The application of enhanced virtual environments for co-located childhood movement disorder rehabilitation

N H Mumford[1], J Duckworth[2], P H Wilson[1]

[1]School of Psychology, Australian Catholic University,
Melbourne, AUSTRALIA

[2]School of Media and Communication, RMIT University,
Melbourne, AUSTRALIA

nhmumford@gmail.com, peterh.wilson@acu.edu.au, jonathan.duckworth@rmit.edu.au

[1] *www.acu.edu.au,* [2] *www.rmit.edu.au*

ABSTRACT

In this paper we discuss potential benefits and future directions in virtual reality rehabilitation for co-located motor training in children with developmental movement disorders. We discuss the potential for co-located VR to promote participation using cooperative virtual environments, facilitate social learning, and quantify levels of social interaction. We pay particular attention to the capacity of co-located systems to enhance levels of participation and the psychosocial outcomes of VR therapy. Finally, we offer directions for future research.

1. INTRODUCTION

Developmental movement disorders (DMD) like Cerbral Palsy (CP) and Developmental Coordination Disorder (DCD) effect approximately 0.2% (Oskoui, Coutinho, Dykeman, Jetté and Pringsheim, 2013) and 5-10% (Henderson and Henderson, 2002) of children, respectively, and are characterised by significant disruption to functional capabilities. CP is diagnosed when neurological damage has occurred prenatally or during birth, and typically results in more severe movement deficits (Liptak and Accardo, 2004). Conversely, DCD is described in the DSM-V (APA, 2013) as 'clumsiness' in children, and is not associated with overt neurological damage (see (Wilson, Ruddock, Smits-Engelsman, Polatajko and Blank, 2013) for review). Though diagnostically distinct, CP and DCD are both characterised by varying degrees of motor coordination deficit in upper- and lower-limb function, and postural control (Spittle and Orton, 2013). Recent theory suggests that DMDs may share similar neuro-cognitive deficits associated with higher order motor control and executive processes, causing disordered movement (Pearsall-Jones, Piek and Levy, 2010). For example, working memory dysfunction, especially in task situations that are time-limited, is seen as a common deficit among DMD children (Jenks et al., 2007; Piek, Dyck, Francis and Conwell, 2007). Moreover, it is well documented that the movement problems associated with DMDs commonly result in long-term psychosocial deficits (Bottcher, 2010; Chen and Cohn, 2003). These may include isolation, low self-esteem, reduced social support, and elevated anxiety (see (Bottcher, 2010; Chen and Cohn, 2003) for review). Sobering is the fact that psychosocial problems of this type in childhood are associated with later psychopathology in adulthood (Kessler et al., 2010).

The presence of psychosocial deficits associated with DMDs highlights a need for social interaction to be included as a core part of rehabilitation, enabling higher rates of participation, more opportunity for skill development and acquisition of social competencies. For example the Breathe Magic program, founded in the UK, requires groups of children with hemiplegia to learn (bi-manual) magic tricks, such as card tricks, culminating in a magic show after the 3-week program (Green et al., 2013). This program has demonstrated significant improvements in motor function (Green et al., 2013) and, based on child and parent reports, improved engagement with typically-developed peers and family members at home. Other group-based movement rehabilitation programs have found similar results (Aarts, Jongerius, Geerdink, Limbeek and Geurts, 2010; Dunford, 2011; Hung and Pang, 2010; Pless, Carlsson, Sundelin and Persson, 2000).

We are unaware of any research with the dual aims of improving psychosocial outcomes among DMD populations in addition to movement skill. Any such study would still need to address issues that are part and parcel of any rehabilitation program. Notable among these are that rehabilitation requires significant time and resources to organise and that repetition in therapy can be experienced as boring, sapping motivation,

particularly in children (Wang and Reid, 2011). The application of new technologies needs to be mindful of these issues if the efficiency and efficacy of treatments are to be enhanced. Virtual Reality (VR) technologies are widely thought to offer a number of exciting options for augmenting current rehabilitation practices (Rizzo, Schultheis, Kerns and Mateer, 2004). Yet little work has addressed the use of VR systems to encourage co-located interaction, providing a dual lever for movement and social skill development in children with DMD. In this paper we provide a conceptual and empirical rationale for VR-rehabilitation of DMDs, detailing the dual advantages of co-located systems for movement and social skill development specifically in this broad population. We then describe applications of co-located VR in paediatric rehabilitation, and make design proposals for the future.

