused on developing a training exercise that aims to stimulate/train the adequate behavioral patterns/responses to perform one specific IADL successfully. Therefore, in NeuroVRehab.PT we privileged activity segmentation into its basic units (e.g., creating a shopping list, searching for products, checking the shopping) as a means to promote the patient's awareness of where and how errors occur, along with the availability of simple strategies that patients could apply when shopping in the real world (e.g., organizing the shopping list and checking it before leaving each supermarket section). Promoting patients' awareness, training practical strategies to overcome or avoid errors, and the periodical monitorization of action and goals are crucial steps in the Goal Management Training paradigm (GMT) [67]. The GMT has been used in the cognitive rehabilitation of patients with attention and executive deficits [67], including MCI patients, with positive results on quality of life [68], capacity to identify relevant occupational goals and efficient strategies, and the monitorization of task progression [69].

Nonetheless, not all the participants were sure about the transfer capacity of NeuroVRehab.PT. For instance, participant 3 stated that patients' predisposing characteristics (e.g., previous shopping experiences) rather than the VE characteristics would influence patient adherence and skill transfer. The perspective that different people need and want to (re)learn different things and do this in different ways, using different strategies, is an established fact in the neurorehabilitation field, and programs should be committed to identifying which activities patients perceive as relevant in the actual context of their life [70]. In other words, no matter how well a system is designed or optimized to perform a task, it needs to relate to their users and correspond to their expectations [71]. Shopping for groceries is still a gender-based established activity, at least among older Portuguese generations. This will negatively influence how comfortable some older adults will feel performing a task that they are not used to, or that they might consider as conflicting with his/her role in the family and the social system. Therefore, in future feasibility and efficacy digital health intervention studies, factors such as perceived usefulness, expectations regarding digital interventions, and the perceived social impact of resorting to mental health programs [72] should be taken into account when establishing the participant inclusion criteria.

Although NeuroVRehab.PT has been designed to be used independently by VaMCI patients, health professionals were in agreement regarding the importance of the presence of the therapist during the training sessions (at least, in the first sessions). The therapeutic bond established between the health professional and patient (i.e., therapeutic alliance) is a strong predictor of psychotherapy outcome [73], the decision to start treatment, and patient attrition [74–76]. Feelings of frustration triggered by successive experiences of failure are common among patients with cognitive impairments and, when not managed properly, can lead to feelings of confusion, anxiety, and dropouts [76]. In our study, the need for the therapist's presence was associated with two main roles: to support the learning process of how the platform works, and to help patients cope with failure and frustration. This finding is supported by an extensive body of literature that shows that learning can be fostered when guided by a more experienced agent [77].

Furthermore, we acknowledge that VaMCI patients may also experience other difficulties observed in healthy older adults, such as the fear of failure and peer judgment, anxiety about using computers, and a low assessment of their skills and capacity to learn new things [78]. Therefore, an intermediate phase of user testing with healthy older adults is being planned to analyze age-related usability issues, gender and social variable influences, and the system stability [79], which may compromise the use of NeuroVRehab.PT by VaMCI patients.

## 5. Conclusions

Taken together, our results show that the NeuroVRehab.PT is an engaging, ecologically valid neurorehabilitation digital platform for VaMCI patient neurorehabilitation. Although some interface components such as the navigation controls should be optimized to improve the patients' UX, health professionals considered this platform a significant step forward to the design of efficient and family-inclusive digital interventions for cognitive stimulation and IADL training. The present study also highlighted the impact that the perceived personal and social relevance of the training activities might have on patients' adherence and long-term use and, ultimately, the interventions' efficacy. Finally, our results are elucidative regarding the potential positive impact of the therapeutic bond between the health professional and patient on an intervention's outcomes, and so this should not be dismissed even in interventions supported mostly by digital resources.

**Supplementary Materials:** The following are available online at http://www.mdpi.com/2077-0383/9/12/3821/s1, Table S1. COREQ–COnsolidated criteria for REporting Qualitative research checklist, Doc S1. Ethical standards; Table S2. Shopping Behaviors Questionnaire in Older Adults descriptive data ($n$ = 110).

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