Influence of virtual environment complexity on motor learning in typically developing children and children with cerebral palsy

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Abstract— **Motion-controlled video games in virtual environments (VEs) are physical therapy interventions for motor skill learning in children with neuromotor conditions, such as cerebral palsy. Many VEs feature complex audiovisuals designed to motivate and engage children in repetitive use; however, the value of these enhancements remains unclear. The purpose of this study was to examine the effect of a simple versus a complex VE on motor learning of a novel balance task in typically developing (TD) children and children with cerebral palsy (CP). In addition, we explored the relationship between children's motivation, engagement and their motor learning outcomes in each VE. Twenty-seven TD children and 6 children with hemiplegic or diplegic CP participated. Participants were randomized to practice the same novel postural control task in either a simple or a complex flat-screen display VE. Motor learning was measured by an error metric per trial. Following 40 acquisition trials, children completed motivation (Intrinsic Motivation Inventory) and engagement (User Engagement Scale) measures. They returned 2-7 days later for retention and transfer tests. Children with CP had significantly greater performance errors as compared to TD children at all sessions; however, there was no difference in performance between simple and complex VE conditions at any session, nor were there any differences in engagement or motivation between conditions or groups. Lower self-reported motivation was associated with greater performance error at retention and transfer in all participants. Study results provide no evidence for an effect of VE audiovisual complexity on children's motor learning or affective state.**

Keywords—virtual environments, motor learning, motivation, engagement, children, cerebral palsy

I. Introduction

Virtual environments (VEs) are one component of the pediatric rehabilitation toolbox [1, 2]. A predominant rationale for VE use is that these systems may engage and motivate patients to increase the frequency of therapeutic practice [3-6] . A greater intervention dosage can maximize opportunities for the practice-dependent neuroplasticity underlying motor learning [7, 8]. In addition, enhanced motivation or engagement may directly impact motor learning, through possible dopaminergic pathways [9, 10]. Yet despite the common reliance on these affective mechanisms as justification for VE use [11], few studies have explored the specific attributes of VEs that motivate and/or engage children in practice. Similarly, little work has examined potential relationships between differing VE attributes, user affect and the motor learning outcomes achieved by VE-based interventions.

Motivation encourages, elicits and sustains goal-directed actions and behaviors [9]. Individuals can be intrinsically motivated to meet internal goals, or extrinsically motivated by factors such as threat or reward [12]. In contrast, engagement is defined as an experience-based cognitive and affective quality [9]. A majority (80%) of studies in a recent scoping review of VE use in adult stroke rehabilitation described user motivation or engagement as a rationale for VE interventions or as an explanation for study results [11]. However, only 19% of studies measured participants' levels of motivation or engagement, and none used inferential statistics to examine the relationship between these constructs and intervention outcomes. Similarly, in the pediatric literature, one study found that children report more motivation in VE-based interventions as compared to conventional therapy [13], but overall, their motivation and engagement are infrequently measured with psychometrically valid instruments [14, 15]. This inconsistent measurement limits conclusions about the potential impact of affective constructs on children's motor learning outcomes in VEs [14, 15].

Engagement in active video games can be enhanced by design principles such as clear goals and mechanics, interactive choices, and the provision of feedback, competition and

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rewards at individualized challenge levels [16]. Handheld, controller-based video games generally present these elements via viscerally appealing audiovisual graphics in which a wide range of stimuli are presented simultaneously. These 'complex' environments are designed to attract and sustain children's attention, motivating and engaging them in sustained periods of game play. Commercially-available active video gaming systems (such as the Nintendo Wii and Microsoft Kinect for Xbox), the most common VEs used in rehabilitation contexts [1, 2], offer similarly complex and stimulating audiovisual environments. Therefore, to be attractive to a market accustomed to environmental complexity, smaller companies making rehabilitation-specific VEs strive to achieve the same level of graphical quality in their applications as their mass-market counterparts. Yet little is known as to the impact of audiovisual complexity in VEs on either user affect or motor learning [17].

