Motion-based virtual reality cognitive training targeting executive functions in acquired brain injury community-dwelling individuals: a feasibility and initial efficacy pilot

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Abstract—**Acquired brain injury (ABI) is a leading cause of long-term cognitive disability, often involving deficits in executive functions (EF). ABI patients usually stop receiving cognitive treatment when leaving the rehabilitation facility or shortly thereafter, due to the high cost of therapy sessions and the mobility requirement to access therapy. Software solutions offer a promising tool for accessible and affordable cognitive rehabilitation in the home environment. However, research provides limited evidence for effective transfer of benefits from computerized cognitive training to real-life functions. Virtual reality (VR) exergames using motion-interaction offer a more realistic and natural training environment, and are therefore expected to facilitate a more effective transfer. Although commercial exergames may bring about some cognitive gains, they usually do not target cognitive functions directly. Here we describe a novel exergames platform, the Active Brain Trainer (ABT), designed to directly target EF, using games in multiple realistic contexts. The software adapts in real-time to the patient's behavior, providing feedback and rewards, and hence may enhance usability and compliance. The primary goal of the current study is to assess the feasibly and acceptability of this platform for community-dwelling ABI patients during the chronic phase. A secondary goal is to assess the initial efficacy on EF and functional benefits from program training. Participants were instructed to use the games for 15-20 sessions. Neuro-psychological assessments of EF and daily life functions were performed before and after training. Participants also filled a satisfaction questionnaire following training. All training and assessments were conducted in the participants' homes. Game performance was recorded throughout training sessions. Preliminary results from the six ABI patients who successfully completed the program so far show no adverse effects. Participants reported enjoyment and satisfaction from training. Participants performed increasingly more challenging EF tasks within game environments. Initial results show improvements in functional tasks and most executive neuropsychological assessments following training. Additional participants are currently being trained to increase the power of the results. These preliminary findings support the feasibility and potential efficacy of the motion-based cognitive training of EF for community-dwelling individuals with ABI.**

Keywords: cognitive training; exergames; motion-based; acquired brain injury; community-dwelling; executive functions

I. INTRODUCTION

Acquired brain injury (ABI) causes long-term disability for millions worldwide, leading to ongoing cognitive impairments [1]–[3], forming significant barriers to daily-life functioning and hampering quality of life [4]–[7]. Commonly, cognitive impairments following ABI include impairments in executive functions (EF [8]) that sub-serve goal-directed and purposeful behavior [9]. EF refer to a set of cognitive processes, including attention, inhibitory control, working memory, and mental flexibility. Impaired EF can be manifested in a constellation of functional issues, such as problems with reasoning, decision making, and difficulties in initiating, following, and shifting plans [5], [8], [10]. These limit the ability for independent living and employment, and increase caregiver burden [11].

However, effective tools to improve executive dysfunctions are scarce [12]. Research in the fields of neuroscience and neurorehabilitation has shown that training cognitive functions, and EF in particular, can improve performance and modify the underlying brain mechanisms (Brain Plasticity) [13]–[16]. Evidence suggests that cognitive training can have therapeutic benefits for people with ABI [4], [11], [17]. However, many of the methods and tools available today to clinicians and patients involve artificial and simplistic stimuli, scenarios, and tasks, and are therefore quite limited in their transfer to everyday functions [18]–[20]. Even with computerized cognitive training, interactions are mostly unnatural, requiring simple keyboard or mouse presses. Another concern is that people with ABI usually receive treatment only for a few months following discharge, or not at all, leading to limited recovery and even to functional decline [21], [22] once discharged home. Therefore, there is a pressing need for innovative treatment solutions to improve executive dysfunctions for community-dwelling individuals with ABI.

Recent studies indicate that physical activity serves as a major key player in maintaining and improving brain health in general, and cognitive function specifically [23]–[26]. Evidence from both animals and humans suggests that combining physical activity with cognitive training can have greater effect on cognitive functioning than each activity alone [24], [26].

