ABSTRACT

Title of Dissertation: THE EFFECTS OF AGE-RELATED DIFFERENCES IN STATE ESTIMATION ON SENSORIMOTOR CONTROL OF THE ARM IN SCHOOL-AGE CHILDREN

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Previous research examining sensorimotor control of arm movements in school-age children has demonstrated age-related improvements in performance. A unifying, mechanistic explanation of these improvements is currently lacking. This dissertation systematically examined the processes involved in sensorimotor control of the arm to investigate the hypothesis that improvements in performance can be attributed, in part, to developmental changes in state estimation, defined as estimates computed by the central nervous system (CNS) that specify current and future hand positions and velocities (i.e., hand 'state'). A series of behavioral experiments were employed in which 5- to 12-year-old children and adults executed goal-directed arm movements. Experiment 1 demonstrated that improvements in proprioceptive functioning resulted in an increased contribution of proprioception to the multisensory estimate of hand position, suggesting that the CNS of children flexibly integrates redundant sensorimotor feedback based on the accuracy of the individual inputs. Experiment 2 demonstrated that improvements in proprioceptive functioning for localizing initial hand position reduced the directional variability of goal-directed reaching, suggesting that improvements in static state estimation contribute to the age-related improvements in performance. Relying on sensory feedback to provide estimates of hand state *during* movement execution can result in erroneous movement trajectories due to delays in sensory processing. Research in adults has suggested that the CNS circumvents these delays by integrating sensory feedback with *predictions* of future hand states (i.e., dynamic state estimation), a finding that has not been investigated in children. Experiment 3 demonstrated that young children utilized delayed and unreliable state estimates to make on-line trajectory modifications, resulting in poor sensorimotor performance. Last, Experiment 4 hypothesized that if improvements in state estimation drive improvements in sensorimotor performance, then exposure to a perturbation that simulated the delayed and unreliable dynamic state estimation in young children would cause the adults to perform similarly to the young children (i.e., eliminating age-related improvements in performance). Results from this study were equivocal. Collectively, the results from these experiments: 1) characterized a developmental trajectory of state estimation across 5- to 12-year-old children; and, 2) demonstrated that the development of state estimation is one mechanism underlying the age-related improvements in sensorimotor performance.

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Dissertation submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
2011

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ACKNOWLEDGEMENTS

I would like to thank all of those who have helped me throughout this process, especially:

- Dr. Jane Clark, for being my advisor, providing a tremendous amount of support and guidance throughout my graduate training, and putting up with me for a total of 7 years and 2 degrees.
- Dr. Jose Contreras-Vidal, for serving as my unofficial co-advisor and offering tremendous insights and valuable feedback on my research.
- Dr. Mario Oliveira, for not only providing tremendous feedback on ongoing research projects, but also serving as a mentor and allowing me to barge into his office unannounced to chat, complain, etc.
- Dr. William Levine and Dr. Jae Kun Shim for serving on my dissertation committee and offering insightful comments, suggestions and questions throughout the dissertation process.
- Team Motor Development, especially Florian Kagerer, Woei-Nan Bair, Li-Chiou Chen, Jason Metcalfe, Jin Bo, Melissa Pangelinan, Kristin Cipriani, and Du Yue, for all their help and support over the years, especially with mass data collection during the summer and subject recruitment.
- My parents, Randy and Linda, for the incredible support, friendship, and love they provide.
- To an incredible group of friends, appropriately referred to as 9+, for reminding me that life does indeed exist outside of the lab.
- Last, and most importantly, to Melissa for her incredible support, patience, understanding and love. I certainly would never have made it through this process without her by my side.

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CHAPTER I: INTRODUCTION

Previous research has demonstrated that adults execute goal-directed arm movements with remarkable consistency and accuracy (Flash & Hogan, 1985; Morasso, 1981). The development of this behavior across childhood is significant because changes in the developing sensorimotor system and in the physical characteristics of the body can impact motor learning and control. Indeed, previous developmental research examining sensorimotor control of the arm in school-age children has demonstrated age-related differences in movement straightness and smoothness, temporal and spatial variability, and movement speed (Bo, Contreras-Vidal, Kagerer, & Clark, 2006; Contreras-Vidal, 2006; Contreras-Vidal, Bo, Boudreau, & Clark, 2005; Hay, 1979; Jansen-Osmann, Richter, Konczak, & Kalveram, 2002; Yan, Thomas, Stelmach, & Thomas, 2000; Yan, Thomas, Stelmach, & Thomas, 2003). Although characterizations of these age-related behavioral differences are pervasive in the developmental literature, a comprehensive, mechanistic explanation has not been identified. This dissertation systematically investigates the processes involved in sensorimotor control of the arm to identify potential mechanisms underlying the age-related behavioral differences in school-age children. Such research may reveal processes that can be considered ‘rate-limiters’ in sensorimotor development.

Detailed conceptual frameworks have been developed that decompose the execution of goal-directed arm movements into a series of computational problems that are solved by the central nervous system (CNS) (e.g., Bullock & Grossberg, 1988; Shadmehr & Wise, 2005; Todorov & Jordan, 2002; Wolpert & Kawato, 1998). Although specific parameters and characteristics differ across frameworks, the computational problems inherent in goal-directed arm movements remain the same. A generalized framework is depicted in Figure 1.1. The primary focus of this dissertation is *state estimation* (shaded region) as the accurate execution of goal-directed arm movements depends on the precise estimation of both current and future hand positions and velocities (i.e., hand 'state') (e.g., Shadmehr et al., 2005; Vindras, Desmurget, Prablanc, & Viviani, 1998). State estimation is dependent on two inputs: 1) afferent information from the available sensory modalities (Figure 1.1: sensory systems → state estimator); and, 2) the output of a forward model (Figure 1.1) that *predicts* the future states of the system based on copies of descending motor commands, knowledge of the arm's dynamics, and prior state estimates (Blakemore, Goodbody, & Wolpert, 1998a; Miall & Wolpert, 1996; Wolpert & Flanagan, 2001).

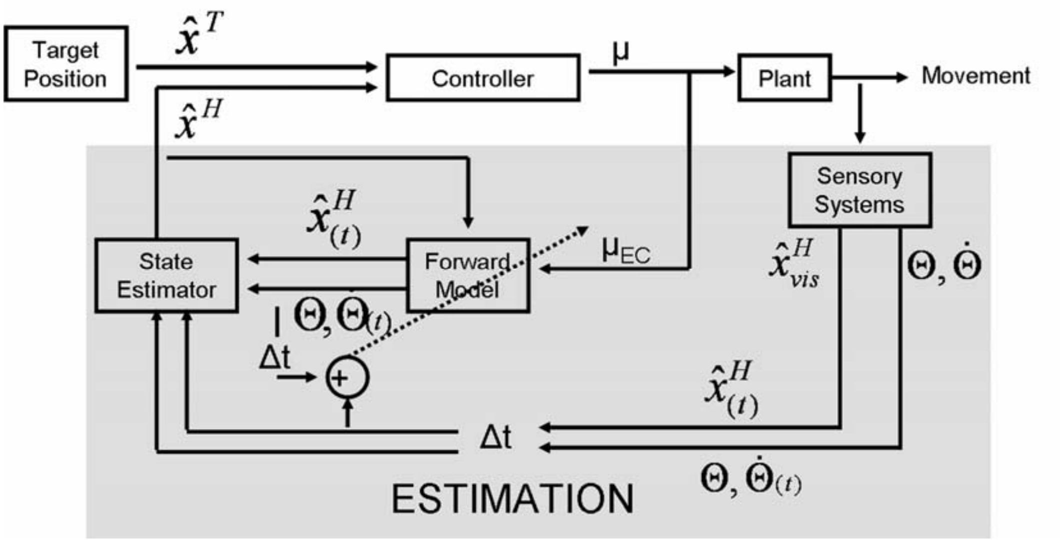

Figure 1.1. Conceptual Framework depicting the processes underlying goal-directed arm movements. Refer to the text for detailed description. $\hat{x}$ *= estimate in extrinsic (Cartesian coordinates);* ^{T} *= target;* ^{H} *= hand;* μ *= motor command;* $_{EC}$ *= efference copy;* Δt *= time delay;* Θ *= hand position in joint-centered coordinates;* $\dot{\Theta}$ *= hand velocity in joint-centered coordinates.*

In the context of hand localization, if the arm is not occluded, both vision and proprioception can provide sensory feedback of hand state. Therefore, estimation is dependent not only on an individual sensory modality, but also on the ability to integrate information from multiple modalities. Previous developmental research has employed localization tasks to probe the influence of visual and proprioceptive functioning for hand localization (Contreras-Vidal, 2006; Mon-Williams, Wann, & Pascal, 1999; von Hofsten & Rosblad, 1988). Although non-monotonic age-related improvements were reported in the localization of visual, proprioceptive, and simultaneous visual-proprioceptive stimuli, the magnitude of the improvement in the localization of proprioceptive stimuli between 7 and 9 years of age was greater than the improvement in the localization of visual stimuli (von Hofsten et al., 1988). This result is consistent with research by Contreras-Vidal (2006) and suggests that the improvements in proprioceptive functioning, a critical component of ‘static’ (i.e., stationary) state estimation, may contribute to the age-related improvements in sensorimotor performance reported in the extant literature (Bo et al., 2006; Contreras-Vidal et al., 2005; Hay, 1979; Jansen-Osmann et al., 2002; King, Kagerer, Contreras-Vidal, & Clark, 2009; Yan et al., 2003).

During the execution of rapid, ballistic reaching movements, relying on sensory afferents to generate feedback-dependent corrective movements can result in erroneous and inefficient movement trajectories due to the delays in sensory processing. Thus, *predicting* future states based on efference copies of a motor commands can be used as an internal reference to circumvent the processing delays, a finding that has been previously demonstrated in adults (Desmurget & Grafton, 2000; Tseng, Diedrichsen, Krakauer, Shadmehr, & Bastian, 2007; Wagner & Smith, 2008; Wolpert et al., 2001). This prediction depends on two factors: 1) an accurate estimate of the system’s most current state (Figure 1.1: State Estimator); and, 2) a developed forward model that can map the current state of the system to future states based on efference copies of motor commands

(Figure 1.1: Forward Model) (Desmurget et al., 2000; Wolpert, Ghahramani, & Jordan, 1995). An inability to accurately and reliably predict future states may be manifested in an increased reliance on *delayed* sensory feedback during the execution of reaching movements. Hay and colleagues (Hay, 1979; Hay, Bard, Fleury, & Teasdale, 1991; Hay & Redon, 1999) demonstrated a shift *away* from feedback-dependent control around 9-10 years of age, a result that potentially suggests that the ability to predict future states of the arm during reaching movements develops around 9-10 years.

The primary purpose of this dissertation is to investigate the hypothesis that the age-related differences in sensorimotor control of the arm can be attributed, in part, to developmental changes in state estimation. More specifically, improvements in the acuity of proprioceptive feedback and in the ability to predict the consequences of descending motor commands are, at least partially, responsible for age-related improvements in movement straightness and smoothness, spatial and temporal variability, and movement speed.

Specific Aims

The following four specific aims are investigated in this dissertation.

Specific Aim 1: ***To determine the effect of unimodal (vision/proprioception) sensorimotor localization on multisensory-motor integration in 7- to 13-year-old children***.

Vision and proprioception can both provide estimates of static (i.e., stationary) hand state. To increase the accuracy and reliability of this estimate, information from multiple modalities is integrated (Figure 1.1: state estimator). Whereas unimodal sensorimotor acuity in adults is precise and stable, developmental changes across childhood result in robust differences in the localization of unimodal stimuli (Contreras-Vidal, 2006; von Hofsten et al., 1988). These changes in unimodal sensorimotor acuity are likely to impact multisensory-motor integration.