Evidence is lacking for the *indirect* mechanisms by which motivation or engagement may enhance motor learning; namely, by eliciting greater practice dosage or intensity. Bryanton et al. [13] compared ankle selective motor control exercises in children with cerebral palsy (CP) using a VE exercise system as compared to conventional exercises, finding that children completed more repetitions of the conventional exercises, although the quality of movement was higher in the VE group. Lohse et al.[9] evaluated potential *direct* mechanisms, exploring differences in skill acquisition and retention in typically developing young adults practicing a novel video gaming task with enriched audiovisual stimuli as compared one with no audiovisual stimuli (sterile condition). They found that participants who played under the enriched condition reported greater engagement and demonstrated greater retention as compared to the sterile condition. A follow-up study using electroencephalography did not replicate this finding, but it did show that more engaged learners had increased information processing, as measured by reduced attentional reserve [18]. In a study comparing learning of a novel balance skill in a VE versus an equivalent physical environment in typically developing children, there was no relationship between self-reported motivation, engagement and motor learning [19].

The affective impact of interaction with a complex VE may either facilitate or hinder motor learning. As such, an increased understanding of these relationships can inform decisions about VE design and use in clinical practice. We were interested in the impact of VE complexity on motor performance in children with CP as compared to TD children. We first looked for any Group (CP vs TD) and Condition (Simple vs Complex) effects on skill acquisition. Next, we looked at Group and Condition effects on motor retention and transfer. Finally, we looked at how individual differences in engagement or motivation might impact acquisition, retention or transfer in each VE.

II. METHODS

We used a standard motor learning experimental paradigm involving an initial acquisition phase (Visit 1) and a delayed retention and transfer phase (Visit 2).

A. Setting

The study took place in the Rehabilitation Games and Virtual Reality (ReGame-VR) Laboratory at Northeastern University. The lab is equipped with the Stability and Balance Learning Environment (STABLE; Motek Forcelink, The Netherlands). The STABLE involves a forceplate (Motek ForceLink, using National Instruments Analog to Digital Converter with a Sampling Rate of 250kS/s at 16-Bit; Centre of Pressure error < 10mm), and 6 VICON cameras.

B. Participants

Typically developing children aged 8-13 years were recruited from the local community to participate in this study. Inclusion criteria were absence of visual, auditory, cognitive or language impairments that would prohibit participation in study procedures (as reported by parents/guardians). Exclusion criterion was the presence of a seizure disorder. Children with hemiplegic or diplegic CP aged 8-13 years were recruited from the CP clinic at Boston Children's Hospital. Inclusion criteria were Gross Motor Function Classification System functioning at Level I or II and cognitive functioning at or near school grade level. Exclusion criteria were recent Botox injections or orthopedic surgery, or a seizure disorder.

C. Procedures and randomization

After providing guardian consent and child assent as per IRB approved procedures, participants completed a computerized version of the Conner's Continuous Performance Task Version 3 (CPT-3), a gold-standard measure of baseline attentional abilities [20] (data to be reported elsewhere). The CPT-3 normed overall detectability score was used as a minimization factor in a computer-based random number generator randomization process along with age and gender in order to facilitate balanced groups [21].

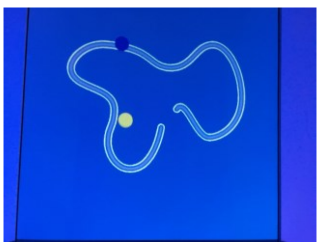
D. Task

Participants stood on the force plate while wearing a lightweight harness anchored to the ceiling. The task was individualized to each participants' limits of stability. Participants in both conditions undertook a custom-developed visuomotor tracking task in which they used mediolateral and anterior-posterior movements of the center of pressure (CoP) over a stationary base of support to move an avatar representing their CoP along a winding path, following a reference object. Children were instructed to follow the reference object as closely as possible along the path. Participants were asked to keep their feet stationary; inadvertent foot movement was tracked via motion capture markers on each foot. Trials in which children moved their feet were excluded, and testing continued until 40 successful trials were obtained. Figs. 1 and 2 illustrate the simple and complex VE conditions.

Table I illustrates differences and similarities between the task in the complex and simple VE using game design characteristics as outlined by Lohse et al [16]. The task was mechanically identical in both environments.

