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Using game authoring platforms to develop screen-based simulated functional assessments in persons with executive dysfunction following traumatic brain injury

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ABSTRACT

The assessment of functional status is a critical component of clinical neuropsychological evaluations used for both diagnostic and therapeutic purposes in patients with cognitive brain disorders. There are, however, no widely adopted neuropsychological tests that are both ecologically valid and easily administered in daily clinical practice. This discrepancy is a roadblock to the widespread adoption of functional assessments. In this paper, we propose a novel approach using a serious game authoring platform (eAdventure) for creating screen-based simulated functional assessments. We created a naturalistic functional task that consisted of preparing a cup of tea (SBS-COT) and applied the assessment in a convenience sample of eight dyads of therapists/patients with mild executive dysfunction after traumatic brain injury. We had three main aims. First, we performed a comprehensive review of executive function assessment in activities of daily living. Second, we were interested in measuring the feasibility of this technology with respect to staffing, economic and technical requirements. Third, a serious game was administered to patients to study the feasibility of this technology in the clinical context (pre-screening test). In addition, quantitative (Technology Acceptance Model (TAM) questionnaires) and qualitative (semistructured interviews) evaluations were applied to obtain user input. Our results suggest that the staffing, economic and technical requirements of the SBS-COT are feasible. The outcomes of the pre-screening test provide evidence that this technology is useful in the functional assessment of patients with executive dysfunction. In relation to subjective data, the TAM questionnaire showed good user acceptability from a professional perspective. Interview analyses with professionals and patients showed positive experiences related to the use of the SBS-COT. Our work indicates that the use of these types of authoring platforms could have positive long-term implications for neuropsychological research, opening the door to more reproducible, cooperative and efficient research by allowing the facilitated production, reuse and sharing of neuropsychological assessment tools.

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1. Introduction

Neuropsychological evaluation can be defined as a method used to examine human brain function by studying its behavioral products [1]. This evaluation is achieved by combining and contrasting information from many sources (such as clinical interviews and medical histories) to diagnose and locate a neuropsychiatric illness. By means of both qualitative (e.g., approach to tasks and observed behavior) and quantitative (e.g., standardized and scaled) measures, a trained clinician can establish the patient's cognitive strengths and weaknesses in a variety of domains, including memory, attention, problem-solving, language skills and intellectual functioning [1].

However, in many relevant contexts, evaluating functional status is equally or even more important for diagnostic and therapeutic purposes than for cognitive measures by themselves. At this point, it is important to clarify that, to the extent possible in this work, we will use the framework given by the World Health Organization's International Classification of Impairments, Disabilities and Handicaps (ICIDH) [2] to define the meaning of "*cognitive*" and "*functional*" impairments. Cognitive impairment corresponds to a particular type of impairment in body function (usually resulting from structural or functional brain disease) assessed by previously standardized neuropsychological measures, whereas functional impairment refers to the impact of any disease or condition on daily living activities or social participation of the subject, without regards to its particular physiological causes. Although there can be a generative relationship among cognitive and functional impairments, it is possible to distinguish one from the other, as cognition and function belong to different domains of analysis and provide different information for clinical decision-making purposes.

For instance, establishing the diagnosis of dementia requires the simultaneous existence of both functional and cognitive impairment [3], whereas in mild cognitive impairment, the *lack* of functional impairment, rather than the cognitive impairment *per se*, is what distinguishes this condition from dementia. In fact, adequate functional assessment is essential since cognitive status is not always a good predictor of functional status [3,4].

Among the wide variety of mental abilities typically assessed in neuropsychological evaluation, the focus of the present work is on two closely related functional domains whose respective assessments are difficult to isolate in clinical practice: (1) executive function (EF) and (2) naturalistic actions. (1) EF, one of the most complex cognitive domains, is defined as those processes that underlie goal-directed behaviors [5–10]. Different methods of evaluation, from observational protocols to highly advanced technology, can be developed to assess EF. Due to the great complexity of cognitive impairments associated with EF and their repercussions in activities of daily living, an accurate and efficient assessment is of particular relevance. Nevertheless, the current literature demonstrates limitations in the assessment of EF (in Section 2.1 it will be reviewed). (2) Naturalistic actions correspond to previously learned behaviors in the service of everyday, simple tasks (e.g., tooth brushing) and extended activities (e.g., grooming), which require one to use objects and sequences of multiple steps to achieve nested goals [11,12]. According to Giovannetti et al. [12], naturalistic assessment has proven interesting for providing clues about the organization of complex, routine actions, including the conceptual knowledge base and the role of EFs and general resources in the generation of adaptive behavior. As the complexity of naturalistic actions increases, the involvement of executive control becomes increasingly integral, especially for controlling action execution, even in the case of some over-learned or automatic tasks [13].

The relationship between EF and naturalistic assessments is intimately interconnected with functional status because (1) these factors are predictors of autonomy loss (activities of daily living impairment), (2) impairments increase the risk of re-admission to health services when not properly diagnosed, and (3) naturalistic activity impairment and dysexecutive syndrome, by themselves, pose significant psychological, social and economic burdens to caregivers [4,8]. EF research has employed self and informant questionnaires, clinician rating scales, neuropsychological testing and naturalistic observation of subjects in everyday life or in simulated everyday tasks to predict everyday function [8]. Even though some everyday functional assessments have been developed, these instruments have limitations that restrict their adoption into clinical settings.

We have three main aims in this publication. First, we describe the state of the art in EF assessment in activities of daily living in the clinical field and the eAdventure game authoring platforms. Second, we develop a screen-based simulated naturalistic functional task (preparing a cup of tea) using the serious game development platform eAdventure to study the feasibility of technological requirements (staffing, economic and technical). Third, we study the feasibility of this real-life simulated task as a pre-screening test in a sample of patients with mild executive dysfunction (EDF) caused by traumatic brain injury. In addition, quantitative (Technology Acceptance Model (TAM) questionnaires) and qualitative (semistructured interviews) evaluations were applied to obtain the subjective experiences of the participants (therapists and patients).

2. Theoretical framework

The explanation of the theoretical framework will encompass two main topics. The first one will be focused on explaining the executive dysfunction and the methods of assessment (Section 2.1) and the second one on the eAdventure game authoring platforms (Section 2.2).

2.1. Executive dysfunction

The current conceptualization of brain function includes different cognitive dimensions, such as memory, attention, perception, language and EF. EF is one of the most complex cognitive domains in humans. Luria et al. [14] first proposed the essential role of EF in cognition and behavior in 1964. The first definition of EF was posed by Muriel Lezak, in 1982, as "those mental capacities necessary for formulating goals, planning how to achieve them, and carrying out the plans effectively" [15]. EF encompasses a wide range of cognitive processes and behavioral competencies, such as the ability to sustain attention, reasoning, problem-solving, resistance to interference, utilization of feedback, multi-tasking, planning, sequencing, cognitive flexibility, metacognition, and the capacity to address novelty [5,16], among others. As a consequence of the great diversity of cognitive processes that depend on EF, numerous activities of daily living are affected when this cognitive domain is altered. Some of the most relevant handicaps are related to establishing and maintaining appropriate social interactions, the ability to work or attend school, autonomy at home, and instrumental activities of daily living [13,17–21].

