Developmental cognitive neuroscience perspective on motor rehabilitation: the case for virtual reality-augmented therapy

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ABSTRACT
Developmental disorders and disabilities affecting movement can have far reaching, longer-term consequences for the child and their family, and present a great challenge for intervention. In the case of upper-limb function, in particular, poor compliance and use of repetitive training routines can restrict progress. In this paper we consider how an understanding of the neurocognitive bases of disorders like cerebral palsy and Developmental Coordination Disorder (DCD) can inform the choice of therapeutic techniques. Using a cognitive neuroscience approach, I explore the hypothesis that motor prediction is a common, underlying issue in these disorders. I then discuss the role that feedback-based and predictive control plays during the course of normal development and highlight recent applications of augmented feedback (AF) in motor therapy. Critically, VR-based technologies afford many options for the provision of multisensory AF. I describe recent examples of this principled approach to treatment, and conclude by suggesting avenues for future development in VR-assisted therapy.

1. INTRODUCTION
The effects of brain dysfunction and injury during childhood have profound developmental consequences for the child and place a significant socio-economic burden on families and the community (Penn, Rose, & Johnson, 2009). In the case of cerebral palsy and problems of development like Developmental Coordination Disorder (DCD), the movement difficulties present a huge challenge for therapists (P. H. Wilson, 2005). The choice of therapy must at once enable therapists to engage the child in the process of treatment, while also maximising the strength of treatment effects in what is often a limited window of time in a clinical setting. The holy grail for therapists is to find a therapeutic modality that will yield quite generalised effects on movement form and functional skill.

A principled approach to rehabilitation of manual function has been particularly slow to evolve. Most interventions for children with neurological disorders require intensive practice (e.g., Constraint Induced Movement Therapy—CIMT) and/or have poor patient compliance (Jannink et al., 2007). By comparison, virtual-reality (VR) based treatments afford new options for engaging children, maintaining their level of motivation, and for providing a set of scalable movement tasks that utilise real-time feedback. VR-augmented therapies have been applied successfully in adult movement rehabilitation, however, a systematic approach to rehabilitation in children is yet to evolve (Green & Wilson, 2012; Henderson, Korner-Bittensky, & Levin, 2007).

In this paper, I present a new model for movement rehabilitation of children with motor disorders including cerebral palsy and Developmental Coordination Disorder (DCD), a form of severe movement clumsiness in childhood. From the perspective of developmental cognitive neuroscience, I examine our current understanding of the key concepts of predictive control and multimodal integration. I will show these concepts to be pivotal in re-conceptualising our approach to motor intervention. In doing so, I will highlight principles underlying the use of multimodal, augmented feedback (AF) in therapy, and explain how VR-based systems are the ideal vehicle.

2. THE DEVELOPMENT OF MOTOR CONTROL
I present a conceptual model for the use of AF in VR-based therapy. A critical task of motor learning and development is the child’s ability to extract (implicit) knowledge of the dynamics of their own motor system (Hyde & Wilson, 2011a, 2011b). More precisely, the child must learn the systematic relationship between
their own motor output commands and the effects that these commands have on the physical system; this knowledge enables predictive control, an aspect of internal modelling (Shadmehr, Smith, & Krakauer, 2010). Mature reaching is now thought to be controlled by an integrated system of feedback and feedforward control. This system enables the performer to adjust rapidly in real time to changing environmental constraints, like a moving target, with some movement parameters (like trajectory) changing in as little as 70-80 ms. The ability to implement such changes is only viable to the extent that the nervous system can predict the future location of the moving limb using a forward (internal) model (Desmurget & Grafton, 2003). This flexibility is one of the hallmarks of skilled motor behaviour, and develops gradually over childhood (Hyde & Wilson, in press).

That predictive control develops rapidly over childhood has been shown in a range of contexts including force adaptation (Konczak, Jansen-Osmann, & Kalveram, 2003), isometric force control (Smits-Engelsman, Wilson, Westenberg, & Duysens, 2003), anticipatory postural adjustments (Hay & Redon, 1999), and rapid online control of reaching in response to visual perturbation (Hyde & Wilson, in press). Critically, during middle childhood we see a transition in motor control, with greater reliance on visual feedback, accompanied by longer movement times but not enhanced accuracy (Bard, Hay, & Fleury, 1990; Chicoine, Lassonde, & Proteau, 1992). In later childhood we see a more mature integration of feedback and feedforward control, speeding target-directed responses and improving accuracy.