2. ADVANTAGES OF VIRTUAL REALITY REHABILITATION AMONG CHILDREN WITH MOVEMENT DISORDERS

VR and associated technology is a combination of computer/information technology that allows users to interact efficiently with simulated programs in real-time. VR promotes a sense of participation within the virtual environments (VEs) and allows clinicians to present relevant stimuli that are embedded in a meaningful and recognisable context (Riva, 2002). Some key advantages to VR-rehabilitation are: greater enjoyment and engagement with rehabilitation; greater control and adaptability of tasks, provision of augmented feedback, and automated data collection (Burdea, 2003; Thornton et al., 2005). Accordingly, research has explored these advantages among child populations. For instance, our prior project, Elements, which was developed for adults with traumatic brain injury (Duckworth and Wilson, 2010), was adapted for children with hemiplegia. The adapted rehabilitation system called RE-ACTION utilised a horizontal table-top display requiring children to move soft graspable objects (e.g. a cylinder 60mm diameter, 90mm height) to prompted positions on the screen. During these movements the VE provided real-time augmented feedback to the children, and tracked performance variables (e.g. movement speed) (Green and Wilson, 2012). After three weeks of therapy, the children demonstrated significant improvements in motor control, based on system-measured and standardised assessments. They also reported finding the VR-tasks more enjoyable than their usual rehabilitation (Green and Wilson, 2012). Following on from such positive results, it is plausible that VR programs encouraging multiple users to interact (i.e. co-located VR) may offer specific advantages for enhancing motor-control, and psychosocial outcomes in DMD populations.

2.1 Advantages of co-located VR-rehabilitation

2.1.1 Cooperative VEs promote participation. Perhaps the primary advantage in using co-located VR among DMD populations is the potential to design and customise the programs to promote participation. Based on the International Classification of Functioning, Disability, and Health – Children and Youth Version (ICF-CY), the standard for conceptualising levels of function and planning rehabilitation, participation refers to a child's involvement in physical, recreational, and social life situations (WHO, 2007). Critically, participation covers more than merely being physically able to take part in life situations, but includes a sense of belonging, and of being involved in these social settings (Granlund, 2013). This highlights the need to develop social skills as part of a rehabilitation framework/system that has as its primary aim, motor function. As shown in Figure 1, the ICF-CY model proposes a bi-directional relationship between reduced participation and negative personal outcomes (see (Granlund, 2013; Rosenbaum and Stewart, 2004) for further discussion on participation).

We contend that using engaging VEs that promote physical movement training, together with social interaction, may improve the physical, social, and recreational aspects at the participation level in the ICF-CY model (WHO, 2007), and reduce both motor and psychosocial deficits in DMD children, while leveraging their interest and motivation. For instance, the successful completion of VR tasks involving collaboration may improve psychosocial function, enhancing self-esteem, and confidence. The ability to match task levels and challenges to capabilities may also promote a sense of competency, further improving participation. As an illustrative example, in a VR-rehabilitation program called the VRSS system, which has been successfully used to improve upper-limb movement among children with hemiplegia, participants wear movement sensors on their hand, and back (to track posture), and perform tasks projected on a vertical display. One such task is to pick up coloured cubes, and stack them (Olivieri et al., 2013). This program could, potentially, be expanded to include multiple users, and encourage cooperative interaction. For instance, two users could coordinate in the block lifting and stacking exercise, with one manipulating red blocks into the stack, while another moves blue blocks.

2.1.2 Potential for social learning. Social/observational learning is a critical aspect of child development (Pratt et al., 2010). Co-located VR programs can provide opportunities for children to observe how their peers perform tasks in the VE, and develop new movement strategies of their own. Peer modelling has been shown to be