TABLE I. TASK DESCRIPTION IN SIMPLE AND COMPLEX CONDITIONS

	Complex VE	Simple VE
Feedback	Knowledge of results: Score and visual of CoP path overlaid on target path post task completion Knowledge of performance: CoP position visualized throughout task; additional visual stimuli appeared on screen, based on user performance	Knowledge of Results: Score and visual of CoP path overlaid on target path post task completion Knowledge of performance: CoP position visualized throughout task
Salience	Enriched visuals and audio	Task presented against blank screen; no audio
Competition	Against self (previous score)	
Reward	Score	
Difficulty/ Challenge	Predetermined	
Choice/ Interactivity	No choice Audiovisuals dependent on performance	No choice
Clear Goals & Mechanics	Yes	




Figs 1 & 2: Simple and complex VEs.

E. *Procedures*

Children completed baseline balance testing on the STABLE system, including eyes closed stance, single leg stance, tandem stance, and mediolateral and anteroposterior limits of stability. Baseline electroencephalography (EEG) data was collected in sitting and standing, as well as during task acquisition. This data is currently being analyzed and is not reported here. Following standardized instructions, children completed forty, 30-second acquisition trials, taking breaks as needed. They then completed the language-modified Intrinsic Motivation Inventory (IMI) with 27 items assessing dimensions of interest/enjoyment, perceived competence, effort/ importance, and tension/pressure [22]. They also completed a language-modified User Engagement Scale (UES) with 15 items assessing domains of aesthetics, focused attention, perceived competence, perceived usability, and satisfaction [23].

At the second visit, 2 to 7 days later, participants completed 15 retention trials in the same condition as acquisition, 15 cognitive transfer trials in the same condition as acquisition but with an additional cognitive task, and 15 motor transfer trials of a more challenging version of the path, in the same condition as acquisition. Specifically, the cognitive transfer trials used a peripheral tactile detection response task, a surrogate measure of attention detecting acute sensitivity to increases in cognitive demand. The task evaluates impact of increased cognitive demand on attentional networks in the brain via event response time [24]. Participants wore a vibrating device at the base of their neck and held a button in their preferred hand, pressing to respond to stimuli by pressing together the index finger and thumb; the average response time was calculated).

F. *Statistical analyses*

Participant demographics were described using counts and proportions, with differences between groups in attention, IMI, UES, and peripheral detection task evaluated using independent *t*-tests. All analyses were completed using R (version 3.5.2)using linear mixed effects models, via the lme4 package. Statistical inference on fixed effects was conducted via successive likelihood ratio tests for each model that test each parameter against the full model and generate an ANOVA-like table of the Chi-square statistics with corresponding *p*-values, which can be interpreted as omnibus tests of each factor. First, we investigated learning effects in the initial visit. Specifically, we analyzed performance as a function of Group (CP vs TD) and Condition (Simple vs Complex), as well as Trial Order (1 to 40) as a continuous variable. We tested for any interactions between Group, Condition, and Trial Order on error score. Second, for the second visit, we investigated retention as well as transfer (cognitive and motor) as a function of Group and Condition. Finally, we explored the impact of individual difference variables on acquisition, retention and transfer.

III. RESULTS

A. *Participant demographics*

Table II lists participant demographics. Two TD participants (1 in each group) only completed Visit 1 and were excluded from the analyses.

B. *Motivation and engagement*

There were no significant differences between TD children and children with CP in any self-report measure subscale or total scores. All children rated motivation highly (total score mean 5.1/6); there was no significant between-condition differences in IMI total or subscale scores. Fig. 3 illustrates that TD children in the complex condition rated the Aesthetics subscale of the UES significantly higher as compared to those in the simple condition [$t(df = 24.842) = -1.987$, $p = 0.029$].

TABLE II. PARTICIPANT DEMOGRAPHICS

	TD		CP	
	Simple VE (n = 14)	*Enriched VE (n = 13)*	*Simple VE (n = 4)*	*Enriched VE (n = 2)*
Age	11.4 yrs. (SD 1.79)	11.2 yrs. (SD 1.52)	8.75 yrs. (SD 1.71)	8.5 yrs. (SD 2.12)
Gender	8 males	7 males	4 males	1 male
Sports Involvement: (Recreational or Competitive)	N = 10	N = 8	N = 3	N = 1
Experience with Active Video Games	Yes = 8	Yes = 4	Yes = 3	Yes = 1
Active Video Games: Hours per Week (mean, SD)	4.7 (4.28)	1.5 (1.29)	1.0 (0.5)	6.0 (0)
CoP Displacement (cm): Eyes Open, Feet Together	1.52 (0.34)	1.61 (0.38)	1.66 (0.24)	1.47 (0.31)
CoP Displacement (cm): Eyes Closed, Feet Together	2.17 (0.85)	2.09 (0.58)	3.98 (2.30)	2.12 (0.40)
CoP Displacement (cm): Area Limits of Stability Test	221.2 (55.4)	207.6 (36.4)	262.1 (72.5)	165.1 (2.69)
CPT Overall Detectability Score (mean, SD)	45.7 (7.81)	49.7 (8.55)	47.0 (8.49)	53.0 (10. 4)
Peripheral Detection Score (ms; mean, SD)	522 (164)	627 (154)	580 (241)	806 (225)