Hypothesis 1: Changes in unimodal (vision / proprioception) sensorimotor functioning systematically impact the relative contributions of each modality to the multisensory estimate, suggesting that developmental differences in multisensory-motor integration can be, at least partially, explained by improvements in unimodal functioning.

Specific Aim 2: ***To characterize the effect of age-related differences in the accuracy and reliability of proprioceptive feedback for <u>static</u> (i.e., stationary) state estimation on functional sensorimotor behavior in 5- to 12-year-old children***.

Prior to the execution of a goal-directed arm movement, the CNS utilizes visual and proprioceptive information about the static (i.e., stationary) position of the hand to generate an appropriate motor plan (Figure 1.1: Sensory Systems → State Estimator). Whereas static visual acuity is relatively stable in school-age children (Nelson, Rubin, Wagner, & Breton, 1984), age-related changes in proprioceptive acuity may result in impaired static state estimation in younger children (i.e., 5-6 years) in the absence of vision of the hand (Contreras-Vidal, 2006; von Hofsten et al., 1988). Impaired static state estimation, in turn, may underlie the decreased sensorimotor performance in younger children reported in previous research (Bo et al., 2006; Contreras-Vidal et al., 2005; Hay, 1979; King et al., 2009; Yan et al., 2000; Yan et al., 2003).

Hypothesis 2: Five- to seven-year-old children have less precise proprioceptive feedback for static state estimation, compared to older children (eight- to 12-years), resulting in decreased sensorimotor performance.

Specific Aim 3*: **To characterize the effect of age-related differences in the accuracy and precision of dynamic (i.e., during movement execution) state estimation, provided via vision, proprioception, and/or motor outflow, on functional sensorimotor behavior in 5- to 12-year-old children.***

To avoid delays inherent in sensory feedback, efference copies of a descending motor commands can be used to predict the future states of the system. This prediction can be combined with an estimate of the most current state of the arm (Figure 1.1: Forward Model → State Estimator) and serves as an internal feedback system in order to generate on-line corrections *during* movement execution. Critically, this process is thought to be dependent on an ability to accurately *predict* the consequences of a motor command, a computation that requires a developed forward model.

Hay and colleagues have reported non-monotonic changes across school-age children in the utilization of feedforward and feedback control strategies during reaching tasks (Bard, Hay, & Fleury, 1990; Hay, 1979; Hay, Bard, Ferrel, Olivier, & Fleury, 2005; Hay et al., 1999). Importantly, 7-9 year-old children were thought to be feedback dependent. An increased reliance on feedback (i.e., Figure 1.1: Sensory Systems → State Estimator) suggests that these children are not predicting future states based on efference copies of motor commands (Figure 1.1: Forward Model) but are rather relying on delayed afferent inputs.

Hypothesis 3: Five- to 9-year-old children rely on delayed and unreliable sensory feedback during the execution of goal-directed arm movements, resulting in impaired dynamic state estimation and poor sensorimotor performance compared to 10- to 12-year-olds and adults.

Specific Aim 4*: To demonstrate that age-related improvements in sensorimotor control of the arm across childhood are, in part, explained by improvements in state estimation.*

The over-arching hypothesis of this dissertation is that state estimation is a rate-limiter for the development of sensorimotor control of the arm in school-age children. The purpose of this visual feedback perturbation is to systematically disrupt dynamic state estimation in the adult participants. By increasing variability and inserting a temporal delay into the visual feedback, the magnitudes of which are based on the performance of 5- to 7-year-old children, the perturbation would theoretically create an environment that precluded accurate and reliable dynamic state estimation. Ideally, this perturbation would make dynamic state estimation in the adults equally inaccurate and unreliable as the younger children, allowing us to directly assess the relationship between dynamic state estimation and sensorimotor control. Specifically, if improvements in state estimation are responsible for age-related improvements in sensorimotor performance, then exposure to this dynamic state estimation perturbation will result in similar sensorimotor performance across 5- to 12-year old children and adults, effectively eliminating the age-related improvements demonstrated in previous research and in Specific Aims 2 and 3.

Hypothesis 4: Exposure to a predictive state estimation perturbation results in equivalent sensorimotor performance in 5- to 7-year-old children and adults, suggesting that age-related improvements in state estimation are responsible, in part, for the age-related improvements in sensorimotor control of the arm reported in the extant literature.

Summary

The set of experiments included in this dissertation systematically investigates the hypothesis that improvements in state estimation are responsible, at least partially, for the age-related improvements in sensorimotor performance reported in previous research. Specific Aim 1 probes the relationship between unimodal sensorimotor (vision / proprioception) functioning and the integration of multisensory-motor information (Figure 1.1: Sensory Systems → State Estimator). Integrating multiple sensory inputs is critical for hand localization as both vision and proprioception can provide estimates of hand state. Specific Aim 2 builds on the first aim by investigating the effect of age-related improvements in proprioceptive localization, a critical component of static state estimation, on *functional* sensorimotor behavior. It is hypothesized that the age-related improvements in proprioceptive functioning contribute to the age-related improvements in sensorimotor performance reported in the extant literature. However, relying on sensory feedback to provide estimates of hand state *during* the execution of rapid arm movements (i.e., dynamic state estimation) can result in erroneous movement trajectories due to delays in sensory processing. Thus, Specific Aim 3 examines age-related improvements in state estimation during movement execution, a process that involves predicting the future states of the arm based on copies of the motor commands (Figure 1.1: Forward Model). Last, Specific Aim 4 extends the third aim by investigating the effect of the development of dynamic state estimation on functional sensorimotor behavior. ***Collectively, these experiments characterize the development of state estimation in typically-developing children; and, link this developmental trajectory of state estimation to age-related improvements in sensorimotor control of the arm.***

This line of research is significant as it provides novel insights into mechanisms underlying sensorimotor development of typically-developing (TD) school-age children. Once the rate-limiters of typical sensorimotor development are revealed, specific factors and/or experiences that may facilitate or enhance the developmental process can be identified. Moreover, an investigation into typical sensorimotor development may provide insights into children with movement disabilities such as Developmental Coordination Disorder (DCD). An increased understanding of these developmental motor impairments could lead to the design and implementation of behavioral interventions that target the specific mechanisms or processes underlying DCD. This will influence not only motor functioning, but will also have academic (e.g., Cantell, Smyth, & Ahonen, 1994), socio-emotional (e.g., Skinner & Piek, 2001), and physical health implications of children with DCD (e.g., Faught, Hay, Cairney, & Flouris, 2005).

Six chapters are included in this dissertation. Following this introduction, the second chapter contains a review of the relevant literature. The third through fifth chapters provide the methodology, expected findings, and discussions for the four specific aims. The final chapter includes a general discussion, including the implications and significance of the proposed research and suggestions for future directions.

CHAPTER II: REVIEW OF LITERATURE

School-age children demonstrate substantial improvements in the control and coordination of arm movements across childhood. The arm movements of younger children (i.e., 4- to 5-year-olds) are generally characterized as slower, less accurate, less smooth and more variable, as compared to older children (i.e., 11-12 year-olds). Although these age-related changes in behavior are extensively documented in the literature, less is known about the *processes* that underlie these changes. An understanding of the underlying processes of change is a critical component of motor development research (Clark & Whitall, 1989).

This dissertation aims to provide a unifying, mechanistic explanation of the processing underlying the age-related improvements in sensorimotor behavior of the arm. To achieve this aim, we will systematically investigate the processes underlying goal-directed arm movements based on established conceptual frameworks in motor control (Bullock et al., 1988; Shadmehr et al., 2005; Shadmehr & Krakauer, 2008; Todorov et al., 2002). Specifically, the hypothesis of this dissertation is that the age-related *differences in sensorimotor control of the arm across 5- to 12-year-old children can be attributed in part to age-related improvements in 'state estimation'*, defined as the estimates computed by the central nervous system (CNS) providing the current and future positions and velocities (i.e., 'state') of the arm (e.g., Miall & King, 2008; Shadmehr et al., 2008).

The review of literature includes three sections. The first section will discuss the age-related changes in sensorimotor performance of the arm from infancy to childhood and will explore the explanations of these data provided in the extant literature. The second section will focus on the motor control frameworks that serve as the foundation for this dissertation, with an emphasis on state estimation. The final section highlights the knowledge gaps in the extant literature.

Age-related Changes in Sensorimotor Behavior

Infancy

Across the first year of life, infants demonstrate substantial behavioral changes in the execution of arm movements. One of the earliest examinations of reaching behavior, with respect to the age of the infants, was conducted by von Hofsten (1982). When 5- to 9-day-old newborns fixated on an object in the environment, they were more likely to 'reach' towards that object and their movements were more accurate, as compared to times of non-fixation. These data suggest that an elementary mode of eye-hand coordination is present in newborns. It should be emphasized that this eye-hand coordination is under-developed as contact with the object was made on a small percentage of movements.

The arm movements over an infant's first four months are frequently labeled as '*pre-reaches*' (Bushnell, 1985; Trevarthen, 1984; von Hofsten, 1984). These are characterized by: 1) dependence on open-loop (i.e., feedforward) control strategies; 2) decreased accuracy; and, 3) increased reliance on the 'felt' position of the hand (i.e., somatosensation) as opposed to a visual estimate (Bushnell, 1985). There is a general consensus that more successful, *visually-guided* reaching emerges around four months of age, although there is considerable between-subject variability in the onset of this behavioral achievement (Berthier & Keen, 2006; Thelen, Corbetta, & Spencer, 1996; White, Castle, & Held, 1964). During the early stages of this visually-guided reaching (up to 6 months), reaches are generally controlled by muscles of the shoulder joint whereas muscles that control the more distal joints (i.e., elbow) tend to be restricted

(Berthier, Clifton, McCall, & Robin, 1999; Spencer & Thelen, 2000). This strategy is consistent with Bernstein's (1967) notion of 'freezing' degrees of freedom during early motor learning. Visually-guided reaching, as compared to pre-reaching, is characterized by an increase in accuracy and an increased reliance on visual feedback to not only localize the hand, but also to guide the hand to the desired target (Bushnell, 1985). Thus, infants older than four months appear to utilize the available feedback in order to increase the accuracy of the arm movements. This suggests that there is a shift from a feedforward (i.e., open loop) to a feedback (i.e., closed loop) control strategy around four months of age. Moreover, vision appears to be the preferred sensory modality for these feedback-dependent processes. Evidence for this increased dependence on visual feedback of hand position comes from experiments during which a conflict was introduced between visual and proprioceptive estimates of hand position (i.e., mirror drawing). Infants younger than approximately four months were less affected by the perturbation, as compared to infants older than four months, suggesting that the older infants attempted to utilize the manipulated visual feedback to perform the task whereas the younger infants relied on the non-manipulated proprioceptive cues of hand position (Lasky, 1977).

Although the reaching movements of infants between four and eight months are commonly classified as visually-guided, this interpretation is equivocal. In a longitudinal study that included testing between 6 and 25 weeks of age, Clifton and colleagues demonstrated that reaching with or without vision of the hand resulted in identical behavioral performance (Clifton, 1993; Clifton, Rochat, Robin, & Berthier, 1994). The authors suggested that the reaching movements across this age range are *not* necessarily visually-guided; rather, the infants can use proprioceptive feedback of arm position to successfully reach the desired target.