EDF is extremely common in neurological and neuropsychiatric pathologies with either severe or mild impairments, such as brain tumors [22], traumatic brain injury (TBI) [23], stroke [24], multiple sclerosis [25], Gilles de la Tourette syndrome [26], schizophrenia [27], obsessive-compulsive disorder [28], and neurological patients with frontal pathology [29–33]. In addition, EDF is very important in age-associated brain diseases such as vascular cognitive impairment, frontotemporal dementia (FTD), vascular dementia and parkinsonian disorders [34–40].

In relation to patients with TBI, which are the sample population of this study, EDF is among the most common cognitive impairments, even in cases of mild TBI [41]. The main difficulties related to EDF in these patients include deficits in planning, reasoning, mental flexibility, self-monitoring, self-correction, perseveration, purposeful behavior, and higher error rates on everyday activities [13,41]. In these patients, EDF produces impairments in many everyday living activities, such as study, employment, recreational activities, and social relationships, as well as reduced personal autonomy [42–48]. Although the evaluation of patients with severe impairment of EDF is straightforward, the evaluation of mild impairment is challenging. As Mesulam states, good results are frequently obtained by assessing patients who show cognitive and behavioral handicaps in everyday life using traditional neuropsychological tests [49].

EDF has been reported to be one of the determinants of psychosocial difficulties and one of the main determinants of functional impairment in patients with brain disorders [39,50]. Therefore, the evaluation of EDF is necessary for patients with brain disorders across a broad range of ages (from children to older adults) [5,51].

2.1.1. Ecological validity and evaluation of everyday function

Due to the great complexity of the cognitive impairments associated with EDF and the repercussions of EDF in activities of daily living, the accurate and efficient assessment of EDF is of particular relevance. However, the current literature reveals that the assessment of EDF is subject to limitations [52–54]. Conventional tests lack ecological validity [5,53,55] and cannot be used to understand the types of difficulties patients confront in everyday life scenarios. Consequently, there is a consensus in the scientific community that more ecological assessment tools are needed to efficiently predict an individual's daily functioning [9].

Ecological validity is defined as the capacity of a given test to predict a patient's everyday functional status based on his or her performance in the testing environment [4,8]. However, some studies have identified several problems that restrict the ecological validity of traditional assessments, particularly in the case of the so-called "*paper-and-pencil* tests" (traditional tabletop batteries performed in the clinician's office) [3,4]. Studies carried out so far have generally indicated that the relationship between *paper-and-pencil* measures of EF and everyday functioning is poor [4]. For instance, many patients with EDF in everyday life show normal or above-average performance on traditional paper-and-pencil tests [56,57]. Thus, paper-and-pencil tests are not adequate assessment batteries (e.g., Wisconsin Card Sorting Test, Stroop Task, and Trail Making Test) to measure EF [58] because the cognitive functions required to answer successfully are not based on the performance of activities of daily living [58].

In response to the deficiencies of conventional tests for assessing EF, instruments have been developed to assess EF in *real-life* settings, thus increasing their ecological validity [59]. These tests assess cognitive impairment, the impact of these problems in daily life, and the ability of the person to have an independent life [5,60]. Some examples of these tests with ecological validity are the Rivermead Behavioral Memory Test [61], the Behavioral Assessment of the Dysexecutive Syndrome –BADS [62], Test of Everyday Attention [63], and the Multiple Errands Test (MET) [9,56,57,64].

Another strategy to increase ecological validity in the clinical field is naturalistic assessment, which is usually performed in specially prepared facilities designed to resemble the real-life settings where naturalistic actions are usually performed (i.e., an assessment kitchen), thus providing (generally) adequate ecological validity. Although these types of *real-life* functional evaluations provide more accurate estimates of the patient's deficits compared with those from tests carried out within laboratory conditions [9,59], they present some limitations that have prevented their adoption in neuropsychological evaluation. One of the most significant limitations is the fact that even the simplified versions are time consuming and not always feasible in typical clinical settings [13,21]. Therefore, these evaluations have to be adapted and validated in each center due to the need for proper facilities and specialized clinical personnel to evaluate (by direct observation) the subject's performance. These disadvantages also make it difficult to attain standardized measures.

2.1.2. Neuropsychological assessment in simulated environments

Computers have been used in neuropsychology with increasing frequency for many years because of the many advantages that go beyond administration simplicity and data collection [65–67]. As Woo [65] and Collerton et al. [68] have shown, computers can improve neuropsychological assessment in several ways:

(1) Computers provide precise measurements at the millisecond level, providing a more sensitive measure of cognitive impairment, especially in high-functioning older adults and in patients with milder levels of cognitive deficit.
(2) Many batteries take less than an hour to administer, whereas many standard neuropsychological evaluations require more than four hours.
(3) The presentation of items in some batteries can be adapted to patient performance levels to avoid floor effects (the test restricts how low a patient's scores can be) and ceiling effects (the test restricts how high scores can be).
(4) Computer tests have increased standardization because they are administered the same way every time.
(5) Scoring is automatic, meaning the results are available immediately, and human scoring error is reduced.
(6) Examiner effects are reduced, which is an important advantage because clinicians may differ in how they administer standard tests, which in turn may impact patients' responses.
(7) The batteries are easily transported (portability).
(8) Multiple tasks can be made available on a single computer.

However, current computer-based assessments present some relevant limitations such as the limited assessment of each cognitive domain (i.e., one measure to assess a particular cognitive domain) and a participant's possible lack of familiarity with computers [65]. Moreover, the most frequently used computer-based measures for clinical evaluation (e.g., proprietary neuropsychological batteries implemented as multi-platform software or embedded systems) are designed to evaluate cognitive constructs and/or operations, but not functional status, which is the focus of the present work [9].

With the aim of overcoming the problems of ecological validity in neuropsychological assessment, many authors employed Information and Communication Technologies (ICT), particularly virtual reality (VR)-based technology, as a tool to design neuropsychological tests simulating real-life situations and with potentially higher ecological validity [69,70].

The current literature supports the utility of VR in the assessment of different cognitive domains [71–73], including EF. For instance, McGeorge et al. [74] developed a virtual environment to specifically assess planning deficits in patients with EDF. The task consists of participants completing a list of errands on three floors of a department of psychology. Lo Priore et al. [75] designed an immersive virtual reality-based tool named V-STORE, which allows participants to explore an internal goods store in which pieces of fruit must be placed into baskets. Marié et al. [76] and

Klinger et al. [77] designed the Virtual Action Planning-Supermarket (VAP-S). It simulates a supermarket with multiple aisles in which food and items for daily use are displayed. The task consists of filling a virtual cart with different items from a pre-established list and then paying for the items at the checkout counter. Rand et al. [78] developed a functional virtual environment named the Virtual Mall (VMall), which is a large supermarket in which participants engage in a simple shopping task. Further development of this tool resulted in a more complex shopping task named the Virtual Multi Errands Test (VMET) [59]. Zhang et al. [79] designed a kitchen scenario in which participants have to prepare a soup in a 30-step process.