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Recent technological developments, such as virtual reality (VR), and more specifically, exergames (a portmanteau of "exercise" and "gaming"), provide a new space for cognitive rehabilitation, combining physical and cognitive treatment approaches in fun and realistic ways. Here we tested a novel VR platform of video games, the ***Active Brain trainer (ABT)*** (Intendu Ltd., Herzliya, Israel), designed to train specific EF. The games were designed with the following key features: (1) **Natural body movements and gestures** are required to interact with all games, mimicking real life situations, and expected increase brain plasticity. (2) Since real-life situations usually require the combination of multiple functions simultaneously [16], each game focuses on **one *main* executive function,** challenged throughout all game stages, as well as additional, secondary, executive functions, to increase transfer to real-life performance [27]–[29]. (3) Transfer is also more likely to occur when playing in **realistic settings and environments** [30]–[33]. Therefore, ABT games involve cognitively challenging tasks within a safe virtual environment using realistic situations such as interaction with people, food, transportation, and so on. Examples of various realistic VR game environments are shown in **Fig. 1**. (4) **High variability** at the level of the exemplars, contexts, and movements, as well as multiple secondary executive functions, increase **gameplay richness and novelty.** (5) All ABT games are founded on **evidence-based** paradigms that are known to be effective in training or in assessing cognitive functions (see example below). (6) The ABT games progressively **adapt** in real-time to the player's performance (accounting for both success rate and reaction time) in order to maintain high accuracy levels and allow each player to progress through training at his/her own pace, **personalizing** and adjusting the games to individual capabilities and needs to enhance plasticity [16]. (7) And last, in order to deliver on-going internal **motivation**, known to enhance engagement and compliance, and to boost learning and plasticity processes [27], [30], [32], [34], multiple levels of **feedback and rewards** are embedded in the program: First, a positive audiovisual feedback is immediately provided following a correct response, accompanied by earning virtual coins . The coins accumulate in a "coin jar" which serves as a scoring mechanism. Conversely, an incorrect response results in a negative audiovisual feedback and the subtraction of coins from the jar. Second, to convey a sense of progress, players are notified by a cheerful sound when they reach a higher game level, accompanied by an animation showing the advancement along an axis of levels. Level numbers presented along this axis are maintained across sessions, providing feedback for both within and between session progress. Third, at the end of each game, players are provided with virtual gold medals and a corresponding message, rewarding them for their current progress relative to the previous session (1 coin for playing despite reaching a lower score; 2 medals for maintaining the same game level of the previous session; and 3 medals for exceeding the game level of the previous session).

The primary goal of this study is to assess the feasibly (participation, attrition, adverse events) and acceptability (satisfaction, motivation, usability, interest) of cognitive training with the ABT for community-based ABI patients. A secondary goal is to assess the initial efficacy and potential benefits from program training (improvement within training games, generalization to executive and functional performance). We hypothesize that patients will successfully complete the training program, and show improved EF within and, most importantly, outside the game environment.

FIGURE 1. Example of four game environments. Note the avatar representing the player position; score counter (coin jar) on the top left; and game clock on the top right.

II. METHODS

The study was approved by the ethics committee of the Lowenstein Hospital, Ra'anana, Israel (protocol 0002-15-LOE).

A. Participants

A convenience sample of nine individuals with ABI living in their homes was recruited from hospital lists via Lowenstein Hospital, via flyers distributed in rehabilitation and community centers, and by word of mouth. Thus far, six participants have completed the study, and the three others are still undergoing training. Additional patients are further recruited to power this preliminary trial. **Inclusion criteria:** (1) diagnosed with ABI; (2) aged 18-75; (3) at least one functional upper limb, as measured by the ability to bring one hand to the back of the neck; (4) ability to understand instructions as assessed by therapist; (5) impaired EF as assessed by a score of ≤ 22 (out of 30) on the Montreal Cognitive Assessment (MoCA) [35]; (6) visual acuity sufficient to follow stimuli on the monitor; and (7) living at home. **Exclusion criteria:** (1) epileptic seizure within the last two years; (2) other neurological or psychiatric conditions; (3) undergoing computerized cognitive therapy. Given that Kinect® allows people who are not computer savvy to interact with the games using simple gestures, computer experience was not a study pre-requirement.