In addition to the improvements in reaching performance around four months of age (Thelen et al., 1996; White et al., 1964), there is evidence to suggest another shift in reaching behavior around seven to nine months. Thelen and colleagues (1996) employed a longitudinal experimental design examining the reaching behavior of infants from three to 52 weeks of age. Results demonstrated an abrupt improvement in the movement trajectories and a decreased number of movement units around 30 to 36 weeks. Interestingly, this improvement in performance reported in Thelen et al. (1996) coincides temporally with research suggesting a shift back to the ballistic, feed-forward control strategy that was evident in the pre-reaching period (Bushnell, 1985). Bushnell (1985) argued that the disappearance of visually-guided reaching around seven to nine months can be explained by the extensive sensorimotor stimulation that infants experience after the onset of successful reaching. This experience results in an overlearning of the skill and this ‘mastery’ leads to the eventual disappearance of visually-guided reaching. This explanation is less than compelling given that substantial age-related changes in sensorimotor performance are evident throughout childhood (e.g., Contreras-Vidal et al., 2005; Jansen-Osmann et al., 2002; King et al., 2009). The notion that ten-month-old infants have mastered the skill of reaching seems to be an oversimplification of the developmental process.

Although the processes underlying this non-linear trajectory are not well understood, there is evidence to suggest that the postural control is a rate-limiter in the development of reaching (Bertenthal & von Hofsten C., 1998; von Hofsten, 1992). For example, ‘complex’ postural responses during the execution of reaching movements appear at approximately the age of successful reach onset (four months) (Van Der Fits & Hadders-Algra, 1998). Moreover, more stable reaching patterns develop around 30 – 36 weeks, which is an approximate age range during which infants attain the ability to sit independently (Thelen et al., 1996). In sum, age-related improvements in reaching across infancy may be partially attributed to age-related improvements in postural control.

Collectively, the research reported above suggests a non-linear developmental trajectory for reaching across the first year of life, ultimately resulting in the infant’s ability to reach for, grasp and manipulate objects in the environment. Reaching during the first four months, commonly referred to as pre-reaching, is characterized by ballistic, feed-forward and inaccurate movements. More successful reaching is achieved around four months; importantly, this developmental achievement may be, at least partially, explained by an increased dependence on visual feedback in order to guide the hand towards the desired target. A second shift in reaching behavior occurs around seven to nine months. Infants are thought to return to the ballistic, feed-forward control mechanisms that were prominent before four months of age. However, the reaching movements of the older infants (approximately eight months and older) are more accurate despite the return to the feed-forward control strategy. There is evidence to suggest that improvements in postural control are one factor that facilitates these changes in reaching behavior across the first year of life.

Childhood

The age-related changes that appear across the first year of life described above continue with substantial improvements in the control and coordination of arm movements across childhood (approximately 5-12 years of age). Specifically, reaching/aiming movements are faster, straighter, smoother, and less variable in older children (e.g., 9 to 12 years) compared to younger children (e.g., 4 to 6 years) (Bo et al., 2006; Contreras-Vidal, 2006; Contreras-Vidal et al., 2005; Jansen-Osmann et al., 2002; King et al., 2009; Yan et al., 2000; Yan et al., 2003).

Although these improvements in reaching performance are well documented in the extant literature, identifying the processes that underlie these age-related improvements is still an open research question. Although several explanations have been posited, we will focus on the two that are the most pervasive in the developmental literature. 1) age-related improvements in sensorimotor performance are the result of changes in the underlying control (i.e., feedforward vs. feedback) mechanisms employed by children; and, 2) age-related improvements in sensorimotor performance are the result of the fine-tuning of acquired internal representations that specify the relationships between (sensory) input and (motor) output.

Feedforward and feedback control

The planning and execution of goal-directed arm movements can be conceptualized as regulated by two different control mechanisms: feedforward and/or feedback. Feedforward control is dependent on the planning prior to the initiation of a movement and is responsible for the initial ballistic phase of a reach trajectory. Feedback control utilizes the available afferents in order to make corrective movements that ultimately facilitate the hand reaching the desired target. Researchers differentiate these two control strategies by manipulating the availability and/or reliability of sensory feedback or by examining the kinematic profiles of the reaching trajectories. For example, reaching movements by adult participants are frequently characterized by bell-shaped velocity profiles (Flash et al., 1985). These single-peak, bell-shaped profiles are thought to indicate that the movements are controlled predominantly by feedforward mechanisms. However, a profile containing additional velocity peaks (or zero acceleration crossings) suggests that the latter portions of the movement were regulated by feedback control mechanisms (e.g., Yan et al., 2003).

Research by Hay and colleagues suggests that the improvements in sensorimotor behavior across school-age children can be explained by shifts in the relative contributions of feedforward and feedback control (Bard et al., 1990; Hay, 1979; Hay et al., 1991; Hay, 1978). Specifically, the execution of reaching movements by seven- to eight-year-old children is considered to be feedback-dependent. Conversely, the performance of younger children (i.e., five- to six-year-olds) is thought to be feedforward-dependent and the performance of older children (i.e., approximately 9-12 years) is thought to be a combination of the two strategies. These findings are based predominantly on experiments that removed *visual* feedback of hand position during the execution of goal-directed reaches. End-point accuracy is substantially reduced in the 7-8 year-old children, suggesting that these children rely on the visual feedback of hand position to perform reaching movements (Bard et al., 1990; Hay, 1978). Moreover, 7-8 year-old children have the longest movement times and the smallest peak velocities and accelerations compared to both the younger and older children, providing further evidence for an increased reliance on sensory feedback (Bard et al., 1990; Hay et al., 1991).

The interpretation that younger children (five- to six-year-olds) rely predominantly on feedforward control mechanisms is not without opposition. Research by Yan and colleagues suggests that 5-6 year-old children utilize the available feedback to monitor their arm movements on-line (Yan et al., 2000; Yan et al., 2003). Specifically, a smaller proportion of the arm trajectory results from feedforward processes in five-year-olds compared to both eight- and ten-year-old children (Yan et al., 2003). [The proportion of the trajectory labeled as feedforward was based on the duration from movement onset to the first zero crossing of the acceleration profile.] Moreover, research in our laboratory has demonstrated that four- to six-year-old children have longer movement times when on-line visual feedback of the hand trajectory is presented, suggesting that these younger children utilize the available feedback in order to move the hand towards the desired target (Bo et al., 2006; Contreras-Vidal et al., 2005).

Internal Representations

Research in motor control has suggested that the execution of goal-directed arm movements is facilitated by acquired internal representations[1] that specify the relationships between (sensory) input and (motor) output (e.g., Wolpert & Ghahramani, 2000). These internal representations are best conceptualized as neural networks capable of performing specific functions that facilitate the accurate execution of a wide variety of movements (e.g., Shadmehr et al., 2005). In general, there are two types of internal representations (or models): forward and inverse (see Shadmehr et al., 2005; Wolpert et al., 1998 for detailed review of internal representations, including inputs and outputs). Forward models describe the causal relationships of a sensorimotor system. Typical inputs to a forward model are a motor command and an estimate of the current 'state' (i.e.,

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[1] Internal representations will be discussed in more detail in Section B of this literature review.

position and velocity) of the body. The output of this forward model is the predicted *next state* of the system. This predicted next state is advantageous in circumventing the delays inherent in processing sensory feedback (Desmurget et al., 2000). Inverse models simply invert the relationship between the variables described for the forward model. Given the current state of the system and the desired next state of the system, the inverse model approximates the motor commands necessary to achieve this task. Importantly, since the behavior of the system is dependent on the specific task being performed (i.e., an arm during a reaching task) as well as its interaction with the environment, both the forward and inverse models contain representations of these variables (e.g., the interaction between the arm and gravity).

As the characteristics of the individual, the environment and the task can vary on both short- and long-term time scales (e.g., due to muscle fatigue, physical growth during childhood, manipulation of a tool, etc.), these internal representations must be adaptable. The adaptability of internal representations has been frequently investigated by experimentally manipulating the sensorimotor and/or the dynamic environments in which participants perform a motor task. Exposure to these perturbations results in an initial decrease in performance; however, participants are able to adapt their subsequent movements to be more appropriate for the manipulated environment. Previous research has demonstrated that adults can adapt to visuomotor rotations (e.g., Kagerer, Contreras-Vidal, & Stelmach, 1997; Krakauer, Pine, Ghilardi, & Ghez, 2000), gain adaptations (Krakauer et al., 2000; Prager & Contreras-Vidal, 2003) and dynamic force field perturbations (Gandolfo, Mussa-Ivaldi, & Bizzi, 1996; Shadmehr & Mussa-Ivaldi, 1994).

Previous developmental research has posited that the progressive fine-tuning of these acquired internal representations across childhood are, at least partially, responsible for the age-related improvements in sensorimotor performance (Bo et al., 2006; Contreras-Vidal et al., 2005; Jansen-Osmann et al., 2002; Konczak, Jansen-Osmann, & Kalveram, 2003). Four, 6-, and 8-year-old children performed discrete reaching movements to peripherally located targets (Contreras-Vidal et al., 2005). During one experimental phase, the visual feedback of the reach trajectories was rotated 45°, creating a mismatch between desired and actual movement trajectories. While all groups of children were able to reduce the magnitude of their movement errors over the course of this exposure phase, only the 8-year-olds demonstrated significant aftereffects once the visual feedback rotation was removed. [Aftereffects are characterized by movement errors that are opposite in direction to those initially experienced after the introduction of the sensorimotor perturbation]. The presence of aftereffects are thought to indicate that an internal representation has been updated in order to be more appropriate for the manipulated environment (Shadmehr et al., 1994). It should be noted that 5-6 year-old children demonstrated significant aftereffects in a similar visuomotor adaptation paradigm when the length of the exposure phase was extended approximately twofold (King et al., 2009). This suggests that the younger children can acquire internal novel representations but the rate of this process is significantly slower in younger children. Other researchers have employed dynamic force field perturbations during the execution of reaching movements; results again demonstrated that the ability to acquire novel internal representations is not fully developed until approximately 10 years of age (Jansen-Osmann et al., 2002).

Summary

The extant developmental literature has demonstrated that goal-directed arm movements executed by older children (10-12 years) are faster, straighter, smoother, and less variable compared to the performance of younger children (4-6 years). Two potential explanations have been proposed to account for these age-related improvements: 1) non-monotonic changes in the relative contributions of feedforward and feedback control; and 2) a progressive fine-tuning of acquired internal representations that relate sensory input to motor output. This dissertation aims to expand on these previous explanations and demonstrate that age-related improvements in sensorimotor performance are the result of changes in state estimation, defined as the estimates computed by the CNS of the current and future positions and velocities (i.e., 'state') of the arm (Wolpert et al., 1995). This process of state estimation is dependent on the output of a forward internal representation, which predicts the next state of the system based on a copy of a descending motor command and previous state estimates. Thus, the development of this forward internal representation is hypothesized to be responsible for the age-related improvements in sensorimotor performance reported in the extant literature. Moreover, improvements in state estimation can also account for the age-related changes in the relative contributions of feedforward and feedback control reported by Hay and colleagues in previous research (e.g., Bard et al., 1990; Hay, 1979).

The next section of this review of literature (Section B) explores the motor control frameworks that serve as the foundation for this dissertation, with an emphasis on state estimation. The final section (C) will highlight the knowledge gaps in the extant literature in order to further elucidate the specific aims of this dissertation.

Motor Control Conceptual Frameworks

Detailed conceptual frameworks have been developed that decompose the execution of goal-directed arm movements into a series of computational problems that are solved by the central nervous system (e.g., Bullock et al., 1988; Shadmehr et al., 2005; Todorov et al., 2002; Wolpert et al., 1998). Although specific parameters and characteristics differ across frameworks, the computational problems inherent in goal-directed arm movements remain consistent. A generalized framework is depicted in Figure 1.1 (see Chapter I) and the components of this conceptual framework are briefly introduced next. Subsequent sections will expand on these components in more detail.