However, the use of VR in the field of cognition remains in the experimental phase [80] and continues to present several limitations. For example, only a handful of studies have established the ecological and construct validity of simulated environments [81]. VR might produce motion sickness (discomfort, nausea, vomiting, headache, fatigue, etc.) because of its "inability to simulate the motion environment accurately enough" [82]. Moreover, there are different studies that show that the use of head-mounted displays prevents participants (healthy and cognitively impaired) from completing the assessment [83,84]. In addition, VR shows three additional limitations that are directly related to this publication. First, the design and development of VR is a high-cost technology that requires regular maintenance [70]. Second, the participation of non-VR experts (such as neuropsychologists and clinicians) in the development process is usually hindered by technical constraints. Third, some VR systems have specific requirements (i.e., lighting and large space, a green backdrop) and technical challenges that hamper their adoption in the clinical field [85,86]. These limitations of VR explain the scarce application of VR in clinical settings.

Serious games, another method of ICT defined as digital applications specialized for purposes other than diversion (e.g., training and educating, communicating, rehabilitation) [87], have not been used for neuropsychological assessments. The applications of serious games have been restricted to rehabilitation for enhancing cognitive and physical function in different disorders with EDF, such as Alzheimer's disease, mild cognitive impairment [88–96] and treatment of mental health disorders [97].

The availability of free software for serious games, such as eAdventure, represents an opportunity for the use of serious games in the neuropsychological assessment of activities of daily living.

2.2. eAdventure game authoring platforms

2.2.1. The potential of adventure game authoring platforms in the development of simulated naturalistic assessments

Screen-based simulations are well-known computer-based tools, especially in education, for creating procedural simulations and other teaching aids, although they have not been used extensively in neuropsychological assessment. Notably, the set of game states (i.e., possible game situations) and the interactions that execute the game changes are usually script-controlled, as opposed to more complex, model-driven simulations [98]. Among the different types of screen-based simulations, adventure games are considered a good tool for teaching concepts due to their narrative structure [99]. Taking advantage of the strengths of adventure games, the game-like simulations allow for an accurate reproduction of procedures in real environments (closely related to the types of tasks for evaluating functional status).

In the following paragraphs, we analyze why adventure and game-like simulations are adequate game genres for the development of everyday functional assessments and discuss which authoring methods improve the role of neuropsychologists and other clinical personnel in the development of these types of assessments.

2.2.2. The relationship between adventure and game-like simulations and naturalistic assessments

The adventure game genre is focused on the player, who assumes the role of the protagonist in an interactive story driven by exploration and puzzle-solving activities instead of physical challenges [100]. The main features of adventures games are as follows:

(1) The player must assume the role of an avatar that is part of an environment.
(2) The player can explore and navigate more or less freely inside this environment.
(3) The player can talk to other characters and collect or manipulate objects, interacting with them in different ways.
(4) The narrative nature gives context to the task or problem to be solved by the player.
(5) The player has the necessity to create, evaluate and decide among alternative strategies to solve a given problem.

Considering the procedure and real environment reproduction features, the game-like simulations fit with naturalistic activities, especially the MET-like ones. Although using simulations of this type does not involve psychomotor skills, game-like simulations allow for the evaluation of some types of everyday functional impairments, especially those more likely to be caused by impairment in EFs, because they do not directly involve psychomotricity (which, in contrast, would be essential in other types of cognitive impairments, such as apraxia syndromes).

2.2.3. The video game (and game-like simulation) development process is complex and expensive

Video game (and game-like simulation) development is a complex and expensive process. Currently, there are many different approaches, ranging from general purpose programming languages (e.g., Oracle Java, C++, etc.) to specific game development languages, frameworks or game engines. The use of these technologies requires high technical skill, implying the involvement of programmers and software engineers. In addition to the technical staff, the game development process requires professionals from other different fields, including artists, scriptwriters, and others, to work together to ensure the quality of the final product. Furthermore, for those games developed for certain specific fields, experts in those areas are needed to contribute the related expertise. Each game should be considered as a full and complex software development project that usually implies sophisticated graphics, animations and a high level of interaction with the user. All of these characteristics make it difficult for non-technical personnel to create games or modify them for specific purposes. This fact becomes even more critical in the clinical domain, where professionals typically lack advanced technical knowledge and are subject to budget/time constraints.

Game development platforms have emerged as a way to simplify game development, offering a full range of possibilities to fit the game development to different budgets and technical constraints. Although some of these development platforms provide powerful and flexible solutions that reduce the implementation effort (e.g., game toolkits such as Unity; http://unity3d.com/), they still require a significant amount of both technical and platform-specific knowledge. Moreover, games produced in those environments may have technical requirements that are far too advanced to be executed and deployed using standard equipment, requiring top-tier computers or high-speed Internet connections to execute the games.

To simplify delivery and development, some game authoring platforms (e.g., GameSalad http://gamesalad.com/ and Game Maker http://www.yoyogames.com/make/ among others) provide easy-to-use environments by reducing flexibility in the game development. These platforms are focused on the development of a specific game genre with a set of configurable features, reducing the flexibility of the process. However, contrary to previous approaches, these authoring tools do not provide any mechanism for extracting information from the user's sequence of interactions for assessment purposes.

2.2.4. The eAdventure game authoring platform can simplify the development of simulated environments for naturalistic assessments

eAdventure is a game authoring platform created specifically for easing the development of adventure games and *point-and-click* simulations for people without technical or programming backgrounds [101]. This platform includes an easy to-use editor to define the game elements and the script and a game engine to run the developed games. Moreover, the platform includes specific educational features such as assessment tasks and in-game adaptation mechanisms [102]. With regards to art assets, real environments can be recreated at a low cost using photos and videos instead of costly animations. Regarding deployment, games can be packaged in several formats, allowing the execution of games in many different platforms as stand-alone or web environments. The possibility of modifying previously created game assessments allows not only the improvement of these games by obtaining user feedback but also adaptation of the assessments to specific environments and user needs.

On these grounds, many of the challenges of developing computer-based naturalistic assessments can be addressed using game authoring platforms. In regards to the scope of this work, the adventure *point-and-click* games created in eAdventure offer the required flexibility for creating interactive evaluation environments, and the built-in evaluation features allow the implementation of automated assessment of a subject's performance while maintaining reasonably low development costs. Performance aspects that can be assessed include (1) commission and omission errors, (2) sequencing errors, (3) perseverative errors, and (4) execution timing. Moreover, eAdventure allows the deployment of the assessments using Android tablets; this enables testing on computerized touch screens, which can be easier to learn to operate and more intuitive than other interfaces [67].