One important feature of the mature motor system is the ability to adapt movement seamlessly and efficiently in real time while maintaining speed and accuracy (Shadmehr & Krakauer, 2008). Hyde and Wilson (Hyde & Wilson, in press), for example, have shown that younger children are slower to adjust their reaching to visual perturbation than older children, suggesting a reduced ability to integrate predictive estimates of limb position with online feedback. For static targets, the movement times of older children (8-12 years) were around 550 ms and increased to around 800 on trials when the target jumped at movement onset. By comparison, the relative increase for younger children aged 5 to 7 years was significantly greater, from around 640 to 1030 ms. Moreover, younger children took longer to correct their movement trajectory on jump trials. These online corrections are thought to involve internal feedback loops which enable the seamless integration of predictive error signals with ongoing motor commands (Dubrowski, Bock, Carnahan, & Jüngling, 2002; Van Braeckel, Butcher, Geuze, Stremmelaar, & Bouma, 2007). Indeed, there is strong evidence that visual feedback is used to control reaching throughout the reaching cycle (Saunders & Knill, 2003, 2005) rather than simply towards the end of movement—path corrections are evident within 70-100 ms following target jumps, at least in healthy adults. In short, this process of rapid online control develops rapidly over childhood and is quite well developed in older children (Lhuisset & Proteau, 2004).

3. DEVELOPMENTAL MOTOR DISORDERS: THE CASE OF DCD AND CP

In the case of DCD, there is converging data to show that these children have a fundamental deficit of motor prediction, necessitating a reliance on slower, feedback-based control (Hyde & Wilson, 2011a). This accounts for the generally more laboured and inefficient movement patterns we see in this group. In the case of CP, the motor deficits extend to movement initiation as well as prediction (Green & Wilson, 2012).

3.1 Developmental Coordination Disorder

Deficits of motor prediction in children with DCD are evident across a range of tasks, performed under different spatial and temporal constraints. These have included sequential eye movements (Katschmarsky, Cairney, Maruff, Wilson, & Currie, 2000), visual tracking (Langaa, Mon-Williams, Wann, Pascal, & Thompson, 1998), coupling of grip and load force during lifting (Pereira, Landgren, Gillberg, & Forssberg, 2001), visually-guided reaching (Wilmut & Wann, 2008), and visual-motor adaptation (Kagerer, Bo, Contreras-Vidal, & Clark, 2004). Of the first listed example, performance on a double-step saccade task (DSST) is particularly instructive. Here children were required to make eye movements to two targets presented sequentially, the first target for 140 ms and the second for 100. Because the second target is extinguished before initiation of the first eye movement, the performer must use a forward estimate of the end position of the first saccade in order to then generate a motor command that will enable “capture” of the second target (Heide, Blankenburg, Zimmermann, & Kömpf, 1995). Intriguingly, children with DCD are as accurate as typically developing children for the first eye movement, but significantly less so for the second. This pattern of performance underlines a basic deficit of prediction in children with DCD which may be attributable to immaturities at the level of parietal cortex and its reciprocal connections with the cerebellum.
3.2 Cerebral Palsy

Children with cerebral palsy (or spastic hemiplegia) show fundamental deficits in not only the ability to execute movements but also in movement representation and planning (Mutsaarts, Steenbergen, & Bekkering, 2006; Steenbergen & Gordon, 2006). The planning issues are manifest, among other things, in the ability to imagine how a prospective action will unfold (aka motor imagery). This facility to anticipate the spatiotemporal unfolding of an action (without execution) has been assessed using mental rotation tasks involving pictorial representations of body parts (like hands or whole-body stimuli). Steenbergen et al. (Steenbergen, van Nimwegen, & Crajé, 2007) tested both left- and right-sided hemiplegic patients and found that while there was no group difference between patients and healthy controls on accuracy or the timing of responses, the hemiplegic patients were generally slower. They concluded that the patients were not adopting an egocentric frame when making responses but rather used a more visually-mediated strategy. Similar results have been shown for children with CP (Williams et al., 2011). Taken together, poor motor imagery in CP seems to reflect a core deficit in the ability to generate (forward) internal models of movement. This argument is supported by neuroimaging data showing overlap in the neural networks that support both motor imagery and predictive control (De Lange, Hagoort, & Toni, 2005).

4. IMPLICATIONS FOR TREATMENT: AUGMENTED FEEDBACK AND ATTENTIONAL TRAINING

A critical part of the motor learning process is use of feedback as a means of comparing the executed action with the intended outcome of a movement. In typical learning over repeated trials, we see a gradual reduction in the discrepancy between the two. In atypical motor development, sheer repetition does not necessarily translate into improved motor skill; this is evident in both severe DCD and CP. Moreover, in the case of CP, the mechanisms by which sensory information is processed may be compromised, which further compounds the ability to implement error correction and predictive control. Importantly, methods of augmented feedback have been shown to benefit both populations, with multisensory (extrinsic) feedback and techniques that cue attentional focus being shown to exert good treatment effects (van Dijk, Jannink, & Hermens, 2005; VanVliet & Wulf, 2006).