The primary focus of this dissertation will be on *state estimation* (shaded region in Figure 1.1) as the accurate execution of goal-directed arm movements depends on the precise estimation of both current and future hand positions and velocities (e.g., Shadmehr et al., 2005; Vindras et al., 1998). State estimation is dependent on two inputs: 1) afferent information from the available sensory modalities (Figure 1.1: sensory systems → state estimator); and, 2) the output of a forward model (Figure 1.1) that *predicts* the sensory consequences of a descending motor command based on knowledge of the arm's dynamics and prior state estimates (Blakemore et al., 1998a; Miall et al., 1996; Wolpert et al., 2001). In the context of hand localization, if the arm is not occluded, both vision and proprioception can provide sensory feedback of hand state. Therefore, estimation is dependent not only on an individual sensory modality, but also on the ability to integrate information from *multiple* modalities with available motor outflow.

During the execution of rapid, ballistic reaching movements, relying on sensory afferents to generate feedback-dependent corrective movements can result in erroneous and inefficient trajectories due to the delays in sensory processing. Thus, *predicting* sensory consequences based on an efference copy of a motor command can be used as an internal reference in order to circumvent the delays inherent in processing sensory feedback, a finding that has been previously demonstrated in adults (Desmurget et al., 2000; Tseng et al., 2007; Wagner et al., 2008; Wolpert et al., 2001). Predicting sensory consequences depends on an accurate estimate of the most current state of the system and a developed forward model that can map the current state of the system to future states based on an efference copy of the motor command (Desmurget et al., 2000; Wolpert et al., 1995).

Static State Estimation

As emphasized in the framework depicted in Figure 1.1, an accurate estimate of hand position is critical for the successful execution of goal-directed arm movements. Indeed, inaccurate localization of *initial* hand position results in systematic end-point errors (Vindras et al., 1998). If the hand is stationary (i.e., static), initial position can be provided both proprioception and/or vision, assuming that the hand is not occluded. The subsequent sections of this literature review will address each of these sensory systems in more detail, followed by an examination of multisensory integration as well as methodologies that have traditionally been employed in the motor control literature to probe static state estimation.

Proprioception

Proprioception is based on sensory feedback from receptors in the muscles, tendons and joints and refers to our ability to sense the positions and velocities of the body (Matthews, 1988). The primary proprioceptors that provide feedback to the CNS are muscle spindles, golgi tendon organs (GTOs) and joint receptors. The following paragraphs will provide a brief overview on these types of receptors and how each contributes to the estimates of the body in space.

Joint receptors exist predominantly in the joint capsules and were originally thought to be primary contributors to the estimation of joint position. However, it is now widely thought that the influence of these receptors for position sense is relatively minimal, except at the extremes of the joint range of motion where they are likely to serve a protective function (Burke, Gandevia, & Macefield, 1988; Matthews, 1988; Purves et al., 2008). Despite the limited role in position sense, joint receptors are thought to provide information about joint movement (Proske, Schaible, & Schmidt, 1988). GTOs are located in the tendons that connect skeletal muscles to the appropriate bones. They predominantly respond to increases in muscle tension (e.g., passive stretch and active contraction) and thus help protect muscles from excessive loading. The muscle spindles, embedded within the extrafusal muscle fibers, are largely considered the primary contributors to both limb position and movement sense (Matthews, 1988; Purves et al., 2008). Importantly, two types of fibers, primary and secondary, innervate the muscle spindles and are thought to be specialized for the direction and velocity of limb movement and for static limb position, respectively.

Much of the research indicating that muscle spindles are the primary contributors to limb position and velocity come from tendon vibration experiments (Goodwin, McCloskey, & Matthews, 1972; Jones, 1988; Lackner, 1988; Lackner & Taublieb, 1984; Levine & Lackner, 1979; Matthews, 1988). Vibrating a muscle tendon at a frequency of approximately 100Hz gives the participants the illusion that the muscle is lengthening. For example, if the biceps tendon is vibrated, the participant perceives the arm to be extending despite the fact that the participants' arms may be constrained. This effect is so robust that when a participant views a light-emitting diode attached to the finger, he/she still 'sees' this light as moving as if the arm is actually extendeding (Levine et al., 1979). This illusion is presumably due to the muscle spindles detecting a perceived stretch of the muscle and speaks to the role of spindle afferents in detecting joint position and movement.

Neural Processing of Proprioceptive Stimuli

The majority of the axons of proprioceptors travel up the spinal cord via the dorsal column tracts, decussate at the medulla and then travel up to the ventral posterior lateral (VPL) nucleus of the thalamus via the medial leminscal tracts (see Purves et al., 2008 for review). Many of the proprioceptive signals from the lower half of the body also travel to the cerebellum via the spinocerebellar tract; this information is critical for the execution of gross motor skills. Neurons in the VPL then project to the primary somatosensory cortex, located just posterior to the central sulcus.

The somatosensory cortex is perhaps best known for its somatotopic representation, where specific areas of cortex are devoted to processing sensory information from specific areas of the body (e.g., Penfield & Boldrey, 1937). The distribution of this somatotopic organization is non-uniform, as some areas of the body (i.e., face and hands) have a disproportionately large amount of neural tissue devoted to sensory processing whereas other regions of the body (i.e., torso) are represented by only a small amount of cortical tissue. This somatotopic representation is considered to be extremely plastic as neurons respond to different sensory stimuli from different areas of the body based on specific experiences (Elbert, Pantev, Wienbruch, Rockstroh, & Taub, 1995; Merzenich et al., 1984). In the context of goal-directed reaching, relevant proprioceptive information is thought to be projected from the somatosensory cortex to the posterior parietal cortex (PPC). The PPC is thought to involved in the integration of visual and proprioceptive information for hand localization (Andersen, Snyder, Bradley, & Xing, 1997; Graziano, Cooke, & Taylor, 2000) and in the computation of the spatial difference vector between actual and desired hand positions (Batista, Buneo, Snyder, & Andersen, 1999; Buneo & Andersen, 2006).

Delays in Proprioceptive Processing

The processing of proprioceptive inputs does take time and any delays can negatively impact sensorimotor performance. The muscle spindle (i.e., knee jerk) reflex takes approximately 40-50ms; however, this pathway is limited to the spinal cord and is substantially faster than pathways involving the cortex (Nijhawan, 2008). Cordo and colleagues employed a behavioral task requiring participants to open their hand at a prescribed target position while the forearm was passively moved at unpredictable velocities without visual information (Cordo, Carlton, Bevan, Carlton, & Kerr, 1994). These methodological constraints forced participants to rely on proprioceptive information to estimate hand position; results indicated that proprioceptive processing operates at a delay of approximately 150ms. This value is similar to simple reaction time experiments in which participants respond to touch stimuli as fast as possible (reviewed in Nijhawan, 2008).

Developmental changes in Proprioceptive Functioning

Utilizing several different behavioral paradigms, proprioceptive functioning has been found to improve throughout childhood and adolescence (Goble, Lewis, Hurvitz, &

Brown, 2005; Laszlo & Bairstow, 1980; Visser & Geuze, 2000; von Hofsten et al., 1988). Laszlo and Bairstow (1980) demonstrated significant age-related improvements in proprioceptive acuity across 5- to 12-year old children in a task requiring children to determine the relative vertical positioning of the two hands after passive movements by the experimenter. In a subsequent study utilizing the same task, improvements in acuity were reported in 14- to 16-year-olds (Visser et al., 2000). Similar improvements into adolescence were also demonstrated across three different joint-angle matching tasks (Goble et al., 2005). Last, von Hofsten and Rosblad (1988) utilized a localization task in which participants attempted to match the 2-D Cartesian coordinate position of one hand with the other hand. Although age-related improvements were reported across 5- to 12-year old children, the most substantial improvements occurred between 5 and 8 years of age. These age-related improvements in proprioceptive functioning are thought to drive improvements in functional sensorimotor behavior (Contreras-Vidal, 2006; Laszlo & Bairstow, 1983).

Vision

Assuming the hand is not occluded, the visual system can provide information about its current position and velocity. Importantly, for accurate static state estimation, the visual system utilizes the available cues to localize the hand in the radial (towards / away), azimuth (left / right) and vertical (up /down) dimensions. Two-dimensional localization (azimuth and vertical dimensions) is achieved via retinotopic organization (see Purves et al., 2008 for review): light in specific areas of visual space is detected by specific retinal photoreceptors. Thus, the patterns of photoreceptor activation provide information about the location of visual stimuli in the environment. This topographic organization is maintained throughout the visual processing pathways, including retinal ganglion cells, neurons in the lateral geniculate nucleus (LGN) of the thalamus and the primary visual cortex (Hubel & Wiesel, 1962; Hubel & Wiesel, 1961; Wiesel, 1960). [A more detailed review of this neural processing is the focus of the subsequent section.] Localization in the radial direction is predominantly achieved via a process called stereopsis, or binocular disparity (first described by Wheatstone, 1838). Since the eyes view the world from two different positions, 2-D information from the two eyes are combined to form a 3-D percept. It should be noted that monocular cues, such as interposition, motion parallax, and relative size, also provide information about the depth of stimuli.

Neural Processing of Visual Stimuli

Axons of retinal ganglion cells exit the retina and target several neural structures, including the LGN of the thalamus, the pretectum, suprachiasmatic nucleus of the hypothalamus and the superior colliculus (see Purves et al., 2008 for review). The pathways targeting the pretectum and the suprachiasmatic nucleus are critical for the pupillary light reflex and regulation of the diurnal cycle, respectively. However, this review will focus on the projections to the superior colliculus and the primary visual cortex via the LGN of the thalamus, as these pathways are involved in the orientation towards and localization of stimuli necessary for accurate goal-directed reaching.

Similar to other visual processing areas, the superior colliculus, or the optic tectum in non-mammals, represents the visual field topographically, where specific neurons respond to stimuli in specific regions of visual space (see Stein & Meredith, 1993). Moreover, the superior colliculus contains topographic maps of auditory and somatosensory space that are roughly aligned with the map of visual space, making it an ideal structure for orientation and attention towards environmental stimuli, such as desired target positions. The alignment of the sensory maps has been investigated by placing prismatic lenses, which horizontally displace the visual field, over the eyes of juvenile barn owls (Knudsen & Knudsen, 1989). While donning such prisms, owls shifted their head orientation towards visual stimuli in response to the prism-induced visual displacement. Following the removal of the prisms, orientation of the head to auditory stimuli was also displaced horizontally (Knudsen et al., 1989). Auditory neurons located in the optic tectum became calibrated to the visually-displaced receptive fields, resulting in the re-alignment of sound localization (Knudsen & Brainard, 1991). This sensory re-alignment ensures that movements of the eyes are accurately directed towards the desired target, independent of the sensory modality of the stimuli.

The primary visual pathway, or the retinogeniculostriate pathway, consists of the retinal ganglion cell axons that synapse with the dorsal LGN of the thalamus and then project to the primary visual cortex via the internal capsule. Although the neurons in both the LGN and the visual cortex contain topographic representations of visual space (Hubel et al., 1962; Hubel et al., 1961), the patterns of representation in these two structures are different. Neurons in the LGN are similar to those in the retina, where receptive fields are classified as on-center/off-surround (or off-center/on-surround) circular arrangements (Hubel et al., 1961; Wiesel, 1960). Conversely, the receptive fields of neurons in the visual cortex are defined based on lines with preferred orientations. Specifically, a visual stimulus that appears along a line with a specific orientation results in excitation whereas a visual stimulus that appears outside of this preferred linear orientation results in inhibition (Hubel et al., 1962). The relationship between the topographic representations in these two areas can be explained by the convergence of multiple thalamic neurons on a single cortical neuron, with the centers of the thalamic cells aligned along the preferred orientation of the cortical cell (Ferster, Chung, & Wheat, 1996; Reid & Alonso, 1995). It should be emphasized that neurons in the primary visual cortex are tuned to more than just the orientation and location of visual stimuli; they also respond to certain directions of motion as well as spatial and temporal frequencies of visual stimuli (Purves et al., 2008).