Even though these game development platforms, and specifically eAdventure, have been used successfully in (medical) education [103], to our knowledge, there have been no previous attempts to use this type of technology in neuropsychological assessment. This approach would allow clinical researchers with little or no programming background collaborating with programmers to develop or adapt previously created functional assessments. These assessments could then be freely shared, allowing collaborative testing and refining by a community of researchers or practitioners [104].

3. Material and methods

To test the feasibility of our approach from the technical, economic and staffing points of view, we developed a case study following a specific game development methodology with a specially made screen-based simulated naturalistic task that consisted of preparing a cup of tea, which we will call SBS-COT.

First, we will explain the development process of the serious game, for which the eAdventure game development and its implementation in a specific activity of daily living will be described. In this section, we will address the feasibility of this technology with respect to the staffing, economic and technical requirements. Second, we will present the protocol of administration of the SBS-COT in the study sample (health professionals and patients with TBI). This section will address the feasibility of this new assessment tool in the clinical setting.

3.1. Development of the serious game

3.1.1. Applying the eAdventure game development methodology

The game development process required the active collaboration of game writers, content experts, programmers and artists. In this work, we follow a modified eAdventure game development methodology [105], which describes a set of procedures and phases to follow using the eAdventure platform, allowing multidisciplinary teams to develop educational video games and game-based simulations. This methodology follows a document-based approach where content experts and game writers work together with programmers and artists using documents (e.g., game scripts) for describing the game.

In summary, the game script is used to implement the gathered ideas using a graphic user interface (GUI) based on the game development tool in which abstraction is high, thus allowing its use by non-computer programming experts (such as clinicians) at the expense of expressive power. Consequently, the game development tool must be maintained and extended for the specific needs of the simulated functional assessment at hand by working at the lower level of abstraction provided by general purpose computer languages by computer programming experts.

This approach is necessary because current game development tools were originally developed for different aims. In-game-based assessments, we usually use environments and modes of interaction that are abstractions from reality (for instance, it is common in games that if you grab or use an item, the item appears or disappears from the screen and is stored in some form of abstract environment called the inventory, which does not need to have an explicit physical form in the context of the game). However, in the case of naturalistic tasks, it is necessary to simulate the characteristics of familiar, physical objects and methods, which necessitates the development of different solutions to the problem of using objects. In a paradigmatic example during our development process, the inventory function was ultimately useless, and thus the programmers had to modify the eAdventure editor to allow items to remain on-screen even if they were used by the user. During their work at the high level of abstraction provided by the editor, clinicians should note these limitations and communicate them effectively to the computer programmers to modify the abstraction to a lower level.

The involvement of the programmers (AB, BG, CB) was also important at the phase of script development because their knowledge of the low-level inner workings of the game development platform allowed them to identify the feasibility of implementing some interaction methods implied by the script. If a method was not practical from a software and hardware perspective, the programmers proposed other alternatives for consideration by the neuropsychologists (JN, ART, MG). We believe that this way of working allowed the experts from these two different areas to speak a common language that facilitated development.

Such collaboration was possible because the eAdventure platform facilitates collaborative work between domain and game experts [106], thus allowing a greater balance of tasks between clinicians and programmers. In contrast to the development of a VR system, this platform encourages a development process closer to the experience of clinical experts, with each one assuming a specific role in the tasks [106]. Thus, the domain experts provide explicit and tacit knowledge of the neuropsychological assessment, and the computer programmers contribute to the process with their expertise in low-level video game development.

The original eAdventure methodology includes some guidelines that help the script creation process. We found that the first consideration of the script development team should be the structure of the neuropsychological assessments. The basic structure of a video game or simulation is very similar to that of a script used in a play. Accordingly, the game writers (in our case, the neuropsychologists who designed the tasks) must define the following parameters: (1) the scenes where the action will occur; (2) the objects that will appear in each scene; (3) the list of the objects with which the player (subject to be assessed) will be able to interact; and (4) other characters that will be involved and the content of their conversations with the player. All of these elements can be easily included with the eAdventure editor (left part of Fig. 1).

We chose the "*first-person*" gaming approach instead of the *third-person* approach for the following two reasons: (1) usually, *first-person* design is more suitable for the creation of "game-based simulations" (i.e., games that simulate as realistically as possible the actual environment where a specific procedure is carried out) and (2) *first-person* simulations may increase the level of *representativeness* of the task (i.e., the extent to which a clinical test corresponds in form and context to a situation encountered outside the laboratory [9]) when compared to the *third-person approach*. Therefore, in our two examples, users do not see an avatar or part of themselves inside the screen as if they were *directly* interacting with objects within the scenario.

Another aspect we took into account in the design stages was how to explain the rules and goals of the task as well as whether to provide feedback to the users during the simulation. In eAdventure, this can be done by talking with characters or using videos or slides. Moreover, in our case study, we used videos to give instructions by auditory and visual means and slides or videos in the first and second cases, respectively, to show the user how the real system responded to the actions performed.

For the development of the functional assessments presented below, we followed the steps proposed in the eAdventure methodology [105] (these steps are summarized in Table 1):

- **Basic training in the possibilities of the eAdventure platform.** It is worth noting that the team of neuropsychologists (JN, ART, MG) was able to use eAdventure on their own after receiving little training on the platform (less than 18 training hours) using the web tutorials and user manual (available at http://e-adventure.e-ucm.es) along with posting questions in the community technical forum.
- **Creation of an initial version of the script.** A team of neuropsychologists (JN, ART, MG) and a computer programmer (AB) defined (with a custom-made mug of tea making script) (1) how the simulated environment should look; (2) what the interactive elements were; (3) the ways in which