4.1 Augmented Feedback

External (or augmented) feedback (AF) involves providing information about the performance of an action, over and above that available to the performer’s own cognitive and sensory-motor systems. In other words, the external information is additional to the naturally-occurring (or intrinsic) sources of input. There are several basic forms of AF: knowledge of results (KR), knowledge of performance (KP), and concurrent AF. KR involves the provision of information about the outcome of a movement (e.g., percentage success after a set of trials), while KP concerns the manner in which the movement was performed and its form. Concurrent AF involves the provision of real-time feedback, most often in the form of correlated visual, haptic, or auditory input. The benefits of various forms of AF (relative to no AF) have been well documented in the mainstream motor learning literature (Gordon & Magill, 2012; Magill, 2010). For example, AF has been shown to aid the development of coordination on rhythmic tasks, increasing stability. This is provided that multisensory information is presented synchronously with the key movement transitions (Carson & Kelso, 2004)—e.g., flexion-extension movements of the fingers, timed to an external auditory, haptic, and/or visual stimulus.

The case for AF in the rehabilitation of brain injury has also been made in a number of authoritative reviews (van Vliet & Wulf, 2006; Winston, Wing, & Whitall, 2003). However, the quality of evidence has varied quite significantly across studies (van Dijk, et al., 2005). In van Dijk’s systematic review, no conclusive evidence was found for the effectiveness of AF on upper-limb function. However, frequently omitted from these studies was crucial information about the specific form of feedback used, adequate follow-up assessments, and very few studies used RCTs. A narrative account by van Vliet (2006) suggested more positive effects on different aspects of motor function. However, similar to van Dijk, there were a number of outstanding issues in the literature, including the relative effect of visual, verbal, video and kinematic feedback, and the types of task scheduling that yield stronger effects.

4.2 Attentional Training

The mainstream literature has provided some interesting insights into the use of AF and how it best directs the performer’s attention. The work of Wulf and colleagues (Wulf, Chiviacowsky, Schiller, & Toaldo Gentilini Ávila, 2010; Wulf, Shea, & Lewthwaite, 2010) has been most influential in showing the benefits of an external focus of attention during skill acquisition, both in adults and children (Wulf, Shea, et al., 2010).
That is, external cues are provided that encourage the performer to focus on the effects of their movement (e.g., trajectory), rather than their internal state or somatic sensations. Importantly, it does not appear to be the case that performers become excessively reliant on such cuing to the point where performance declines once it is removed (Wulf & Shea, 2004). Indeed, performance on retention and transfer tasks has been shown to be superior after external focus training than internal focus (Wulf, Shea, et al., 2010). More fundamental work has also shown that concurrent AF which biases attention to the effect of the movement yields stronger training and retention effects than feedback about movement form (Todorov, Shadmehr, & Bizzi, 1997; Wulf & Prinz, 2001).

From a cognitivist perspective, the advantage of taking an external focus of attention has been explained by increased automaticity in motor control—aka the constrained action hypothesis (Wulf, McNevin, & Shea, 2001). Put simply, the external focus allows the performer to enlist rapid control processes, including the ability to implement online adjustments. By comparison, switching attention to internal states and body position may encourage greater focus on the self and perhaps self-evaluation, which may interfere with the unconscious flow we associate with skilled performance. A more detailed account of underlying control processes has proved elusive from a purely cognitivist perspective.

Ideas encapsulated in the ideomotor theory of Prinz and colleagues has been more influential, drawing on neurocomputational models of action (Hommel, Müsseler, Aschersleben, & Prinz, 2001; Prinz, 1997). This states quite simply that actions are controlled by their intended effects. Ultimately, the performer learns to predict action effects in advance, with this predictive model used as a template against which actual feedback is compared. As such, the prediction is used to monitor how well an executed action matches its intended trajectory and goal outcome. Action is most efficient, therefore, when planned according to intended effects or outcomes, rather than internal states (Wulf, Chiviacowsky, et al., 2010). The use of AF that helps direct attention to movement effects is, thus, a more powerful medium for skill development and rehabilitation than other forms of feedback.

With respect to motor rehabilitation, there has been relatively little research that has examined the differential effects of adopting an internal or external focus of attention. However, there is some suggestion from cognate research that the advantages of external focus also apply to brain damaged patients (Piron et al., 2007; van Vliet & Wulf, 2006). For example, in cases where predictive control has been disrupted (through brain damage or developmental immaturity), provision of concurrent AF has been shown to assist recovery of upper-limb function (Quaney et al. 2010). What is sobering, then, is that the vast majority of verbal instructions made by movement therapists to patients in clinical settings are related to body movements and sensation, and are likely to induce an internal focus of attention (Durham, Van Vliet, Badger, & Sackley, 2009).