Visual processing extends well beyond the primary visual cortex. Researchers have proposed two different cortical streams of visual processing: a ventral pathway that travels from the visual cortex to inferotemporal cortex via extrastriate areas and a dorsal pathway that travels from the visual cortex to posterior parietal cortex (PPC) via extrastriate areas (Goodale & Milner, 1992; Mishkin, Ungerleider, & Macko, 1983; Ungerleider & Mishkin, 1982). It is thought that this ventral pathway, also referred to as the 'what' pathway, is critical for the recognition of visual objects, whereas the dorsal pathway, or the 'where' or 'how' pathway, is involved in both the localization of objects and in sensorimotor transformations necessary for action (Goodale et al., 1992; Mishkin et al., 1983; Ungerleider et al., 1982).

Influence of Eye Orientation and Head Position on Spatial Localization

Relying solely on the retinotopic organization described above may result in errors in spatial localization as the eyes can move inside the head and the head can rotate about the shoulders. For example, imagine the eyes are fixated at a point in space (fixation point A) and the center of a neuron's preferred receptive field is located 20° to the right of point A (stimulus point B). But, if the eyes are shifted such that the new fixation point is to the left of fixation point A, a visual stimulus in the same location (stimulus point B) is no longer within this neuron's receptive field. In other words, as a result of the shift in fixation point, the same location of a visual stimulus resulted in different patterns of activation. Thus, in order to accurately localize visual stimuli, the CNS must incorporate the position of the eyes within the orbit. Indeed, receptive fields of neurons in the inferior parietal lobe are multiplicatively modulated (i.e., a gain field) as a function of gaze angle (Andersen & Mountcastle, 1983; Andersen, Essick, & Siegel, 1985). This area of the parietal cortex is part of the dorsal visual stream critical for spatial localization discussed above (e.g., Ungerleider et al., 1982). As the head can also rotate relative to the torso, the activity of parietal neurons also systematically varies as a function of head position (Brotchie, Andersen, Snyder, & Goodman, 1995). Collectively, these results indicate that accurate spatial localization of visual stimuli depends on retinal signals, gaze angle and head position with respect to the torso. The posterior parietal cortex is thought to be involved in these integrative neural computations (Andersen et al., 1983; Andersen et al., 1985; Brotchie et al., 1995).

Delays in Visual Processing

If the arm is moving at a relatively rapid pace, relying on visual information for hand localization can come at a cost due to delays in sensory processing. Research has demonstrated it takes an average of 72ms for the visual cortex to respond to a stimulus (Lamme & Roelfsema, 2000), but this delay does not include the time to process the visual information and make corresponding movement adjustments. Visual response latencies in the motor cortex were estimated to be 150ms (Lamme et al., 2000). Early motor control research suggested it took approximately 200ms for visual feedback to modify a movement trajectory (reviewed in Keele, 1968; Paillard, 1996) although other studies have indicated values of approximately 100-135ms (Carlton, 1981; Paulignan, MacKenzie, Marteniuk, & Jeannerod, 1991). More recent research has demonstrated that arm activity was modulated in response to a visual input in slightly less than 100ms (Pruszynski et al., 2010); however, this value was based on EMG activity which will result in shorter latencies than analyses of movement kinematics. An examination of the influence of visual processing delays on motor control predominantly highlights two main conclusions: 1) there are varying temporal delays reported in the literature which are likely a product of the different experimental tasks employed (Elliott & Allard, 1985); and, 2) even the shortest delays reported in the literature (~100ms) can be detrimental to the execution of rapid reaching movements.

Developmental Changes in Visual Functioning

There is an abundance of research investigating the development of the visual system in both infants and children. This brief review will predominantly focus on the ability to accurately localize objects in space as this has direct implications for the experiments conducted in this dissertation. The visual system, with respect to spatial localization, appears to be fully developed prior to the age range of interest in the current study. Nelson and colleagues (1984) reported that visual acuity, a measure of spatial resolution, reached adult-like levels by 6 or 30 months of age. The differences in the estimates were largely attributed to the varying techniques employed to assess visual acuity: optokinetic nystagmus, forced choice preferential looking or visually evoked potentials. Additional studies reported similar results, with visual acuity reaching adult levels by approximately 6 years of age (e.g., Ellemberg, Lewis, Hong Liu, & Maurer, 1999). However, it should be emphasized that there is considerable variability in the estimates at which visual acuity in children is similar to adults. For a more detailed discussion, please see Leat et al (2009).

In the context of hand localization *during* movement execution, it is important for the visual system to track a non-stationary stimulus. Infants as young as five months of age demonstrated smooth pursuit eye tracking of a visual stimulus that was moving in a sinusoidal or triangular motion (von Hofsten & Rosander, 1997). Moreover, infants were able to successfully reach for moving objects by aiming the hand at a location where the object will be located at some time point in the future (von Hofsten, 2004; von Hofsten, Vishton, Spelke, Feng, & Rosander, 1998). This line of research indicates that infants can track a predictable visual stimulus with their eyes.

Multisensory Integration

Within the context of hand localization, redundant sensory information is provided to the CNS via visual and proprioceptive afferents. Ideally, two modalities that provide information about a common stimulus will be congruent with one another; however, due to variability within the sensory systems, all afferent inputs to the CNS are sensory estimates with varying degrees of reliability. How does the brain integrate the two modalities in order to output a single estimate? Several potential integrative mechanisms exist (van Beers, Baraduc, & Wolpert, 2002): 1) The CNS can weight each modality equally by linearly combining the two discrepant sensory estimates. Using this mechanism, the integrated estimate is a simple average of the two unimodal inputs. 2) The CNS can rely solely on the more precise sensory estimate in a 'winner-takes-all' competition. 3) The CNS can have a flexible, re-weighting scheme dependent upon the precision of each unimodal input as well as any existing task constraints. This final re-weighting option provides obvious advantages due to its high level of flexibility. However, it assumes that the CNS is capable of maintaining a representation of the level of precision of each unimodal input, a requirement with high computational demands. Since the level of precision of each sensory input is the inverse of its variance, the nervous system would have to know the amount of variability within each sensory system, a remarkable capability of the CNS that has been previously demonstrated in adults (Ernst & Banks, 2002; Landy, Maloney, Johnston, & Young, 1995; Searle, Braida, Davis, & Colburn, 1976; van Beers et al., 2002; van Beers, Sittig, & van der Gon, 1999).

Previous research has demonstrated unimodal direction-dependent precision for both visual and proprioceptive acuity in adults. Vision is more precise in the azimuth (left-right) direction compared to the radial direction whereas proprioceptive acuity is more precise in the radial direction (with respect to the shoulder) as compared to the azimuth (van Beers et al., 2002; van Beers et al., 1999). Interestingly, when redundant sensory inputs are provided, the CNS has been shown to incorporate the localization distributions described above in order to integrate the multiple sources of sensory afference. Rather than computing a simple average between the two unimodal estimates or relying solely on the more precise (less variable) estimate, the nervous system computes an *optimal* integration estimate dependent on the unimodal direction-dependent distributions (van Beers et al., 2002; van Beers et al., 1999). This indicates that the adult CNS is capable of learning and maintaining *unimodal* localization distributions and subsequently integrating multiple sources of sensory input dependent upon these distributions. It should be noted that probabilistic inference is not restricted to hand localization tasks. Similar frameworks have been demonstrated in auditory-visual integration (Battaglia, Jacobs, & Aslin, 2003), sensorimotor learning (Kording & Wolpert, 2004b), force estimation (Kording, Ku, & Wolpert, 2004a), and motor planning (Sober & Sabes, 2003).

The spatial and temporal relationships between stimuli from multiple modalities also influence multisensory integration. Specifically, for two modalities to be integrated, they need to be spatially and temporally coincident. In other words, visual and proprioceptive stimuli that are perceived to be in the same approximate location at the same point in time are likely to be integrated because they are perceived to originate from the same source. Conversely, if the two stimuli are perceived to be in different spatial locations or at different points in time, it is likely that they did not originate from the same source and therefore will not be integrated. Behaviorally, this was demonstrated in a postural control study by Jeka and colleagues (2000) during which touch and visual stimuli were manipulated. If both touch and visual stimuli were considered dynamic (i.e., oscillating at the same frequency), the postural response was referred to as ‘enhanced.’ However, if one sensory input was dynamic and the other static, the response was ‘degraded.’ In the dynamic-dynamic condition, the stimuli were coincident and thought to provide redundant sensory feedback. In the dynamic-static conditions, the two sensory inputs were now in conflict, and the response was depressed. These temporal and spatial relationships also hold true at the neurophysiological level in the superior colliculus (Stein, 1998; Stein & Meredith, 1990; Stein et al., 1993).

Coordinate Systems

The integration of multiple sensory inputs introduces the following neural and computational problem: How does the nervous system combine two different sensory estimates that are specified in two distinct coordinate systems? For example, visual object localization is specified in an eye- or gaze-centered coordinate system whereas proprioceptive localization is likely provided in a body-centered reference system. To integrate these two sensory estimates, at least one of the estimates must be mapped to a different coordinate system. It is commonly thought that proprioceptive estimates of hand position are mapped to an eye- or gaze-centered coordinate system, a process commonly referred to as forward kinematics (Shadmehr et al., 2005). There are potential benefits of a gaze-centered coordinate system. First, a gaze-centered coordinate system can potentially maximize the high acuity of the visual system by eliminating transformations out of the visual coordinate system. Second, Desmurget and colleagues (2000) conjectured that a gaze-centered coordinate system may facilitate the execution of rapid movements since the eyes foveate a desired target first. Common coordinate systems are not only important for integrating sensory inputs, but also for movement planning. Research has suggested that target positions perceived by different sensory modalities (audition, vision, and proprioception) are specified in gaze- or eye-centered coordinates (Pouget, Ducom, Torri, & Bavelier, 2002). This finding is consistent with research suggesting that the spatial difference vector between current hand and desired target position is also provided in gaze/eye-centered coordinates (Batista et al., 1999; Buneo, Jarvis, Batista, & Andersen, 2002; Cohen & Andersen, 2000).

It should be noted that the existing literature is equivocal with respect to determining in which coordinate frame sensory estimates are integrated and movement trajectories are specified. In contrast to gaze-centered reference frame, others have posited that the reference coordinate frame is hand-centered (Gordon, Ghilardi, & Ghez, 1994) or even context-dependent (Battaglia-Mayer, Caminiti, Lacquaniti, & Zago, 2003). Indeed, recent research by Sabes and colleagues has suggested that the nervous system represents reach plans in multiple coordinate systems which can be flexibly utilized in order to optimize sensorimotor performance (McGuire & Sabes, 2009; McGuire & Sabes, 2011).

Development of Multisensory Integration in Children

Whereas unimodal sensory-motor acuity in adults is precise and stable, developmental changes across childhood result in robust differences in the localization of unimodal stimuli (Contreras-Vidal, 2006; von Hofsten et al., 1988). These changes in unimodal sensory-motor acuity are likely to impact multisensory-motor integration. Previous developmental research has employed localization tasks to probe the influence of visual and proprioceptive functioning for hand localization (Contreras-Vidal, 2006; Mon-Williams et al., 1999; von Hofsten et al., 1988). Although non-monotonic age-related improvements were reported in the localization of visual, proprioceptive, and simultaneous visual-proprioceptive stimuli, the magnitude of the improvement in the localization of proprioceptive stimuli between 7 and 9 years of age was greater than the improvement in the localization of visual stimuli (von Hofsten et al., 1988). Moreover, previous research had demonstrated that static visual acuity is developed at a very young age (Nelson et al., 1984) whereas proprioceptive acuity continues to improve throughout childhood and adolescence (Goble et al., 2005; Pickett & Konczak, 2009; Visser et al., 2000). Collectively, these findings suggest that the improvements in proprioceptive functioning, a critical component of 'static' (i.e., stationary) state estimation, may contribute to the age-related improvements in sensorimotor performance reported in the extant literature (Bo et al., 2006; Contreras-Vidal et al., 2005; Hay, 1979; Jansen-Osmann et al., 2002; King et al., 2009; Yan et al., 2003).