B. Intervention

The intervention included training with eight ABT games, each designed to focus on training one main cognitive function, listed here according to the main function targeted: response inhibition, sustained attention, multitasking, cognitive-flexibility, working memory, planning, self-initiation and persistence, and multitasking.

Example: The game primarily targeting **response inhibition** in **the Food Truck Owner environment** is presented to the players as the "***Bad Neighborhood***" game. It further targets sustained attention, processing speed, decision-making, and cognitive control as secondary functions (**Fig. 1, top left inset**). Response inhibition is a key executive function, defined as one's ability to deliberately inhibit or suppress dominant, automatic, or pre-potent responses when necessary [36]. This ability to override an automatic tendency to respond in a given situation, or to stop a response when a rapid change in plan is required, is a core feature of flexible and adaptive behavior [37]. Impaired response inhibition leads to impulsive responding, stimulus-boundedness and preservation [38]. The *Bad Neighborhood* training game is based on the principles of the *Go / No Go* task and the Continuous Performance Task (CPT) [39]. The *Go / No Go* task is commonly used in research and in the assessment of response inhibition. It requires participants to perform a motor response to one stimulus class and to withhold response to another class [10], [37], [40]. The CPT is a common assessment, used to measure sustained attention and response inhibition [10], [39], [41].

During the *Bad Neighborhood* game, the player operates an avatar of a food truck owner who sells food to customers, and his/her goal is to serve food to as many positive customers (*Go* stimuli), while avoiding thieves (*No Go* stimuli), in order to earn as much money as possible. Categorization to positive and negative stimuli depends on the virtual costumer's shirt color. Throughout the game, multiple food items are continuously placed on the food truck counter, and customers approach the food truck to get food from various positions on the counter. The player needs to serve food to positive customers and avoid serving thieves, attending to the type of customer approaching and the food that is available (CPT-like requirement). In order to serve an approaching customer, the player needs to move the avatar sideways to position it in front of a customer. The player controls the avatar either by stepping sideways during a standing game mode, or by leaning his/her trunk sideways during a seated playing mode, based on mobility and personal preferences. After placing the avatar in the correct position, the player needs to perform a swipe up gesture with his/her arm, causing the avatar to perform the same arm movement, and to actually serve the food from the counter. Customers not served by the time they reach the counter turn around and walk away. Later in training and after establishing success in the basic task, other types of *No Go* stimuli are introduced, such as the appearance of rotten food, which the player should avoid serving. Moreover, the rapid appearance of customers requires speeded and automatic information processing (taxing processing speed), decisions as whether or not serve a customer (requiring decision-making), and varying behaviors depending on changing game requirements (demanding cognitive control).

Task parameters are adapted gradually based on the player's success, taking into account both *Go* and *No Go* trials. Specifically, parameters directly related to the main cognitive function (response inhibition) such as the probability of a *No Go* stimuli and the number of negative stimuli categories (shirt colors), are changed to make the task more difficult (if the player was successful) or easier (if the player was not successful). Other parameters, such as the probability of rotten food, are introduced later in the training after establishing success in the basic task. Finally, the overall speed of the game is controlled by changing the presentation time of each stimulus, based on the reaction time in successful *Go* trials (slowing down when player performed slow movements). Importantly, not all parameters are changed simultaneously, to avoid an abrupt change in the game's difficulty.

The player earns virtual money (game points) by serving positive customers, and looses money for serving negative customers or rotten food. The score counter (top-left of the game screen, see **Fig. 1** for examples) is continuously updated. The clock (top-right of the game screen, see **Fig. 1** for examples) shows the remaining time (in minutes) until the end of the game.