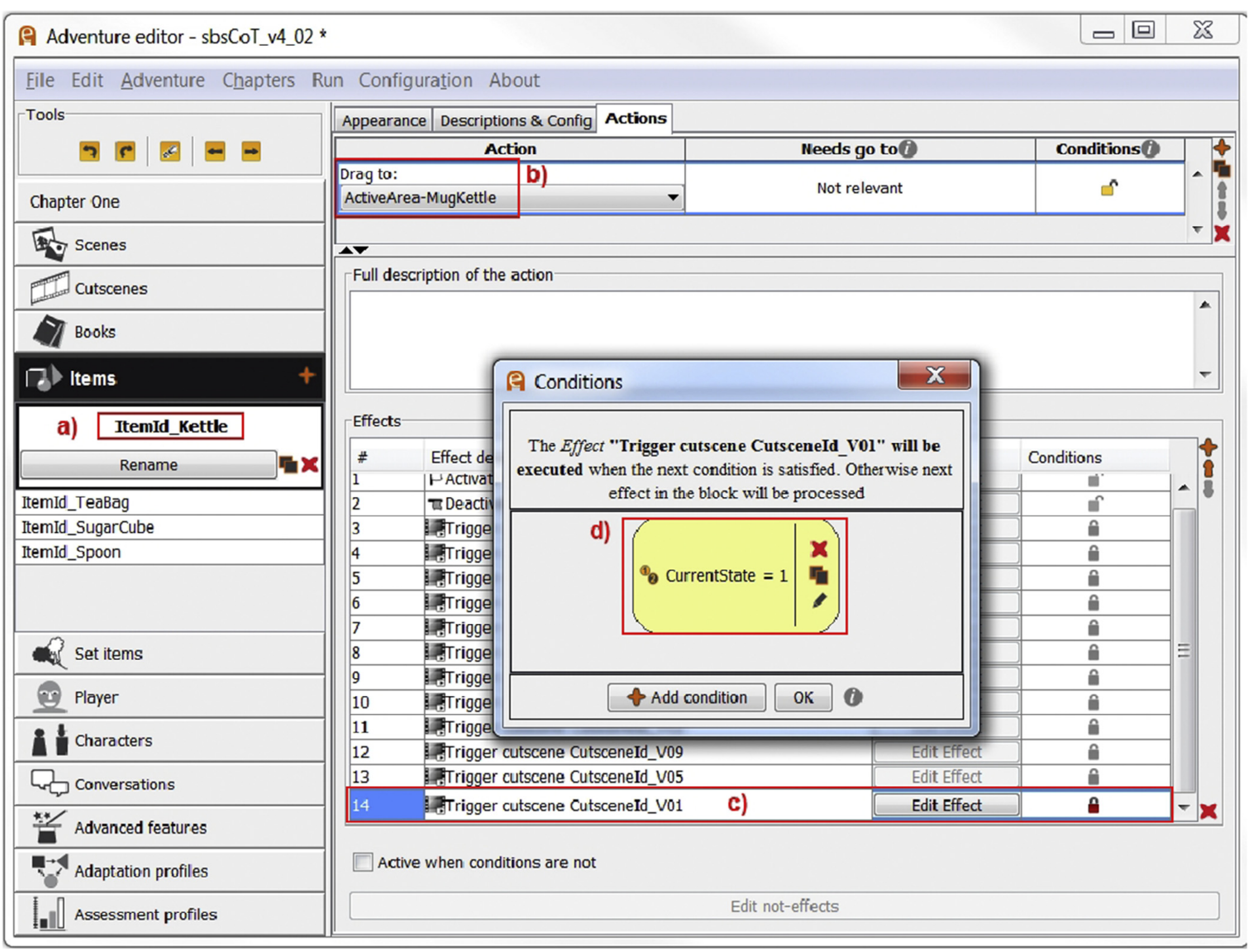

Fig. 1. The eAdventure editor for adding the behavior to the interactions with certain objects.

Table 1
Estimation of the development costs of the SBS-COT if produced by a third party.

Concept	Person-hours	Role(s)[a]	Estimated cost/person-hour ($)[b]	Estimated cost ($)
Conception of the storyboard	10	NP, CP	52	520
Creation of the art assets	5	P, CP, NP	21	105
Implementation of the simulation	16	CP, NP	41	656
Deployment, testing and improvement	18	CP, NP	30	540
Total	49			1,821

[a] The roles involved include CP, computer programmer; NP, neuropsychologist; P, photographer.
[b] Estimated cost per person-hour was gathered from the US Bureau of Labor Statistics and rounded [38]. When more than one role was involved, the average was used.

the user could interact with each of the items, and (4) the outcome of these interactions. It was also necessary to define which interactions were to be recorded to obtain meaningful functional or cognitive performance indicators.

- **Creation of the mockup game.**
We followed a rapid prototyping methodology that has been successfully applied in other games developed with eAdventure [107]. The purpose of developing a mockup game is to create an initial version with non-final resources quickly to validate the script and allow further refining and improvement of the script if the mockup does not cover the requirements. The professionals who developed this step were a photographer, a neuropsychologist and a computer programmer.
- **Modifications of the game development tools to meet the specific needs of the game.**
In collaboration with the authors of the eAdventure platform (AB, BG), new features were added to meet specific requirements of the naturalistic assessment simulations. These improvements were related to visual aspects of the games, such as changing the appearance of the objects when they are grabbed to better suit the real response of the represented elements. The main professionals who developed this step were a computer programmer (AB) and a neuropsychologist (JN).
- **Iterative process.**
This stage involved the following sub-steps, which were performed by a computer programmer and a neuropsychologist. Specific development details about this iterative process are included in Section 3.2:
  1. Improvements in the game script.
  2. Review of the neuropsychological features, including the type of cognitive functions and the goals of the task and relevant behavioral indicators to assess user performance.
  3. Creation and improvement of the art assets. This step implies obtaining the visual material (i.e., photos of each or some states represented in the graph and videos of the relevant interactions). Usually, is necessary to undergo minimum processing of the images obtained to improve the visual appearance.
  4. Implementation of the game script in the development tools (i.e., eAdventure game editor).
     1. Testing with final users (preliminary results in Section 4).

3.1.2. Case study: Implementation of the simulated making of a cup of tea (SBS-COT)

To explore a subject's script-execution capacity and to rule-out the possibility of user-computer interaction issues, we developed a pilot simulation for preparing a cup of tea (a naturalistic task or activity of daily living) (Fig. 2). We used a single scenario in which the objects and the interactions among the objects were performed.

These actions are controlled by the game state (i.e., eAdventure variables and system conditions), and thus each action is executed taking into account the previous actions performed in the simulation. All of these processes were easily completed within the eAdventure graphical environment without any programming.

For the pre-screening test, we choose preparing a cup of tea (an ability directly related to EFs and the performance of instrumental activities of daily living) because, at this stage, we needed a simple, universal task (non-culture-dependent that was similar to other non-simulated naturalistic tests common in specialized settings but easy to understand, relevant, and including a limited number of assets. This task allows for the assessment of different components of EF that are commonly impaired in patients with TBI, such as sequencing, mental flexibility, purposeful behavior and self-correction, and allows for the detection of the presence of perseverations and error rates.

Because the team of neuropsychologists had better knowledge of the eAdventure platform and worked jointly with the programmer, the development time was reduced, and the final game included more sophisticated and useful interactions.

The simulated environment consisted of a table, a kettle filled with boiled water, one sugar cube, one tea bag and an empty cup. In the simulation, the subject can interact with the presented items using a touch screen. This step of the procedure is performed by combining the interactive objects in the correct order. For instance, to fill the empty cup with boiled water, the user needs to drag and position the kettle correctly with respect to the cup to fill it.

To recreate the characteristics of typical naturalistic tests, such as the lack of externally imposed plans of action or structure, which can reduce task sensitivity to executive deficits, the simulation does not give any feedback regarding the level of adequacy of the behavior. However, it has built-in tools that allow the performance of a hidden assessment, which are available to the experimenter when the task is over. In this case, the outcomes of these interactions were as follows:

(1) Whether the items are used (commission or omission errors).
(2) The time and sequence in which they are used (sequencing and timing performance).
(3) The number of failed drag-and-drop attempts (execution or perseveration depending on the target object).