5. RECENT EVIDENCE SUPPORTING THE USE OF VR-ASSISTED AUGMENTED FEEDBACK

Understanding the mechanisms of normal motor development and those disrupted in CP and DCD has important implications for the choice of therapy. AF, presented using various sensory modalities in real time, can greatly leverage the development of skill in these children. Virtual-reality based systems are the perfect vehicle for this treatment, the Elements VR system being a recent example (Mumford & Wilson, 2010; Peter H. Wilson et al., 2007)—see Figure 1. This system targets upper-limb function using a series of tangible user interfaces (TUIs), camera-based tracking, and interactive tabletop workspace. Both goal-directed and exploratory manual tasks are employed using various forms of concurrent AF. The goal-directed tasks are cued from within the virtual workspace, with each form of AF used to reinforce one or more of three outcome parameters (speed, accuracy, and efficiency). Wulf and colleagues have also identified how AF can be used to target particular movement parameters in this way (Wulf & Prinz, 2001; Wulf, Shea, et al., 2010). For exploratory tasks, children can create their own visual and aural compositions by manipulating the TUI; for example, coloured trails – one form of AF – are composed as objects are moved across the display. In general, the AF serves two main purposes: First, it provides children with additional feedback about the outcomes of their actions; this reinforces the child’s sense of position in space and of the relationship between motor command and the resultant action. We argue that this process helps train predictive (or forward) models for action. Second, AF enables the child to focus their attention on the effects of their movement, rather than on the movement itself (Wulf & Prinz, 2001). This has been shown to be leverage skill development during the early phases of learning and during rehabilitation.

A number of studies now support the argument that VR-based systems are an ideal medium through which AF can leverage the development of motor skill in children with movement disorders. The Elements system, for example, has recently been evaluated in childhood CP using a multiple case study design (Green...
Four children with non-progressive hemiplegia participated in 30-min sessions daily for 3-4 weeks. During training, each child was instructed to focus on a type of concurrent AF that was appropriate to the performance variable that was targeted. For example, if the aim was to improve accuracy, the child was instructed to focus on “disk AF” which consisted of an increase in the luminance of the target as the TUI approached it. Children engaged well with the system, found it intuitive to use, and derived reward from the movement-dependent AF. Critically, training saw considerable improvement in the motor skill of children with quite severe CP. This supports earlier work in adult patients with TBI (Mumford & Wilson, 2010). Methods to test the hypothesis that improved predictive control underlies these changes are under current investigation.

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Figure 1. Sample display from the Elements system: Goal-directed task including (visual) augmented feedback.

6. CONCLUSIONS

A principled approach to VR-augmented rehabilitation is only possible to the extent that we fully understand the neurocognitive underpinnings of childhood disorders like CP and DCD. A review of the literature suggests that predictive control is one pivotal component of the motor system that is frequently disrupted in children with these disorders. Predictive control is implemented using a distributed system of cortical and sub-cortical structures including the cerebellum, posterior parietal cortex and their reciprocal connections to frontal motor cortices. Critical to predictive control is the performer’s ability to construct (or re-construct) the systematic relationship that exists between motor command signals and their anticipated effects on the physical system. Implicit knowledge of this relationship underpins the use of forward internal modelling as means of rapid online control, for example (Desmurget & Sirigu, 2009). Intriguingly, AF is one treatment modality that may foster the development of this ability in children with motor problems. More specifically, concurrent AF (which also encourages an external focus of attention) has been shown to be particularly effective when implemented using VR-based systems. The Elements system, for example, has used a combination of aural and visual AF to leverage the recovery of children with not only CP, but also childhood stroke and other congenital disorders affecting movement (Green & Wilson, 2012).

Our use of the term VR-augmented therapy, thus, takes on a dual meaning: it suggests both the promise of VR in leveraging rehabilitation in children, as well as its possibilities as a medium for providing AF. We suggest that multisensory AF is a particularly powerful way of encouraging children to learn (or re-learn) movement skills. Part of this learning process involves the gradual re-construction of the child’s body schema and the ability to anticipate the outcomes of its interactions with a 3D environment. Exactly what aspects of AF (and their combination) yield the strongest training effects is a prime issue for investigation, as is the extent to which functional gains are correlated with the ability to use predictive control. Future research in this area will inform not only the clinical application of VR technologies, but also our basic understanding of the motor control and learning system.

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5. REFERENCES