Age-related differences in the relative contribution of different sensory modalities have been previously examined across a large age range in postural control tasks (Bair, Kiemel, Jeka, & Clark, 2007; Shumway-Cook & Woollacott, 1985). In children younger than three years of age, vision has been considered the dominant modality and the contribution of other sensory information (i.e., proprioception) increased with age until approximately 7-10 years (Shumway-Cook et al., 1985). Older children exhibited adult-like multisensory integration, whereas the young children (i.e., 4- to 6-years) were thought to be in a transition period for the integration of multisensory information. However, *optimal* multimodal integration (i.e., computationally weighting inputs based on their precision), as shown in adults (e.g., van Beers et al., 1999), does not appear to develop until approximately 10 years of age (Gori, Del Viva, Sandini, & Burr, 2008; Nardini, Jones, Bedford, & Braddick, 2008). It was suggested that this protracted development of multisensory integration can be explained by a trade-off between calibration and integration (Gori et al., 2008). Specifically, the need for two sensory modalities to be continuously recalibrated in response to developmental changes supersedes optimal integration of two modalities. However, as Ernst (2008) emphasized, this explanation is less compelling given that many studies have demonstrated both recalibration and integration on very short time scales in adults. Moreover, school-age children have demonstrated substantial adaptation during sensorimotor perturbation tasks over the course of a single experimental session, which can be conceptualized as a recalibration between incongruent visual and proprioceptive feedback (Contreras-Vidal et al., 2005; King et al., 2009). Thus, it is unlikely that children exhibit rapid sensorimotor adaptation but still require a continuous recalibration process over the first 8–10 years that interferes with the development of optimal multisensory-motor integration. Nonetheless, redundant sensory inputs do not appear to be *optimally* integrated until approximately ten years of age (Gori et al., 2008; Nardini et al., 2008).

Neural Substrates of Multisensory Integration

Two potential areas in the CNS that may underlie the integration of redundant sensory inputs for hand localization are the posterior parietal (PPC) and premotor (PM) cortices (Graziano, 1999; Graziano et al., 2000). Both cortical structures receive projections from somatosensory cortex located posterior to the central sulcus as well as the striate and extrastriate (visual) cortices in the occipital lobe. Furthermore, PPC and PM are involved in the sensorimotor transformation process that is necessary for the successful execution of reaching movements, and evidence suggests that the sensory integration could occur in both structures. Neurons in the parietal lobe (Graziano et al., 2000) as well as the PM cortex (Graziano, 1999) have demonstrated activity indicative of visual and proprioceptive monitoring of the arm's position. The relative contributions of vision and proprioception to the integrated estimate have been suggested to change dependent upon the stage of the sensorimotor process (Sober et al., 2003). Specifically, vision is more heavily weighted during the computation of the spatial difference vector, a function of the PPC (Batista et al., 1999; Bullock et al., 1988; Buneo et al., 2006; Shadmehr et al., 2005) whereas proprioception is more heavily weighted during the generation of the appropriate motor commands, a function of the PM and motor cortices (Desmurget, Pelisson, Rossetti, & Prablanc, 1998; Shadmehr et al., 2005). It is possible that probabilistic sensory integration occurs in both cortical structures and that even the probabilistic computations differ depending on the neural substrates and the stage of the motor planning process.

Although the PPC and PM cortex are thought be critical for the multisensory control of reaching, research investigating the neurophysiological basis of multisensory integration has largely focused on the superior colliculus (SC), a midbrain structure described in previous sections and thought to be critical for attention and orientation behaviors. Accordingly, the literature discussed below focuses on research on the SC in both cats and monkeys; however, the same integration principles are thought to be applicable across a range of species as well as neural structures such as the cortex (Stein, 1998).

The deep layers of the superior colliculus contain a large proportion of bimodal and even trimodal neurons (see Stein et al., 1993 for review). As described previously, these neurons have distinct topographic maps corresponding to the receptive fields of each sensory modality to which it responds. Thus, these multimodal neurons are suited to integrate information across modalities. Specifically, the response of a bimodal (e.g., visual and auditory) neuron to a bimodal stimulus originating from the same spatial location and time point will result in an enhanced response (i.e., measured by neural activity or spike rate). This response is significantly larger than the sum of the neuron's response to the unimodal inputs, especially when the multimodal stimuli are weak or ambiguous. Conversely, if the visual stimulus falls within this multimodal neuron's visual receptive field but not within its auditory receptive field (i.e., spatially disparate stimuli), then the response is significantly less than either of the unimodal responses. This can best be explained by the notion of inhibitory surround (see Purves et al., 2008 for review). A neuron has an excitatory response if a stimulus falls directly within its receptive field but an inhibitory response if it the stimulus is just outside of its receptive field. Thus, the degraded response in the hypothetical situation presented above is explained by an excitatory response to the visual stimulus but an inhibitory response to the auditory stimulus.

If two stimuli are temporally disparate, this may also result in a degraded response. However, this creates a unique situation as the visual processing delays are much larger than the auditory delays. Thus, the SC neurons respond to the auditory stimulus *before* they respond to the visual stimulus, creating a situation that appears to create a temporal processing problem. However, research reviewed by Stein et al. (1993) demonstrated that a neuron's response to a particular stimulus is substantially longer than the difference in delay between visual and auditory processing. Therefore, there is a temporal window in which a SC multimodal neuron can still code a stimulus in the same location at the same point in time (and therefore integrate visual and auditory information) despite differences in processing time.

Methodologies Employed to Examine Static State Estimation

There are two predominant behavioral approaches that have been employed to probe static state estimation: localization tasks and the two alternative forced choice (2AFC) paradigm. Localization tasks require participants to move an unseen hand in order to accurately and consistently localize desired target positions provided by visual and/or proprioceptive stimuli (Contreras-Vidal, 2006; Mon-Williams et al., 1999; Sigmundsson, Ingvaldsen, & Whiting, 1997; van Beers, Sittig, & van der Gon, 1996; van Beers et al., 1999; von Hofsten et al., 1988). This approach is advantageous because it simulates the processes involved in static state estimation of the arm. However, there are drawbacks: accuracy and variability in these tasks reflect the localization of both the target and the unseen moving hand that is moving towards the target stimuli, effectively combining uncertainty and bias associated with hand and target localization.

The 2AFC paradigm presents two stimuli and asks participants to select one stimuli based on an established criterion (Ernst et al., 2002; Gori et al., 2008). For example, is visual stimulus A brighter than visual stimulus B? Is haptic stimulus A larger than haptic stimulus B? The two stimuli can be provided by the same sensory modality, allowing investigators to probe the variability associated with that modality; or, alternatively, the stimuli can be provided by two different modalities, allowing the investigators to probe multisensory integration. The strength of the 2AFC paradigm is that it produces very precise probability density functions quantifying the level of precision associated with a sensory modality. Moreover, systematic predictions based on a variety of mathematical models can be generated that examine how the nervous system combines information from multiple sensory modalities (Ernst et al., 2002; Gori et al., 2008).

Despite the attractiveness of this approach, the 2AFC paradigm may not be ideal to probe static state estimation as it relates to functional motor behavior (i.e., goal-directed reaching). First, the 2AFC paradigm requires participants to make explicit decisions about the relative size, location, orientation, etc. of certain stimuli. It was recently proposed that two different ‘streams’ of somatosensory processing exist: one related to ***conscious*** perception and recognition and the second relevant for (***implicit***) sensorimotor performance (Anema et al., 2009; Dijkerman & de Haan, 2007). Thus, the 2AFC paradigm and the spatial localization tasks would potentially be investigating two different underlying processes. If the research question is interested in static state estimation for functional sensorimotor behavior, the spatial localization paradigm may be more appropriate. Second, an estimate of hand/target position, under normal circumstances, involves specifying the position of the hand/target along a *continuum* of possible locations in three-dimensional space. The 2AFC paradigm requires participants to make a choice between two stimuli. Decomposing sensory estimates along spatial continuums into a ‘forced’ dichotomy does little to probe the underlying computations of hand/target localization. Third, the 2AFC paradigm eliminates execution noise whereas the spatial localization tasks combine uncertainty in localization with movement execution. However, this execution noise is an inherent characteristic of the motor system and eliminating it from an investigation of multisensory-*motor* integration is counterintuitive. In the past, researchers designed experiments to minimize ‘noise’ or variability in motor performance; however, an emerging viewpoint in motor control is that such variability or noise is not only a defining feature of the system but can be exploited by researchers to provide insights into the strategies employed by the sensorimotor system to improve performance (Latash, Scholz, & Schoner, 2002; Todorov et al., 2002; Todorov, 2004).

Sensory Prediction and Dynamic State Estimation

The research discussed in the section above predominantly focused on the localization of hand position prior to the initiation of movement, a scenario that does not impose strict time constraints. During the execution of fast reaching movements; however, the system needs to quickly and accurately detect and correct movement errors (i.e., a discrepancy between actual and desired hand position). Many researchers have computationally and experimentally demonstrated that the CNS utilizes a 'forward model' to avoid time delays in sensory processing (Miall, 1992; Wolpert & Gharamanhi, 2000; Shadmehr & Wise, 2005; Miall & Wolpert, 1998). This forward model is able to estimate the current state of the system and predict a future state of the system based on estimates of current position and a copy of the descending motor command. Critically, these state predictions are dependent on the accuracy and reliability of a forward model, characteristics that are certainly influenced by the changing constraints imposed by a developing sensorimotor system.

Functions of a Developed Forward Model

The forward model depicted in Figure 1.1 is thought to be critical for the control of voluntary, goal-directed actions. Wolpert and colleagues outlined four key functions of the forward model (1995). First, the forward model can help circumvent delays inherent in sensory processing. It has been reported that corrective movements in response to visual or proprioceptive afference are subject to a delay of at least 80-100ms (Desmurget et al., 2000), although other studies have reported values up to 200-300ms (Miall et al., 1996). If a reaching movement is completed within 400 to 500ms, these time delays would be detrimental to the accuracy of the movement. Accordingly, a forward internal representation (model) *predicts* the expected sensory consequences (or the next state of the system) based on an efference copy of the descending motor command and the previous, albeit delayed, state estimates (e.g., Ariff, Donchin, Nanayakkara, & Shadmehr, 2002; e.g., Desmurget et al., 2000; Shadmehr, Smith, & Krakauer, 2010; Wolpert, Miall, & Kawato, 1998). Second, the predictions of expected sensory consequences can be used to distinguish between sensations resulting from one's own movement (i.e., reafference) and sensations resulting from environmental stimuli (Blakemore, Wolpert, & Frith, 1998b; Weiskrantz, Elliott, & Darlington, 1971). Third, a comparison of actual sensory feedback and the predicted (or desired) sensory consequences from the forward model can be used as an error signal that drives motor learning (Davidson & Wolpert, 2005). Indeed, these sensory prediction errors have been shown to be critical for adapting to externally-imposed manipulations (Tseng et al., 2007). Fourth, combining predicted next states of the system with the delayed sensory feedback (i.e., dynamic state estimation) provides the most reliable estimate of the state of the system even during the execution of fast reaching movements (Izawa & Shadmehr, 2008; Shadmehr et al., 2010; Shadmehr et al., 2008; Wolpert et al., 1995).

Evidence of Efference Copy

Evidence for the notion of efference copy was provided by von Holst and Mittelstaedt (1973). Their research focused on the optokinetic reaction in a fly: experiments consisted of placing a fly in a cylinder with alternating black and white vertical stripes that rotate in a specific direction. In this environment, the visual system is not able to differentiate the cylinder moving in one direction (i.e., to the right) from the fly moving in the opposite direction (i.e., to the left). However, the fly can in fact differentiate between these two possibilities despite the identical activation patterns of the photoreceptors. von Holst and Mittelstaedt suggested that an efference copy of a motor signal can be sent and subsequently utilized in order to differentiate self-motion (i.e., the fly moving to the left) from environmental motion (i.e., the cylinder moving to the right). In other words, the efference copy of a motor command can be used to generate expected or predicted sensory consequences.