The simulation was created as a photorealistic, drag-and-drop environment recreating a surface where the SBS-COT setup is displayed according to the description described above. Because the simulation was generated from real photographs, it attained a high level of realism without the need to design expensive 3D environments. The combination of photographs and easy-to-use authoring tools allowed us to develop this simulated version of the task without hiring other personnel (such as programmers or photographers). Once a fully functional prototype was available, it was possible to estimate the total cost of development, taking into account the estimated costs per person-hour (gathered from the

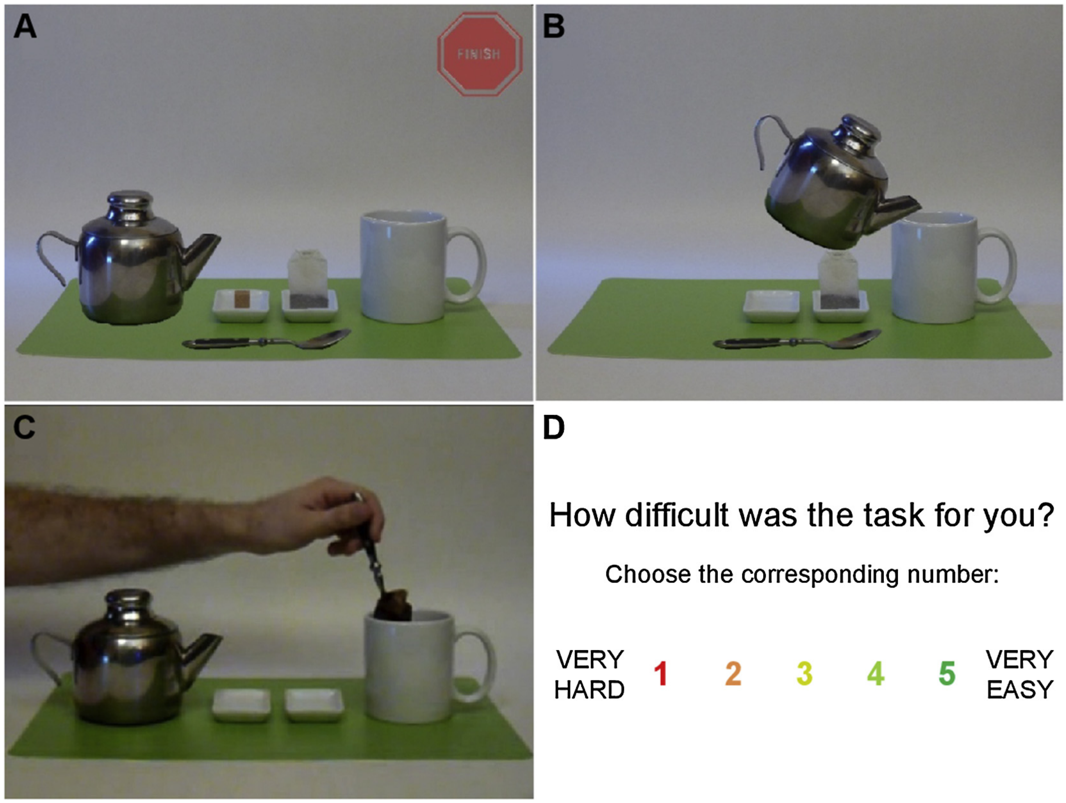

Fig. 2. The SBS-COT. a) Initial situation. b) Interaction of adding water to the cup. c) Video triggered when the user tries to remove the tea with the spoon. d) Final question.

US Bureau of Labor Statistics [94]) and following a procedure described elsewhere [89].

3.2. Administration of the neuropsychological tool in clinical practice

To examine user acceptance and experiences with the SBS-COT, a field trial was performed in real clinical evaluation settings.

3.2.1. Participants

The study sample consisted of a convenience sample of seven dyads of neuropsychologists/patients and one dyad containing an occupational therapist/patient who met the following criteria: (1) the clinician was an acting neuropsychologist or occupational therapist; (2) the professional performed neuropsychological and activities of daily living evaluations on a regular basis and had demonstrated knowledge in the use of one or more standard neuropsychological screening tools and, at least, one or more daily living activities assessment questionnaires. The inclusion criteria for patients were the presence of TBI with a minimum of six months from the onset (to ensure the stability of the cognitive impairments), as well as the diagnosis of mild EDF. The exclusion criteria were patients with communicative problems (e.g., comprehensive or expressive aphasia) because we needed to collect their subjective experiences through an interview. The diagnosis of EDF was made by each therapist applying his/her own assessment method (clinical interview, approach to tasks and observed behavior, standardized questionnaire). Informed consent was provided by the clinical professional and the patient chosen by him/her to participate in the trial.

3.2.2. Procedure

One or two of the authors met with the neuropsychologist the week before the SBS-COT evaluation to inform the professional about the study objectives and provide training in the use of the SBS-COT. On the day of the clinical evaluation chosen by the professional, one of the clinical researchers (a neuropsychologist or physician) (ART, JN), explained the nature of the trial to the patient and asked him or her for their voluntary participation (15 or 30 min before the time scheduled for the cognitive evaluation). The SBS-COT was applied at the end of the session and was administered by each professional volunteer without assistance from the authors. At the end of the session, the same clinical researcher conducted an interview based on direct and succinct open-ended questions regarding the participant's impressions and experiences of using the SBS-COT. Once the interview was completed, a similar set of open-ended questions was made available to the therapists. In addition, a self-report questionnaire [95] was applied for further statistical analysis. All interviews were audio-recorded for later study.

3.2.3. Measures of interest

Our primary measures of interests were twofold. First, we were interested in measuring the feasibility of this approach from the following three perspectives: (1) the technical perspective, by evaluating the soundness of the existing educational-game development methodology when applied to the neuropsychological field; (2) the staffing requirement perspective, by testing whether this type of simulation could be designed by clinical personnel without support from professional programmers or photographers in this prescreening phase; and (3) the cost perspective, regarding an estimation of the overall development cost. To obtain an estimate of the total cost of development, all professionals involved in the development process were asked to register the total amount of time they invested in the process. An estimate of the development costs was obtained by taking into account the estimated costs per person-hour [108] and following a procedure described elsewhere [103].