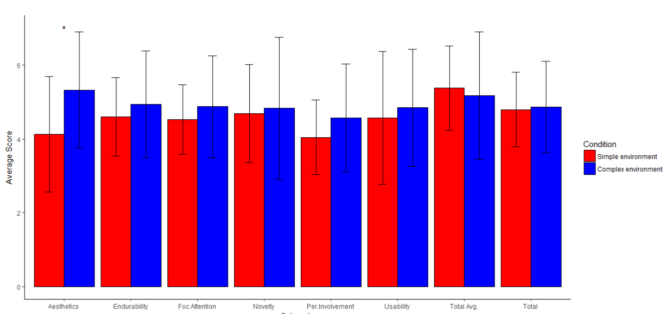


Fig. 3.User Engagement Scale (UES) results for TD children in the simple and complex conditions.

C. Acquisition, retention and transfer performance

For motor learning, we first examined errors in the initial session as a function of Trial, Group, and Condition. There was a main effect of Trial indicating that participants significantly reduced their errors over successive trials [$\chi^2(1) = 21.14$, $p < .001$], as well as a main effect of Group with the CP group exhibiting more error overall than the TD group [$\chi^2 (1) = 15.14$, $p < .001$] (Fig. 4). In addition, there was an interaction between Trial and Group which was driven by greater reductions over trials in motor learning for the TD group compared to the CP group [χ^2 (1) = 8.13, $p < .05$]. There was no main effect of Condition nor were there any other significant interactions. Next, we examined the effects of Group, Condition, and Task (i.e., retention task, cognitive transfer task, and motor transfer task) in the second visit on errors (Fig. 5). There was a main effect of Task with the motor transfer task leading to greater errors than the retention or cognitive transfer tasks [χ^2 (2) = 20.19, $p < .001$], as well as a main effect of Group in the same direction as the acquisition results [χ^2 (1) = 14.98, $p < .001$]. Similar to the initial session, there was no effect of Condition, nor were there any interactions. Finally, we looked for any impact of Motivation or Engagement on errors. There was a main effect of Motivation [χ^2 (1) = 4.16, $p = .04$] with lower motivation scores associated with greater error; however, there was no main effect of Engagement.

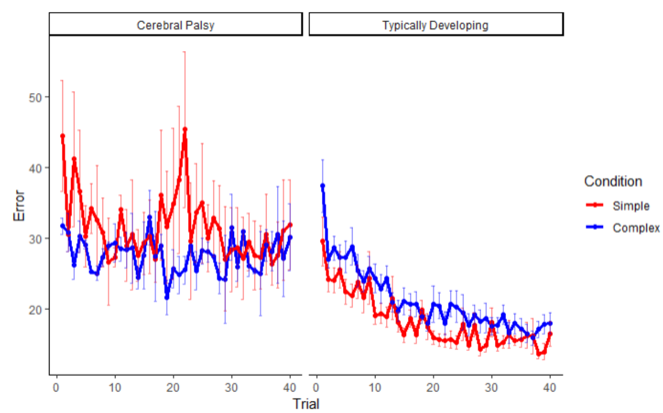


Fig. 4. Mean score (performance error) in the acquisition session for both groups and conditions.