Self-Tickling

One of the more everyday examples suggesting that the nervous system can predict sensory consequences is self-tickling. The response to an individual tickling himself is non-existent, or at least dramatically reduced, compared to the response to a tickle from an external source. The difference in the responses of these two conditions is interesting as the tactile stimuli are essentially identical. It has been proposed that a copy of the efferent motor command can be used to generate expected sensory consequences when tickling oneself (Blakemore et al., 1998b; Weiskrantz et al., 1971). These expected consequences can effectively 'cancel' the actual sensory consequences, resulting in a diminished response to the tactile stimulus. In the case of an externally-generated tickle, the lack of expected sensory consequences results in an exaggerated response to the stimulus.

Grip Force Modulation

In order to hold an object, one must generate more than a minimum amount of grip force so as to not let the object slip but also less than a maximum amount of force to avoid breaking or damaging the object. In other words, the magnitude of grip force must be appropriately scaled to the characteristics of the object and the constraints imposed by the task. The modulation of grip force has been studied by requiring participants to hold an object as the characteristics of the object are either predictably or unpredictably altered. For example, the magnitude of the load force (i.e., the object) can be abruptly increased by the action of an experimenter; this would be an unexpected, or unpredictable, change. Alternatively, the magnitude of the load force can be abruptly increased by the action of the participant; this would be an expected change. In adult participants, if the load force is unpredictably increased, there is a delay in the corresponding increase in grip force as this process is dependent on sensory feedback. Conversely, if the load force is predictably increased, grip force increases in parallel to load force and there is no temporal delay (Flanagan & Wing, 1997; Johansson & Cole, 1992; Witney, Goodbody, & Wolpert, 1999; Witney, Goodbody, & Wolpert, 2000; Witney, Vetter, & Wolpert, 2001; Witney & Wolpert, 2003). This suggests that the nervous system predicted the consequences of the self-produced increase in load force and was able to modify the magnitude of the grip force in an anticipatory manner, a process that is thought to be dependent on a predictive forward model (e.g., Flanagan et al., 1997; Witney et al., 2000).

The development of grip force modulation has been investigated in children. With *unexpected* increases in load force, the corresponding grip force adjustment in young children (i.e., 2 to 5 years) was delayed compared to older children (6-10 years) and adults (Eliasson et al., 1995; Flanagan & Johansson , 2002; Forssberg, Eliasson, Kinoshita, Johansson , & Westling, 1991). A similar developmental trajectory was evident for *predictable* changes in load force, as 6-year-olds, as compared to 4-year-olds, were better able to modulate grip force in parallel with changes in load force. It should be emphasized that improvements in the predictive grip force control were evident between

6 and 8 years as well as between 8-year-olds and adults (Flanagan et al., 2002; Forssberg et al., 1991).

Reaching Movements

During the execution of a fast, goal-directed reach, utilizing sensory feedback to estimate the state of the arm can be detrimental due to the delays in sensory processing. Accordingly, it can be beneficial to predict the expected future states of the system based on a copy of the efferent command, a computation that is thought to be dependent on a forward model. This most direct evidence for state prediction during reaching movements is the research by Shadmehr and colleagues (Ariff et al., 2002). Both eye and hand positions were recorded as it was hypothesized that the oculomotor system could serve as a proxy for the state estimator of the arm. Results indicated that the eye position reliably predicted hand position 196 ms into the future, suggesting that the CNS is able to predict the consequences of descending motor commands rather than relying on delayed sensory feedback for online control of the arm (Ariff et al., 2002; e.g., Wagner et al., 2008). Additional evidence for state prediction was provided by Bard and colleagues (1999). A deafferented patient was asked to reach to visual targets without vision of the moving limb. After movement onset, the position of the target was displaced; importantly, the participant was not aware of this perturbation. During these perturbed trials, the participant made online movement corrections to adjust for the displaced target. The absence of sensory feedback in this participant suggests that the movement corrections were based on state predictions that were generated from motor output (i.e., efference copy).

These predicted states can be combined with the most current, albeit delayed, sensory estimates to provide an up-to-date and reliable estimate of the state of the arm. The extant literature has consistently reported that state estimation, particularly *during* movement execution, is the result of combining these two streams of information: motor output and sensory input (Hoff & Arbib, 1993; Izawa et al., 2008; Shadmehr et al., 2010; Vaziri, Diedrichsen, & Shadmehr, 2006; Wolpert et al., 1995). Wolpert and colleagues (1995) asked participants to make discrete reaching movements in the dark during three different experimental conditions: null, assistive, or resistive forces were imposed during movement execution. After movement offset, the participants were asked to estimate the position of their hand. The pattern of localization errors was consistent with a model that incorporates both motor output and sensory input in order to localize the hand position.

Development of Dynamic State Estimation during Reaching

A few studies have employed double-step reaching tasks (see below) to investigate differences in rapid online corrections and dynamic state estimation between TD children and children with Developmental Coordination Disorder (Hyde & Wilson, 2011a; Hyde & Wilson, 2011b; Plumb et al., 2008; Wilmut, Wann, & Brown, 2006). Results demonstrated that children with DCD had difficulties modifying their movement trajectories online; these deficits were attributed to impairments in predictive estimates of hand state (Hyde et al., 2011a; Hyde et al., 2011b). However, these studies did not investigate age-related changes within a group of TD children. Only one study, to our knowledge, has examined age-related differences in on-line trajectory modifications in TD children. Van Braeckel et al. (Van Braeckel, Butcher, Geuze, Stremmelaar, & Bouma, 2007) employed a modified version of the double-step reaching task; results revealed that the deceleration portion of the movement trajectory in the 7-8 year-old children was significantly longer than 9-10 year-old children. This suggests that these younger children relied on sensory feedback to reach the desired target positions. This experiment predominantly focused on temporal measures and provided little information with respect to the spatial estimation of hand state during movement execution. This knowledge gap is a focus of the current research.

Neural Correlates of Dynamic State Estimation

The ability to predict the consequences of descending motor command is thought to be a function of the cerebellum (Barto, Fagg, Sitkoff, & Houk, 1999; Bastian, 2006; Miall et al., 2008; Miall, Christensen, Cain, & Stanley, 2007; Nowak, Topka, Timmann, Boecker, & Hermsdorfer, 2007; Shadmehr et al., 2008; Tseng et al., 2007). Nowak and colleagues (2007) investigated the ability to generate the appropriate magnitude of grasping forces when a ball was dropped unexpectedly by an experimenter (reactive condition) or expectedly by the participant (predictive). A patient with cerebellar damage (agenesis) performed similarly to age-matched controls in the reactive condition but demonstrated severe impairments in the predictive task, suggesting the cerebellum is involved in predictive motor control. During the execution of a rapid reaching movement, transcranial magnetic stimulation (TMS) applied over the ipsilateral cerebellum significantly impaired estimates of hand position (Miall et al., 2007). Based on the magnitude of the reaching errors, participants appeared to rely on an estimate that was approximately 140ms out of date, providing further evidence for the role of the cerebellum in state prediction. Optimal dynamic state estimation is not simply a function of state predictions generated by the cerebellum. Rather, these predictions are thought to be combined with sensory feedback, via the visual and proprioceptive processing discussed above, in order compute the most accurate and precise estimate of hand state (Gritsenko, Yakovenko, & Kalaska, 2009; Hoff et al., 1993; Izawa et al., 2008; Shadmehr et al., 2008; Wolpert et al., 1995). The integration of sensory inflow and state predictions are thought to be a function of the posterior parietal cortex (Shadmehr et al., 2008).

Methodologies Used to Examine Dynamic State Estimation

Two different experimental methodologies have been previously used to investigate dynamic state estimation of the arm during reaching movements. The first, employed by Reza Shadmehr and colleagues, assumed that the position of the eyes during saccades may provide an estimate of hand state during the execution of ballistic reaching movements (Ariff et al., 2002). Eye and hand position were recorded and results revealed that eye saccades provided an estimate of hand position approximately 200ms into the future, although the estimates were quite variable. The second and more commonly employed methodological approach is the double-step paradigm, where the position of the desired target position jumps to a new location at or after movement onset (e.g., Bard et al., 1999; Flanagan, Ostry, & Feldman, 1993; Goodale, Pelisson, & Prablanc, 1986; Hyde et al., 2011a; Hyde et al., 2011b; Plumb et al., 2008; Prablanc & Martin, 1992; Sarlegna, Gauthier, Bourdin, Vercher, & Blouin, 2006). Since the movements are ballistic, the on-line corrections are thought to depend on state predictions rather than sensory inflow due to the inherent processing delays. The movement trajectories directed towards the displaced target positions provide information about the accuracy and reliability of the state estimate at the time of correction.

Control Policy

Although not a focus of the current research, it is important to address the control policy employed for the execution of target-directed reaching movements. The conceptual framework depicted in Figure 1.1 labels the control policy as a spatial-to-motor transformation, a general term that simply refers to a mapping between the sensory information specifying current and desired hand position and the corresponding motor commands that will drive the hand towards the target. This section of the review will focus on two types of controllers frequently discussed in the motor control literature: inverse internal representations and optimal feedback control (OFC).

Inverse Internal Representations

In contrast to forward models discussed in the preceding sections, the function of an inverse representation (or model) is to approximate the motor commands necessary to achieve a desired goal based on the current state of the system. Importantly, since the behavior of the system is dependent on the specific task being performed as well as its interaction with the environment, the inverse model must contain a representation that specifies the relationship between these variables (e.g., the interaction between the arm and gravity). Support for the implementation of inverse internal representations comes predominantly from perturbation experiments that manipulate the environment in which participants move. For example, in a seminal study, Shadmehr and Mussa-Ivaldi (1994) exposed participants to a velocity-dependent force field. This perturbation resulted in an initial decrease in performance; however, with practice, participants were able to adapt to the manipulated environment. The presence of aftereffects once the force field was removed, distorted movement trajectories that were opposite to those experienced immediately following the introduction of the perturbation, suggests that participants acquired a feed-forward internal representation that specified the novel relationship between the arm and the environment. This result has not only been replicated in other force field experiments (Gandolfo et al., 1996; Shadmehr & Brashers-Krug, 1997), but has been extended to visuomotor rotations (Buch, Young, & Contreras-Vidal, 2003; Kagerer et al., 1997; Krakauer, Ghilardi, & Ghez, 1999; Wang & Sainburg, 2005) and visual feedback gain adaptations (Krakauer et al., 2000; Prager et al., 2003).

A strength of the inverse internal representation framework is that it provides a conceptual basis for understanding how the motor system is able to flexibly and adaptively execute movements across a variety of conditions and tasks (Imamizu et al., 2000; Imamizu, Kuroda, Miyauchi, Yoshioka, & Kawato, 2003; Wolpert et al., 1998). For example, any time a human grasps a tool (i.e., hammer) to perform a particular movement, the dynamics of the task change (i.e., mass, length, moment of inertia, etc.). The dynamics of this ‘novel’ system need to be considered in order to perform the task accurately and efficiently. Under the internal model framework, the inverse internal representation models the new dynamics of the system and can still compute the appropriate motor commands given the altered arm-environment interaction.