Second, we were interested in two different measures related directly to the neuropsychological setting. (1) To administer the video game to people with mild EDF to obtain quantitative outcomes about their performance (pre-screening test), the game included a hidden assessment that registered the time (relative to the moment the patient pressed the start button) required to execute the main actions of the game and their sequencing. These actions were a. pouring water from the kettle into the cup; b. placing sugar inside the cup; c. placing the tea bag inside the cup; and d. stirring the tea. This pre-report was displayed after the end of the game for interpretation by the investigators and enabled the detection of commission, omission and perseverative errors. These outcomes were visualized and interpreted by the neuropsychologist who administered the neuropsychological tool. With these data, he/she was able to detect the cognitive impairments related to the EDF variables of this study (sequencing, perseveration, mental flexibility, purposeful behavior, self-correction, and error rates). (2) To establish the subjective technology acceptance measures, qualitative and quantitative accounts of participant impressions about the SBS-COT and factors potentially affecting its usage and potential adoption were collected. The self-reported quantitative measure of user acceptability was obtained using a validated scale named the Technology Acceptance Model (TAM) [109] from a professional's perspective. The TAM states that the main variables that explain usage behavior are Perceived Usefulness (PU) and Perceived Ease of Use (PEOU). The TAM consists of twelve questions, six of which measure PU (and the others measure PEOU). We used a five-point Likert scale questionnaire ((1) strongly agree to (5) strongly disagree), and then scaled the data to the seven-point Likert scale used for the original TAM. In relation to the qualitative data, and with the aim of identifying themes relating to application usage and behavioral effects/experiences of using the SBS-COT, we interviewed both the professionals and the patients. In interviews with professionals, we focused on the following three questions: (1) What do you think about the task? (2) What do you think about the design of the task? (3) Would you change or aggregate anything to the task? In patient interviews, the following four questions were posed: (1) How did you feel when you were developing the task? (2) Was the task easy or difficult to make? (3) What do you think about the instructions? (4) Do you think that the instructions were compressible? After the interviews were conducted, a thematic analysis was applied [110] to extract the experiential data.

3.2.4. Ethics and human subjects

All of the participants signed an informed consent form prior to inclusion in the study. This study was approved by the Ethical and Scientific Committee of the *Servicio de Salud Metropolitano Oriente*, Santiago, Chile.

4. Results

The results section is grouped into two main outcomes. The first outcome describes the feasibility of this technology with respect to the staffing, economic and technical requirements, and the second describes the feasibility of the neuropsychological tool in the clinical context.

4.1. Development of the SBS-COT

We estimated that the development of the SBS-COT required three different professionals (computer programmer, neuropsychologist, and photographer). These professionals needed a total of 49 h to finish the SBS-COT, which cost approximately US $1821, taking into account the cost/person-hour (see Table 1).

4.2. Clinical assessment

This subsection discusses two different outcomes. The first outcome is related to the feasibility of the SBS-COT as a pre-screening test of EDF, and the second describes the acceptability and usefulness of the neuropsychological tool for therapists and patients.

4.2.1. Quantitative assessment

The outcomes in the pre-screening test showed that the patients did not have any failures performing the task of making a cup of tea (commission, omission or perseverative errors). All patients performed the timing and sequencing of the task correctly, and there was not any perseveration in completing the task.

Descriptive statistics indicated that the professionals perceived the SBS-COT as easy to use (mean = 2.28, sd = 0.86) with a high degree of perceptive usefulness (mean = 2.63, sd = 0.44). In addition, we compared the average scores of PEOU and PU with a paired sample *t*-test, and the results were not significantly different ($p > 0.005$).

4.2.2. Qualitative assessment

After the application of the thematic analysis, several subjective experiences emerged from the professional and patient viewpoints as related to the user acceptability of the SBS-COT.

4.2.2.1. Professional point-of-view. Four different themes related to user acceptability were found: (1) Ease of use, (2) Ecological validity, (3) Script complexity, and (4) Interface. Each category is described as follows:

Ease of Use: All professionals reported that the SBS-COT was easy to use (see Table 2 Theme 1 extract 1).

Ecological validity: Two subjects reported that the assessment tool was ecological, which made it useful (see Table 2 theme 2 extract 2 and 3).

Script complexity: Three subjects reported that the task was too easy, and, therefore, it presented a "ceiling effect" (see Table 2 Theme 3 extract 4). One subject reported that the script objectives and the steps necessary to accomplish the objective of the task were adequate (See Table 2 theme 3 extract 5).

Interface: Six subjects mentioned aspects and issues in relation to the task design. Four of them reported that the task did not present adequate "flow", both in the animation transitions between scenes or game states and in the interactions with the elements presented on the screen, which reduced the realism of the simulated environment (see Table 2 theme 4 extract 6). However, two subjects reported that the interface was adequate, easy for the patient to use and easy to understand given the audible instructions provided (see Table 2 theme 4 extract 7). Finally, three subjects appreciated the use of photography of frequently used objects as a central design feature of the SBS-COT (see Table 2 theme 4 extract 8).

4.2.2.2. Patient point-of-view. Two different themes emerged following patient interviews:

Ease to use: All patients (eight) reported that the task was easy to accomplish (see Table 2 theme 5 extract 9 and 10).

Overlearning: Four patients explicitly reported the relationship between the familiarity with the task at hand and the ease of accomplishing the required goals (see Table 2 theme 6 extract 11 and 12).

5. Discussion

This paper describes very early exploratory work testing the potential of open game authoring platforms in creating shareable,

Table 2
This table shows some relevant subjective experiences coming from neuropsychologists and patients.

Theme N°1: Ease to use (Neuropsychologists)	Theme N°4: Interface (Neuropsychologists)
Extract N°1 "Simple. It is very simple and well explained." "It seems to me very appropriate (design) because it is simple. It does not have so many distractions, and it is precise. It uses objects that are quite familiar, which people usually know and use. Maybe it makes it easier to be familiarized with them." "I think it is well designed, and it is pleasant to the patient."	Extract N°6 "What would I add? Ehhh, I do not know, maybe there is a potential issue with the lady who handles the cup. The action of moving her hand while moving the cup is more attractive, but I am not sure if that would add more difficulty to the task. Or maybe to show the water in the cup. Not sure…but I think more static actions would help. In any case, I found it good." Extract N°7 "In a feedback case, it is flexible. Moreover, the auditory case provides the first phase of the instruction" "I think it is well designed, and it is user-friendly for the patient." Extract N°8 "I think it is original, and the design is very good, showing pictures of real objects of daily use. It allows working with virtual objects and makes it comfortable and accessible to assess. I had never seen a format like this one, not even similar. I find it very useful."
Theme N°2: Ecological validity (Neuropsychologists)	Theme N°5: Ease to use (Patients)
Extract N°2 "I found the ecological topic very interesting. Regarding the validity, I found it very good. As a neuropsychologist, sometimes I feel that I ask patients so many things about calculus and other things not related to their daily life, which I think is not very functional" Extract N°3 "It is very useful to assess the functionality of patients because it is an ecological task and easy to apply. I think it is relevant to highlight that it assesses activities of daily living through simple tasks, which is very valuable in neuropsychological assessment."	Extract N°9 "Well, it was not difficult … it was too easy (smile). Ehhh, I understood the steps really well." Extract N°10 "I did not find it difficult because I took the kettle, and I performed the task properly. Then I took the sugar, and I did that well also. Therefore, I did not find it difficult. What I tried to do worked correctly."
Theme N°3: Script complexity (Neuropsychologists)	Theme N°6: Overlearning (Patients)
Extract N°4 "I found it was a very easy task for assessing planning, extremely easy. I found that a patient could benefit from this task due to the ceiling effect and still show difficulties for planning." Extract N°5 "I would not add anything, or maybe just develop the cinematic of the action to be a bit more natural. But nothing else, because as a task, it fulfills all of the targets. For instance, for the case of a task for planning, it fulfill all the steps; they are clear, and they have appropriate instructions. I would just aggregate a report at the end."	Extract N°11 "Easy, it is something basic, something that everybody makes at any time." Extract N°12 "It was easy because you have performed that task since you were a child. One already knows what steps are first and what the next ones are."

low-cost and easy-to-deploy screen-based simulated functional assessments for clinical use. Our results show that (1) eAdventure is a low-cost screen-based simulation that is easy to program; (2) serious games might be useful in the assessment of EDF in real-life situations; and (3) serious games have good acceptability and usefulness for therapists and patients.