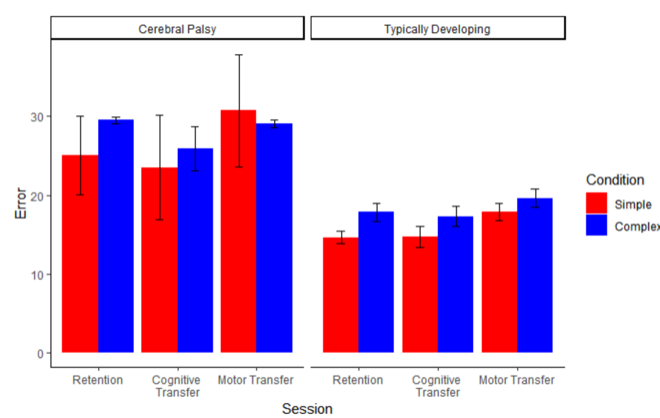


Fig. 5. Mean score (performance error) in sessions 2-4 (retention, cognitive transfer and motor transfer) for both groups and conditions.

IV. DISCUSSION

A better understanding of the technological affordances and user attributes that contribute to motor learning in VEs can inform decisions about their use in pediatric rehabilitation. Complex visual and auditory stimuli, designed to motivate users to engage in repeated practice, is prevalent in games using commercially-available, non-customized VEs. Rehabilitation-customized VEs, designed with smaller programming budgets, may not be able to achieve the same level of graphical complexity. As such, it is important to explore the influence of audiovisual complexity on affect and motor learning in VEs.

This study compared the effects of practice in a simple versus a complex VE on motor learning in children with CP and TD children, as well as the impact on engagement and motivation in each VE. No differences in motor learning between a complex and simple VE were found at any session in either group. Lower self-reported motivation post-acquisition was associated with greater error in retention and transfer sessions for all participants.

Our work was motivated by Lohse et al.'s design [9] exploring enriched versus sterile audiovisual conditions in a 2D gaming task in healthy young adults. The authors found that practice in their enriched condition led to better retention performance as compared to the sterile condition. Their study used a 'catch and throw' task. Although participants were required to use their non-dominant arm, the motor pattern of their task was likely more familiar to participants than was our CoP-controlled visual tracking task. As such, we can speculate that the potentially less challenging nature of Lohse et al.'s task enabled participants to dedicate more of their attentional resources to features of the task environment, such as its enriched aesthetics, leading to enhanced memory consolidation in this condition. Unlike our results, Lohse et al.[9] also found that participants in the enriched condition reported higher engagement on the UES as compared to those in the sterile condition.

Other studies have explored specific game features that might influence performance. Berglund et al. [25] explored differences in healthy young adults' performance in games that emphasized reactive versus strategic mechanics, finding no differences. Our task was reactive; it lacked any strategic elements in which participants drove game play or had the opportunity to choose from multiple strategies for success. This essential nature of the task, which by definition limited participant autonomy, may also have inadvertently been a factor reducing participant motivation. Autonomy is a well-accepted contributor to intrinsic motivation [10].

Studies in which children report higher motivation to engage in VE-based interventions as compared to traditional interventions (i.e. [13]) have not explored the specific VE attributes that may elicit such motivation. To the best of our knowledge, this is the first study to explore the effects of VE audiovisual complexity on motivation and engagement in a pediatric sample. We are confident of the magnitude of difference in audiovisuals between our conditions, as TD children gave significantly higher ratings to the Aesthetics subscale of the UES in the complex condition as compared to the simple condition. But this result did not translate to other self-reported differences in engagement. Our subsequent research will further enhance the complexity of the complex conditions. In the current study, it may have been too simplistic, in comparison to mass-market, non-customized video games with which children are familiar, to influence affective state.

However, TD children and children with CP in both the complex and simple conditions rated the task highly (above the median on each subscale) on the IMI and UES, with no differences between groups (except for the Aesthetics subscale of the UES). The finding of a relationship, which requires replication, between motivation and performance in sessions 2-4 for all participants is the first in our program of research exploring influences of children's self-reported affect (as measured with these questionnaires) and 'de novo' learning of new balance tasks in VEs [19, 26, 27]. Further exploring the role of motivation and engagement is important, as their purported beneficial effects are frequently cited as rationale for VE use in rehabilitation [11]. Yet little is empirically known as to how these constructs impact motor learning outcomes.