pivotal in learning fundamental motor skills in both typically developing and less skilled children (O'Connor, Alfrey and Payne, 2011). Another possibility is allowing children already familiar with the VR programs to 'mentor' new participants, teaching them how to interact with the VEs. This may provide opportunities for social learning for the new participant, and 'teaching' may be a positive experience for the more experienced child.
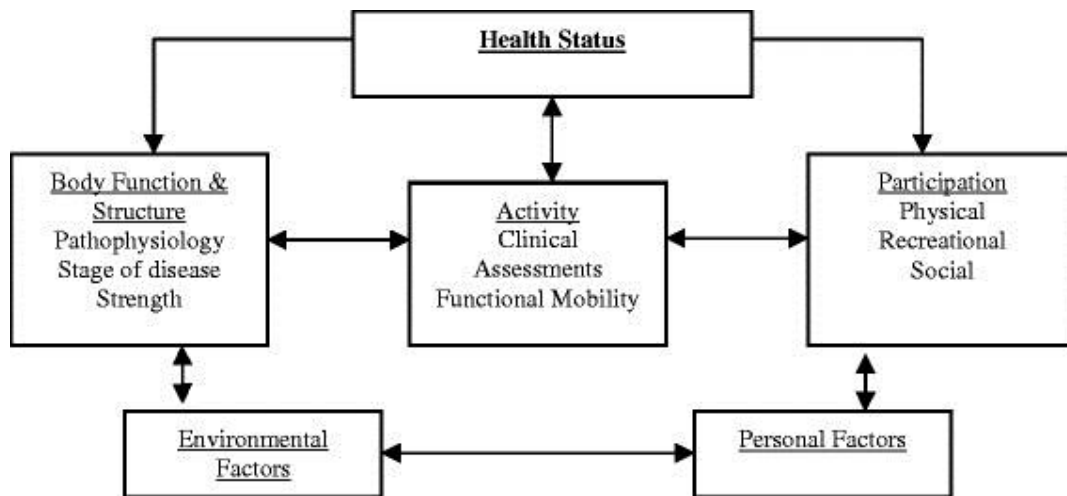

Figure 1. *The ICF-CY model of functioning and disability (WHO, 2007).*

2.1.3 Automatic quantification of social interaction. Social interaction can be a difficult construct to quantify (Crowe, Beauchamp, Catroppa and Anderson, 2011). Current methods rely on self-report, or parent-report questionnaires, or structured observation protocols (see (Crowe et al., 2011) for review). Each of these has inherent limitations. For instance, the potential for creating 'social desirability bias' (Cook and Oliver, 2011). Co-located VR programs, however, may allow researchers or clinicians to record aspects of social interaction between users. For instance, a VE requiring users to coordinate to achieve a goal may track speed of task completion, or how closely participants coordinated their movements, over successive trials to gauge user interaction/coordination. Digital markers on the hand/wrist may also be used to track participants' movements in space while using the VE. This would permit assessment of movement patterns in peripersonal and extrapersonal space, field preferences (ipsi- and contralesional), and interactions between users. In addition, aspects of speech, gesture and facial expression could be recorded as metrics of social interaction. For instance, turn taking in speech may be a useful metric for children with DMD and/or Autism Spectrum Disorders.

3. CURRENT APPLICATION OF CO-LOCATED VR-REHABILITATION IN CHILDREN, AND DIRECTIONS FOR FUTURE RESEARCH

In reviewing the VR-rehabilitation literature, examples of co-located VR were confined largely to Autism-spectrum disorders (ASD). However, even in this population where social skill deficits are a defining feature, very few examples of such systems are available. Generally, VEs either require a single user to interact with an avatar (e.g. (Mitchell, Parsons and Leonard, 2007)), or enlist a multi-user set-up but participants interact within the VE from separate locations (e.g. (Cheng, Chiang, Ye and Cheng, 2010)).

3.1   Co-located VR-therapy in Autism-spectrum populations.

To date, the bulk of research on the use of co-located VR for ASD has emanated from the Weiss lab in Israel (Bauminger et al., 2007; Gal et al., 2009; Giusti, Zancanaro, Gal and Weiss, 2011). Their StoryTable program is a table-top system promoting social skills and interaction. Using a large touch-screen interface, pairs of children interact with the VE to tell a fairy-tale. Participants must both coordinate on selecting constructs for the story (i.e., setting, sounds, music, characters and so on) by touching icons on the screen, and then creating the story. Evaluations of this program have been positive, although based largely on observational assessments. The children found the program easy to use, enjoyable, and demonstrated increased levels of social interaction skills (Gal et al., 2009). Another such system is the SIDES program (Piper, O'Brien, Morris and Winograd, 2006). This table-top VR-system requires four children to solve a movement puzzle collaboratively. Here, children work together in order to direct a frog avatar safely through a virtual space (a 7 x 9 tile grid) by placing virtual direction tiles on the screen (e.g. move one space straight ahead). Initial case-study testing showed that children with Asperger's Disorder found the program engaging, and that it facilitated social interaction during the course

of the program (Piper et al., 2006). However, no data is yet available to demonstrate transfer to the activities of daily living that require social skills. Nevertheless, the successful application of these co-located VR programs further highlights the potential application among DMD populations.