Even though these game development platforms, and specifically eAdventure, have been successfully used in (medical) education [103,111], to our knowledge, there have been no previous attempts to use this type of technology in neuropsychological assessment. This approach would allow clinical researchers with little or no programming background to work together with a programmer to develop or adapt previously created functional assessments [106]. These assessments could then be freely shared, allowing collaborative testing and refining by a community of researchers or practitioners [104]. We also believe that this technology (screen-based simulations) has the potential to become widely adopted in habitual clinical practice.

This approach showed development costs that, in our opinion, are affordable for most of the current projects in neuropsychological evaluation, also considering that the simulation can be freely shared and distributed for cross-site validation studies or adaptation to other testing conditions or target populations, with the aim of measuring EF deficits.

In the information sciences field, the TAM is one of the more widely applied theoretical models to predict the adoption of a new technology by its target users. Although the TAM has already been used to evaluate the acceptability of novel informatics tools in other healthcare areas [112–119], to our knowledge, this is one of the first applications for software tools in the area of cognitive or functional assessment. Nevertheless, and similar to our work, the TAM questionnaire has been applied in healthcare settings to investigate the acceptance of different technological systems by specific healthcare professionals (physiotherapist, nurse, and occupational therapist) [115,120–123], and some of these settings have demonstrated similar good results for the scores of PEOU and PU as our work [121,123].

In relation to subjective data, we found that professionals assessed the use of the SBT-COT positively at the application of the TAM. In addition, the analysis of interviews of professionals and patients showed positive experiences related to the use of the SBS-COT, although the themes related to script complexity and interface had some conflicting reports according to the interviews with professionals.

Patients reported that the task in the SBS-COT was too easy, a perception that was confirmed by the outcomes reported by the video game. These results (quantitative and qualitative) might indicate that the cognitive function needed to accomplish the task had a ceiling effect. This ceiling effect was intentional, since it was outside the scope of this work to evaluate the subject's performance per se; rather, the aim of this work was to analyze the impact and consequences of using a specific type of technology in the clinical setting. In terms of the patient's perception, the results suggest that the technologies present no barriers for their use by patients with TBI. Nevertheless, further studies need to address more deeply whether computer literacy could bias performance, particularly in tasks with higher complexity, and limit the use of some SBS tasks to patients with previous experience with video games [124].

Our task presents similarities in scope and design with the Non-immersive Virtual Coffee Task (NI-VCT), which was developed in a 3D VR system and was recently published by Besnard et al. [81]. However, two main differences could impact the generalization of the selected technology to the clinical setting. First, the SBS-COT uses photorealism instead of 3D rendering in the NI-VCT. We think that photorealism makes it easier to develop a neuropsychological tool in the clinical context because photorealism allows the stimuli to be changed by simply taking different photographs instead of the complexity of programming required to change a 3D rendering. Second, the NI-VCT has a more complex, non-automatized system of reporting performance using human raters (based on a methodology described elsewhere [125]) instead of the automatized reporting system implemented in the SBS-COT. Our results suggest that reporting scores with an automatized system simplifies and facilitates its eventual implementation in the clinical settings in contrast to a more complex and non-automatized system. We are aware that this second approach might be interpreted as simplistic, but we have to emphasize that a key point of this study is that the neuropsychological assessment tool was developed in close collaboration with clinical professionals (physicians and neuropsychologists), and it was easily implemented in the clinical context, which is a feature seldom offered with VR.

The main limitation of our study is the selection of an easy task. However, our study is a proof of concept study aiming to demonstrate the feasibility of game authoring platforms to develop new tools to assess EF and does not allow for the evaluation of the diagnostic utility of the SBS-COT. Moreover, the assessment of mild EDF requires a more complex task, with other components of EF such as multi-tasking [5]. Therefore, future studies should account for the limitations of this work to assess EF and develop screen-based simulations tasks with a higher complexity for a more comprehensive assessment of EF.

Although limited and difficult to generalize, our results allow us to conclude the following: (1) It is technically feasible to use serious game authoring platforms such as eAdventure to develop screen-based simulated functional assessments for clinical use; (2) the development costs of this approach (both in terms of monetary and time spending costs) are lower compared to those of other approaches such as VR; and (3) professionals and patients reported that the SBS-COT was easy to use, even though the perception of utility related to script complexity and interface was not consistent among the professionals, with some conflicting reports.

6. Conclusions and future directions

The use of open-source, serious game authoring platforms can have positive long-term implications for neuropsychological research. If simulations and/or neuropsychological tasks are simpler to produce, reuse and share, this could open the door to more cooperative research with evaluation tools that can be refined, validated and adapted to specific environments by other research groups and, at the same time, easily transferred to habitual clinical settings. Similar approaches, such as collaborative tool development, are commonplace in software engineering and have resulted in some of the most successful, well-known initiatives, such as GNU-Linux, Wikipedia, and GCC. This development methodology makes it possible to address problems that would otherwise be too complex and/or expensive for a single research team and could be successful if distributed [126].

Moreover, the use of computer assessments (in general) can also take advantage of the trend toward more intuitive user interfaces (e.g., multi-touch) and devices (e.g., tablets). Another potential informatic platform is to register the categorical and continuous measures of performance and development of an algorithm to give an overall score. We feel that our early tests with touch-based interfaces showed sufficient promise to justify further exploration, as this approach might alleviate some of the barriers inherent in less intuitive tools (i.e., keyboard and mouse).

Next steps in the project are to take advantage of the new developments in game analytics [127] to get more insight about how patients use the game and how all that interaction data can be used for helping the clinicians to produce a better diagnosis. This is in the line of what is being called evidence-based medicine. Recent development as new specifications for user interaction data tracking such as Experience API (xAPI) [128] and the availability of new cloud infrastructure to collect all the data generated in serious games will greatly simplify the data collection tasks and will allow to create simulations that deal with more complex tasks [129].

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Conflict of interest

We do not have any conflict of interest.

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