C. Assessments

Executive Function Performance Test (EFPT) - Bill Paying subtest [42], [43]. A performance-based assessment of EF. We used the newly modified internet-based bill payment version of the EFPT [69], requiring participants to find two fake bills among a few pieces of mail, pay the bills online, and balance an account sheet. Scores are based on the level of cueing required from the examiner to support task performance, and range from 0 (independent) to 25. A higher score indicates that the patient requires more cueing and demonstrates greater difficulty with EF.

Executive Abilities: Measures and Instruments for Neurobehavioral Evaluation and Research (NIH-EXAMINER) [44]. The battery measures inhibition, cognitive flexibility, working memory, fluency, planning, error monitoring, insight, and social function, using multiple tests. It provides a normalized executive composite score based on the majority of the tests included in the battery. It further provides a separate score for the unstructured task, designed to measure strategic planning (modeled after the six-elements test [45]), which is not included in the composite score. Higher composite and unstructured task scores reflect better EF and planning.

Walking While Talking [46], [47]. A dual task measure of divided attention to examine cognitive-motor interactions. Participants are asked to walk back and forth along a 10 m path, while performing a verbal fluency task (generate as many words starting with a specific letter). The total distance walked and the number of words generated are recorded. More words reflect better cognitive skills under dual task conditions.

Dysexecutive Questionnaire (DEX) [48]. A 20-item rating scale designated to sample common emotional, behavioral, and cognitive problems of everyday life associated with frontal systems dysfunction. A family member was asked to complete the questionnaire using a version designed for people close to the patient, such as a relative or a caregiver. Each item is scored on a 5-point scale according to its frequency from never (0 point) to very often (4 points), therefore a higher score reflects worse symptoms.

Experience and usability Questionnaire [49]–[51]. The questionnaire was adapted and modified from The Short Feedback Questionnaire [49], [52] and System Usability Scale (SUS) [51], [53] to fit the current study, using a 1-5 Likert scale.

D. Procedure

All sessions were conducted at the patients' homes. Sequentially (**Fig. 2**): (1) **Screening** visit (V0) to perform inclusion/exclusion assessments and determine eligibility. (2) **Baseline** (pre) assessment visit (V1) by a neuropsychologist, to provide informed consent and perform baseline assessments. (3) **Installation and orientation** visit (V2) by an occupational therapist (OT). Intendu provided the computer and a Kinect® V2.0 depth camera (Microsoft, Redmond, WA, USA), and connected these devices to the patients' TV screen or computer monitor. The OT ensured that there is enough space for safe training and removed any potential hazards when needed. Following installation, the OT instructed the patient and caregiver how to launch the program, and supervised the patient through an initial training session. (4) **Program use**: participants were instructed to engage with the ABT at home, without the presence of a therapist, for 15-20 sessions of 20-25 minutes each, over a course of 5-7 weeks. The OT monitored training remotely and planned the training sessions per patient based on individual progression (repeating games in which the patient advanced slowly and/or did not max out game levels) via an on-line remote control dashboard. Each session was designed to include four different games (minimum of five minutes per game). (5) **Post** training assessment (V3) assessment visit by the neuropsychologist, repeating the same assessment battery delivered during V1, followed by the experience and usability questionnaire. Baseline WWT data were missing from one participant, and post-intervention DEX data were missing from another participant.

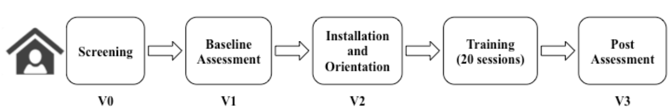

FIGURE 2. Game procedure.

E. Data Analysis

Training. Game stages were normalized between 0-1 to reflect the initial and maximal game stages, respectively, per game. In order to obtain a representative value from the entire session, the mean game stage per session is presented. The games were designed in a way that the cognitive challenge increases when the game stage is higher.