We isolated audiovisual complexity because it is an inherent feature of most non-customized, off-the-shelf VEs used in rehabilitation. Yet games do not require complex audiovisuals to be engaging and motivating. Examples of visually simple games from popular culture, such as Pong and Donkey Kong, show that essential principles of game design (feedback, competition, reward, difficulty/challenge, choice/interactivity, clear goals and mechanics [16]) can all be implemented without a great deal of audiovisual stimulation. However, audiovisual complexity does provide opportunities to enhance individual meaning and salience, by depicting greater narrative context or allowing users to select an environment that appeals to them. Audiovisual complexity may also provide more options for feedback presentation, which could also enhance learning. Task meaning is primarily derived by the relationship of the task to the individual. Tasks can be meaningful when they relate to individual goals, without relying on extrinsic rewards or stimulation provided by audiovisual complexity of the VE. Further exploring how autonomy and individual goals impact learning, rather than extrinsic rewards, is an important next step for research.

While our study is the first of its kind, it is important to note other documented cases in which elaborate, gamification in training settings does not always lead to better learning. For example, Mohammed et al.[28] randomly assigned 47 younger adults to play very basic cognitive games for 20 sessions while 68 younger adults trained on a gamified version of the same task. Participants in the more elaborate game condition reported higher enjoyment compared to the basic game condition; however, there were no significant differences in transfer, which suggests that the inclusion of motivational features did not help nor hinder general learning. Furthermore, others have even found that adding motivational factors to training games may distract from the learning task and lead to fewer improvements [29]. These discrepancies indicate the need for further research on the impact of motivation for learning.

With respect to differences between TD children and children with CP, study results illustrated expected differences in performance, given the underlying motor impairments of children with CP as compared to their TD peers. However, children with CP were able to reduce their error with practice during the acquisition session. Additionally, in our sample, children with CP were younger (though not significantly so) than TD children, which may have further negatively impacted their ability to undertake the task.

A. *Directions for subsequent research*

One option for subsequent research in this area is to explore *indirect* effects. We could ask participants in each condition whether they would choose to undertake more practice trials, to explore whether complexity increases motivation to augment dosage. We could also measure muscular or cardiorespiratory performance intensity, to explore whether complexity increases effort metrics. This line of exploration would explore the value of audiovisual complexity in increasing practice dosage and intensity, but would not shed light on the impact of complexity on learning.

More visually immersive VEs may elicit greater engagement [30]; as such, it would be valuable to repeat the study using a head-mounted display VE. We could also include a measure of transfer to a related real-life task outside of the VE context, as the task-specificity hypothesis of transfer suggests that similarity of practice conditions to the task of interest is key for transfer [31]. This is important because audio-visually complex VEs may be less similar to real-life tasks than are more simple VEs. Finally, the task can be used in intervention research for children with CP to train mediolateral and anteroposterior postural control, with the potential to overlay more complexity as a dual-task as skill progresses.

B. *Study limitations*

A greater number of TD children and children with CP in the simple condition had experience with active video games than in complex condition; this could have influenced their perspective of VE complexity. A small sample size of children with CP limited between-population inferential statistics and reduces the generalizability of findings.

Participants in both the simple and complex conditions received the same visual knowledge of performance and knowledge of results feedback during and after the task. In an attempt to mimic off-the-shelf video games, the complex condition provided additional visual and auditory stimuli throughout the task, stimuli which related to task performance. Linking this additional stimuli to performance-relevant cues implies that it is difficult to separate potential effects of additional complexity with those of additional feedback; however, the stimuli simply reinforced that participants were on the path, which was visual information already available to them. Finally, the simple condition was presented on a vibrant blue color background rather than black and white; having a non-colorful environment may have been more ideal.

V. CONCLUSION

Given the use of VEs in pediatric rehabilitation, it is important to understand the boundary conditions for their effectiveness. This study was the first to explore the effect of audiovisual complexity on motor learning and affect in TD children and children with CP. Children with CP demonstrated significantly greater error as compared to TD children on all sessions, with no difference between simple and complex conditions. There was no difference in motivation or engagement between conditions. Lower motivation was associated with greater error in retention and transfer tests. The lack of benefit for learning seen for enhanced audiovisual aesthetics in a novel VE task is interesting and calls for further research in this regard. Programming of complex audiovisuals represents a significant financial burden for game developers, and computers require larger processing abilities to host such games. As such, further exploration of the role of audiovisual complexity is required to inform decisions by game designers about relevant VE attributes for rehabilitation. More generally, research is required to characterize the conditions that lead to optimal motor learning in VEs. The outcomes of this research program will lead to the development of VEs that can be individualized to children with differing characteristics and abilities.

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