3.2   Directions for future research

As discussed above, the application of co-located VR in the rehabilitation of DMDs offers distinct advantages (Park et al., 2011). The foremost being the potential to facilitate participation. To further the field we propose that the broad approach to therapeutic design be embedded in current theories of motor learning and psychosocial function (particularly ecological approaches to learning), design elements be presented in a manner that engages and motivates users in a group context, and assessment protocols be developed to evaluate the efficacy of co-located systems at multiple levels of function. Therefore, we propose three key stages that must be considered in the development and experimental testing of future co-located VR rehab systems.

The first stage in the process is to ensure that the design and testing methods are firmly grounded in motor control/learning and developmental principles that underpin our understand of DMDs (Wilson, 2012). At the level of motor control, for example, computational models hold that predictive online control is critical to the flexible and efficient control of movement. Consistent with this view, children with DMDs show difficulties in the ability to enlist predictive control when planning and correcting movements in real time (Pearsall-Jones et al., 2010). These difficulties may be compounded by additional cognitive deficits like reduced executive function (Wilson et al., 2013). Thus, to prevent cognitive overload, co-located VR-systems need to be simple and intuitive in their interface and task design. Provision of multimodal augmented feedback during the course of movement can assist the development of online motor control, and the ability to make predictive estimates of limb position and body posture. In VR, augmented feedback may involve additional visual or auditory stimuli that are correlated with self-motion; examples include the use of coloured trail effects, musical notes (the loudness of which is correlated to spatial position), and visual ripple effects that signal object placement, all of which accentuate and reinforce the outcomes of the participant's own action.

Of the second stage, our team has identified several key components of group user interaction from the Computer Supported Cooperative Work (CSCW) field of research: physical space, group awareness, territoriality, and interaction simultaneity (Duckworth, Thomas, Shum and Wilson, 2013). We also propose that design elements from video games such as feedback, rewards, challenges, and social play may increase engagement and intrinsic motivation that support multiple co-located players in rehabilitation (Duckworth et al., 2014). For instance, a VE may provide participants with developmentally appropriate rewards/feedback (e.g. point score related to game performance), both at the level of the individual and the group (a combined reward like unlocking a new game level as the group progresses). The investment in achieving individual or group feedback/rewards could be manipulated by judicious game design. Developers must also consider participants' personal learning preferences in their VR design (García-Vergara, Brown, Park and Howard, 2014; Novak, Nagle and Riener, 2014). For instance, research indicates that children may inherently prefer co-operative or competitive VR-programs, and as such, may benefit more from their preferred system (Novak et al., 2014). This highlights the need for flexibility in style and delivery of VEs, to tailor the experience to suit the individual user.

Important to the third stage is the development of effective research strategies and protocols to measure and test the efficacy of group based rehabilitation. We put forward several mixed-method approaches to assess social function, motor skills, behavioural change and wellbeing. While performance outcomes can be assessed using established quantitative measures (e.g. the McCarron Assessment of Neuromuscular Dysfunction (Waller, Liu and Whitall, 2008) for motor coordination), more complex constructs like social ability and self-efficacy require a combination of quantitative and qualitative methods. In short, a multi-method approach that includes sophisticated multi-level modelling will allow a thorough assessment of efficacy and longer-term outcomes of co-located VR interventions, informing future adoption of these applications.

Development of VR programs requires a multi-disciplinary approach, with input from computer engineers, artistic designers, physical therapists, and other neuro-rehabilitation specialists. The challenge is the principled development of therapy solutions under reasonable timelines and costs, and their implementation not as a 'replacement' for traditional therapies (Parsons, Rizzo, Rogers and York, 2009), but as an adjunct. Available data suggests that the pursuit of co-located VR-rehabilitation is worth the investment, despite these challenges.

4. CONCLUSION

DMDs impact the functioning of children at multiple levels, including motor-control, movement skill, and social function, the sum effects of which can persist into later adolescence and adulthood, if untreated. Developing new therapy solutions, treatment strategies, and rehabilitation technologies to address the combined effect of

these problems is vital. VR-rehabilitation can leverage rehabilitation by presenting VEs that afford more opportunities for movement training, participation and social learning, while at the same time providing motion analysis that can resolve both individual behaviour and co-actor interaction. Despite these advantages, it remains surprising that so little research has directly assessed the motor and psychosocial outcomes of such systems. With due attention to systems design, informed by current theory, and to a rigorous (multi-level) approach to assessment, the potential of co-located VR rehabilitation should be realised.

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