Assessments. Standard scores were calculated per assessment. Cohen's d effect sizes were calculated to measure the strength of the standardized difference between the pre and post assessment means. Significance testing was not conducted given the small sample size.

III. RESULTS

A. *Feasibly, safety, and acceptability*

Six participants completed the training and assessments successfully, and others are still in training. Demographic information of the six study completers is presented in **Table 1**. Overall, participants trained for an average of five and half hours (mean = 5:31:57, SD = 1:35:05 hr:min:s) over 15 (SD = 2.86) sessions, with an average session duration of twenty one minutes (mean = 0:21:37 , SD = 0:2:23 hr:min:s). All participants successfully used the program at home, without direct in-person clinical supervision following the initial setup session, and did not report any adverse effects.

TABLE 1. Patient Demographics

Patient	Age	Gender	Education (years)	Diagnosis	Time Unconscious	Time from injury (years)	MoCA score
P1	37	F	15	Anoxic Brain Damage	2 months	6	15
P2	65	F	8	CVA	2 days	4	16
P3	70	M	16	CVA	N/A	3	22
P4	71	M	15	CVA	N/A	1	18
P5	67	F	12	CVA	1 month	5	22
P6	51	M	18	CVA	2 months	2	19

Participants reported high levels of satisfaction (mean = 4.0, SD = 0.9) and motivation (mean = 4.2, SD = 0.8), without discomfort (mean = 1.3, SD = 0.5) during training (**Fig. 3A**). They further indicated that the feedback provided by the program was clear (mean = 3.7, SD = 1.0). They reported moderate levels of subjective cognitive and motor improvement (mean = 3.0, SD = 1.7; mean = 3.5, SD = 1.5 respectively), and most (5/6) participants mentioned they would like to use the program as part of their OT and home treatment. No one reported technical difficulties with program usage. When asked to rate the duration of the training, the majority reported that the intervention was either too short or that they were pleased with the duration of the intervention (**Fig. 3B**).

B. *Initial Efficacy*

Improvement within training games. Participants were challenged by the games and were able to perform increasingly more challenging EF tasks within the game environments, as evidenced by gradual increases in game stages in all games, presented in **Figure 4** on a game-by-game basis, listed by the main cognitive task targeted by each game (e.g. The *Bad Neighbourhood* game is listed under response inhibition). As can be in **Figure 4**, participants approached the highest game levels (nearing score of 1), in the games primarily targeting response inhibition, sustained attention, and multi-tasking.

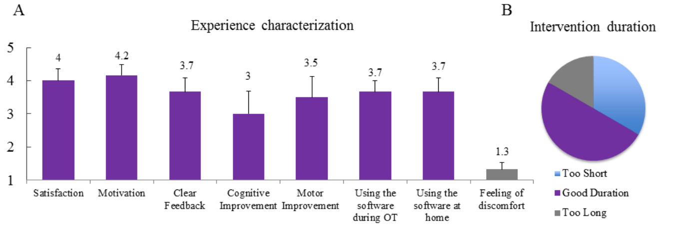

FIGURE 3. Post-training questionnaires. People with ABI living in the community reported ***A)*** positive experience from training with the ABT at home, and ***B)*** were mostly pleased from the duration of the intervention.

Transfer of benefits. Preliminary results suggest transfer of benefits into neuropsychological assessments and functional tasks, as evident by improvement trends following intervention in WWT, EXAMINER executive composite, EXAMINER unstructured task, and EFPT (**Fig. 5**). No changes were observed for the DEX. Effect sizes for the improvement in EXAMINER executive composite and EFPT (d = 0.51 and d = 0.63, respectively) were found to exceed Cohen's convention for a medium sized effect [54]. The effect size for the improvement in EXAMINER unstructured scores (d = 1.0) was found to exceed Cohen's convention for a large sized effect. Changes in WWT and DEX (d = 0.42 and d = 0.05, respectively) were small.

IV. Discussion

Initial findings from this pilot study demonstrate the potential of community-based cognitive training of EF in individuals with ABI, using the Active Brain Trainer (ABT). Our preliminary results indicate that approximately five and a half hours of training with a motion-based VR software designed to improve EF is feasible for individuals living in their homes. The patients were satisfied with the program and were interested in including it as part of their treatment.

The reported results supplement several recent studies showing the feasibility of novel technologies usage by community-dwelling individuals with ABI. For example, Jones et al. [55] reported high acceptability scores from the vast majority (95%) of the participants being either very satisfied or satisfied from using a remotely delivered self-management program for increasing physical activity among community-dwelling adults with ABI. Similarly, Juengst et al. [56] tested the initial feasibility of a mobile health system for tracking mood-related symptoms after traumatic brain injury (TBI), reporting high compliance (completion of 73.4% of the assessments scheduled in the app) and high satisfaction (6.3 on a 7 items scale).

Cognitive rehabilitation has been previously shown to improve functioning even several years after TBI [11], [57]. Initial results from the current pilot study further suggest that training with the ABT exergames can lead to improvements in EF and functional performance years (≥1 year) after an ABI event. These results build on preceding evidence in healthy children [58], youth [59], and healthy older adults [60]–[62] pointing to positive impact on EF from playing commerciallyavailable exergames. However, those exergames

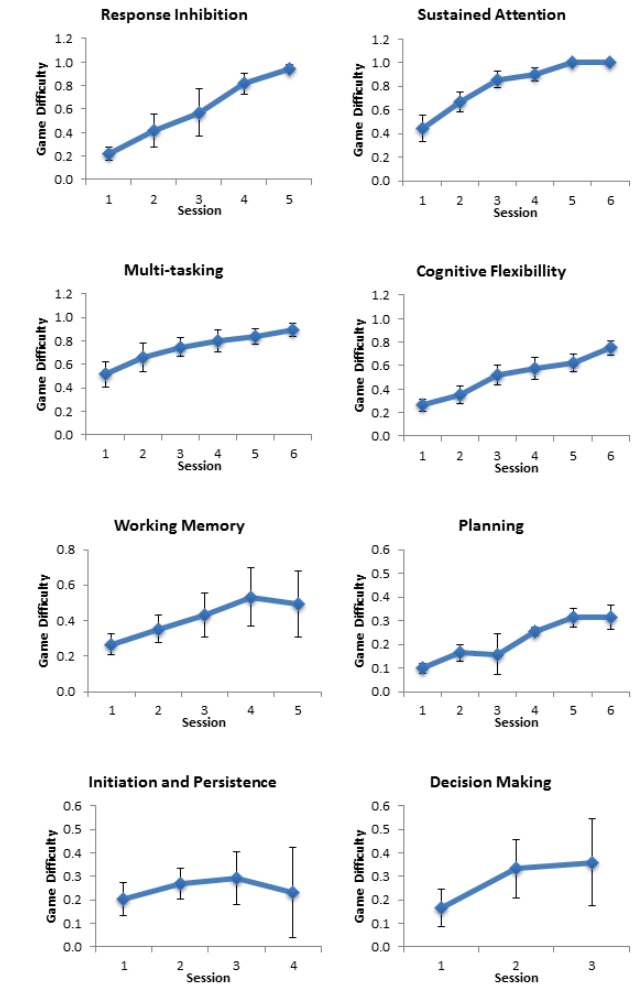

FIGURE 4. Within Games Training Progression. ABI patients gradually preformed more challenging EF tasks, as evident by positive trends in all games, listed here by the main cognitive function targeted by each game.

do not target cognitive functions directly, but rather mainly focus on physical activity and gaming experience. Preliminary findings from healthy participants indeed suggest that cognitive training with Kinect® leads to larger sensitivity in game performance than standard keyboard training [63]. Similarly, Kayama et al. [64] showed greater transfer of cognitive benefits in community-dwelling older adults receiving a boost of cognitive exergames in addition to standard physical training alone. Here we designed an elaborate and comprehensive platform directly targeting EF. The ABT provides the next generation of cognitive training software, expected to lead to more robust executive effects and enhance transfer of training gains to real life. Results from the current pilot study suggest promising benefit trends for people living with ABI years post-injury – a clinical population often lacking any cognitive rehabilitation. Importantly, our results suggest that training of EF with the ABT has the potential for achieving "far transfer" [16], [65] to positively affect real world functions

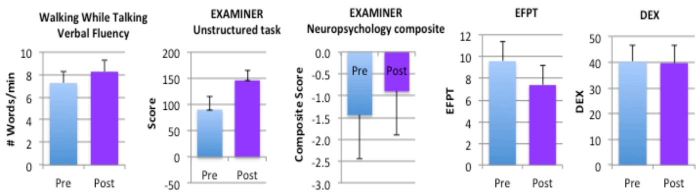

FIGURE 5. Transfer of benefits. Initial efficacy data points to improvements in various executive and functional assessments following training (increase in WWT, EXAMINER Unstructured and Neuropsychology composite, and decrease in EFPT score).

faced by ABI patients in everyday life tasks, which were not directly trained for during this intervention.

Our results are consistent with recent findings from a large meta-analysis of 14 studies encompassing 575 TBI patients [11], and with a systematic review including 28 studies of computerized cognitive rehabilitation in ABI [66]. Hallock and colleagues report that despite limited studies in the field of cognitive training, cognitive training is modestly effective in improving cognitive and functional outcomes in patients with post-acute TBI. The authors recommend that cognitive training should play a more prominent role in TBI rehabilitation. Bogdanova et al. report significant improvements in attention and executive function subsequent to computerized cognitive training in 25/28 studies, as well as promising trends in the remaining studies. Our preliminary data may point to larger training benefits than those reported in the meta-analysis [11], presumably due to the combined cognitive and motor training, as well as to other unique features included in the ABT.

Interestingly, despite improvements on objective tests, family members did not report major improvements in everyday dysexecutive behavior. A similar pattern was reported in a large meta-analysis of cognitive training in TBI, were cognitive training had a significant effect on executive function but not on dysexecutive outcomes [11]. The authors of the meta-analysis attribute this pattern to the nature of the data: executive outcomes originate from objective, quantitative and continuous neuropsychological tests that are therefore sensitive to change. On the other hand, dysexecutive instruments such as the currently used DEX questionnaire, are generally subjective, qualitative, and ordinal, with lower resolution. Therefore, larger behavioral changes are required for the detection of dysexecutive improvements. We are of the opinion that in addition to the different nature of the metrics, longer durations of training and consolidation are needed in order to bring about changes in behavioral habits [67], [68]. We further note that in the case of four out of five patients with DEX data, family members did report some (albeit small) improvement in dysexecutive behavior, while a larger decline was reported for the fifth patient, averaging out the improvements reported for the other patients. These observations again point at the need for enlisting additional participants in order to determine whether training on the ABT can minimize the presentation or the severity of dysexecutive symptoms in post-acute ABI, as well as power other executive and functional improvements noticed in this pilot. As already reported, additional patients are currently being recruited, screened, assessed, and trained.

A few additional caveats should also be kept in mind when interpreting these current results. First, long term follow-ups are required to assess the stability of the positive changes seen in this initial sample. Second, given that patients hit ceiling effects in a few of the games currently tested, new levels are currently developed and added to the games to allow for longer and deeper training. Nevertheless, the obtained preliminary results suggest that cognitive training with motion-based VR can lead to positive changes in community dwelling individuals years after an acquired brain injury, stressing the importance of continuous cognitive treatment to improve the lives of the many in need.

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