One weakness of the inverse internal model framework is that it does not take into account the redundancy (i.e., motor equivalency) in the motor system (Todorov et al., 2002). Specifically, to perform a reaching task, the desired target can be specified in 3-D spatial coordinates whereas the upper arm (including only the shoulder, elbow, and wrist joints) has seven degrees of freedom. Thus, there are many unique configurations of the three joints that will allow the end effector to reach the desired goal. Based on an internal model framework, a spatial difference vector between the initial and final end effector positions is computed and that this spatial difference vector is transformed into desired changes in joint angles which in turn are transformed into the appropriate motor commands to perform the task. However, the transformation between spatial and joint coordinates does not have a unique solution as many different joint configurations are possible. The internal model framework assumes that this transformation chooses a 'desired' trajectory, but it is not clear how this single trajectory is selected from the multiple potential solutions.

Optimal Feedback Control (OFC)

OFC was developed in part to address what some criticized as shortcomings of certain aspects of the internal model approach. It combined some aspects of the internal model framework (i.e, forward model) with cost functions and the concept of motor equivalency in order to create a more encompassing framework for motor control (Shadmehr et al., 2008). The optimal feedback controller functions by receiving the estimated state of the system as well as the associated costs and rewards associated with performance of the task as inputs (Todorov et al., 2002; Todorov, 2004). The cost function indicates not only the objectives of the task but also the potential rewards/risks associated with its execution. By comparing the real-time current and desired states of the system and considering associated rewards and risks, this controller is able to control movements as they are executed. However, it operates under the principle of minimal intervention - it only corrects movement errors or deviations if they have a systematic effect on the performance or task variable. This approach is similar to that of the uncontrolled manifold (Latash, Scholz, & Schoner, 2007; Scholz & Schoner, 1999) which posits that the central nervous system partitions movement variability into task-relevant and task-irrelevant variability. It has been argued by Todorov (2002; 2004) that this minimal intervention principle is based on the fact that corrective movements come at a cost: 1) they generate additional noise in the system which can increase movement variability (Harris & Wolpert, 1998); and 2) there is increased energy expenditure associated with corrective movements that could potentially result in unwanted effects such as fatigue. Using minimal intervention and a forward model that is able to predict next states of the system, the OF controller can control movements in real time.

There are several strengths associated with this approach. First, it is able to account for the redundant motor system (see Todorov et al., 2002; Todorov, 2004). Specifically, variability in joint configurations is not an issue (and thus are not corrected) as long as the performance or task variable is not impacted. In this scenario, the system is allowed to be somewhat variable and in turn this facilitates the execution of flexible and adaptive sensorimotor behavior. Second, under OFC, the entire movement trajectory does not have to be pre-planned. Rather, the system can use the estimated state of the body as well as the associated costs/rewards in order to correct movements as they unfold.

There are also several weaknesses associated with OFC (Todorov et al., 2002; Todorov, 2004). First, it is assumed that the task/performance variable is known to the system. In some tasks (i.e., postural control), the variable to be controlled is not always clear. Second, it is limited to explaining well-learned tasks as the system is able to partition variability into task-relevant and task-irrelevant variability.

Knowledge Gaps

The literature highlighted above provided a considerable amount of information pertaining to the development of sensorimotor control in TD children. However, there are several knowledge gaps in the extant literature that the current research will address:

Knowledge Gap #1: What is the effect of improvements in unimodal sensorimotor functioning on the integration of redundant sensorimotor inputs?

Vision and proprioception can both provide estimates of static hand state. To increase the accuracy and reliability of this estimate, information from both modalities is integrated. Since the acuity of unimodal localization changes across childhood, it is unclear how these changes influence multisensory integration. Experiment 1 will address this knowledge gap.

Knowledge Gap #2: What is the effect of age-related improvements in the accuracy and reliability of proprioceptive feedback for static state estimation on functional sensorimotor behavior?

Whereas static visual acuity is relatively stable in school-age children, age-related changes in proprioceptive acuity have been well documented. Experiment 2 will address the influence of age-related improvements in proprioceptive acuity for static state estimation on functional sensorimotor behavior.

Knowledge Gap #3: How does the ability to estimate hand state during the execution of a rapid, ballistic reaching movement change as a function of age?

To avoid delays inherent in sensory feedback, efference copies of a descending motor command can be used to predict the future state of the system. This prediction can be combined with an estimate of the most current state of the arm and serves as an internal feedback system in order to generate on-line corrections during movement execution. Critically, this process is dependent on the ability to accurately predict the consequences of a motor command. No study to date, to our knowledge, has examined the developmental trajectory of this dynamic state estimation process. Experiment 3 will address this knowledge gap.

Knowledge Gap #4: What is the effect of changes in dynamic state estimation on functional sensorimotor behavior?

There are many underlying processes that could potentially contribute to the age-related improvements in functional sensorimotor behavior across school-age children reported in the extant literature. The extent to which changes in dynamic state estimation, above and beyond the influence of other underlying processes, contribute to these improvements is not yet known. Experiment 4 will address this knowledge gap.

CHAPTER III: EXPERIMENT 1: Improvements in Proprioceptive Functioning Influence Multisensory-Motor Integration in 7- to 13-year-old Children

Abstract[2]

Accurate and efficient sensorimotor behavior depends on precise localization of the body in space, which may be estimated using multiple sensory modalities (i.e., vision and proprioception). Although age-related differences in multisensory-motor integration across childhood have been previously reported, the extent to which age-related changes in *unimodal* functioning affect multisensory-motor integration is unclear. The purpose of the current study was to address this knowledge gap. Thirty-seven 7- to 13-year-old children moved their dominant hand in a target localization task to visual, proprioceptive, and concurrent visual and proprioceptive stimuli. During a subsequent experimental phase, we introduced a perturbation that placed the concurrent visual and proprioceptive stimuli in conflicting locations (incongruent condition) to determine the relative contributions of vision and proprioception to the multisensory estimate of target position. Results revealed age-related differences in the localization of incongruent stimuli in which the visual estimate of target position contributed more to the multisensory estimate in the younger children whereas the proprioceptive estimate was up-weighted in the older children. Moreover, above and beyond the effects of age, differences in proprioceptive functioning systematically influenced the relative contributions of vision and proprioception to the multisensory estimate during the incongruent trials. Specifically, *improvements* in proprioceptive functioning resulted in an *up-weighting* of proprioception,

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[2] Manuscript is published:
Reprinted from *Neuroscience Letters, 483,* King, B. R., Pangelinan, M. M., Kagerer, F. A., & Clark, J. E., Improvements in proprioceptive functioning influence multisensory-motor integration in 7-to 13-year-old children., 36-40, 2010, with permission from Elsevier.

suggesting that the central nervous system of school-age children utilizes information about unimodal functioning to integrate redundant sensorimotor inputs.

Introduction

Prior to the execution of goal-directed reaching, the central nervous system (CNS) utilizes information about the positions of both the target and the arm to generate an appropriate motor plan (Bullock et al., 1988; Buneo et al., 2006). This process depends not only on the precision and accuracy of an individual sensory modality, but also on the ability to integrate information from multiple modalities (i.e., vision and proprioception) with available motor outflow (i.e., efference copy of the motor command). Previous research has employed localization tasks during which participants actively moved an unseen hand to localize visual, proprioceptive, and simultaneously presented visual and proprioceptive stimuli, the latter requiring multisensory-motor integration. Thus, the accuracy and variability of such localization tasks reflect the localization of the target and the localization of the unseen moving hand. Whereas unimodal sensorimotor acuity in adults is precise and stable, developmental changes across childhood result in robust differences in the localization of unimodal stimuli (Contreras-Vidal, 2006; von Hofsten et al., 1988). These changes in unimodal sensorimotor acuity likely impact multisensory-motor integration. The purpose of this study was to investigate the effects of unimodal sensorimotor functioning on multisensory-motor integration in 7- to 13-year-old children.

Previous developmental research examining the localization of unimodal and bimodal stimuli demonstrated that children are consistently more accurate when moving an unseen hand to visual (V) as compared to proprioceptive (P) stimuli (Mon-Williams et al., 1999; von Hofsten et al., 1988). Moreover, performance during bimodal conditions (i.e., VP) is nearly identical to the visual condition, suggesting that when both sensory stimuli are available, vision is the more dominant modality (von Hofsten et al., 1988). Although non-monotonic age-related improvements were reported in all experimental conditions (V, P, and VP), the magnitude of the improvement in the localization of proprioceptive stimuli between 7 and 9 years of age was greater than improvement in localization of visual stimuli (von Hofsten et al., 1988). This result is consistent with research by Contreras-Vidal (2006) who suggested that the age-related improvements in proprioceptive acuity across 6- to 10-year-old children contribute to the age-related improvements in sensorimotor performance reported in the extant literature (Bo et al., 2006; Contreras-Vidal et al., 2005; Hay, 1979; King et al., 2009; Yan et al., 2003).

The current experiment sought to determine how unimodal sensorimotor functioning in children impacts multisensory-motor integration and to provide insights into the underlying processes. In addition to examining localization of visual, proprioceptive, and simultaneously presented visual and proprioceptive stimuli, we introduced a spatial perturbation that placed visual and proprioceptive estimates of target position in conflict. The relative contribution of each modality was estimated based on the end-point position during these incongruent bimodal trials. It was hypothesized that unimodal localization performance would systematically impact multisensory-motor integration in 7- to 13-year-old children. More specifically, greater accuracy of unimodal localization will result in a greater contribution of that particular modality to the multisensory estimate.

Methodology

Participants

Thirty-seven typically-developing children (23 females; 14 males), ages 7 to 13 years, participated in the study. All participants had normal or corrected vision and were right-handed, as determined by their preferred hand used to complete everyday activities such as handwriting. To ensure typical and healthy development, the parents of the child participants completed a neurological health questionnaire to preclude any neurological deficits or developmental delay (Appendix III). Additionally, the children were screened with the Movement Assessment Battery for Children (MABC) (Henderson & Sugden, 1992), and were included in this study if they scored at or above the 20th percentile. All experimental procedures were approved by the Institutional Review Board at the University of Maryland, College Park. Parents or legal guardians of the participants provided informed consent prior to participation (Appendix I). Informed assent was obtained from the children. Upon completion of the experiment, the children received a small prize and a modest monetary compensation.

Apparatus

Participants were seated in a height-adjustable chair in front of a two-tiered experimental apparatus resting on a table (Figure 3.1.A). A digitizing tablet (12”x12” WACOM InTuos^{TM}) was positioned on the bottom tier of the apparatus. The top tier supported a horizontally-oriented flat screen monitor. Participants were informed that they would use both hands, with their pronated right hand moving a digitizing pen across the surface of the tablet, and their supinated left hand moving to positions underneath the tablet. The computer screen provided feedback of the visual targets and, when appropriate, the end-point (EP) position of the pen. Vision of the participants’ hands was occluded using a black cloth secured onto the apparatus and draped comfortably around the participants' shoulders (not shown in Figure 3.1.A). OASIS software (Kikosoft Software® Nijmegen, Netherlands) was used for stimulus presentation and data acquisition via the digitizing tablet; the time series of the x/y-coordinates of the pen position were sampled at 200 Hz. The spatial resolution of the digitizing tablet was 0.01 cm. The digitizing pen was attached to the anterior side of the right index finger such that the pen tip was approximately 1 cm proximal to the distal end of the finger.

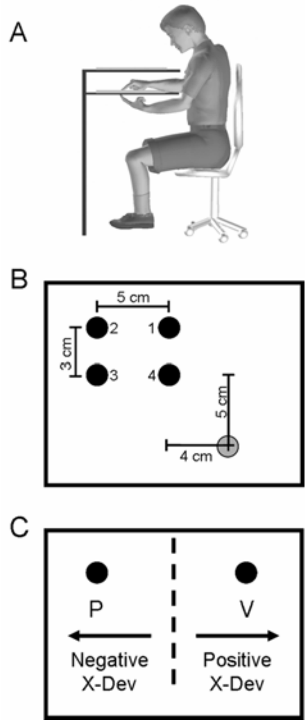

Figure 3.1. Experiment 1 set-up and protocol. ***A***. *Visual stimuli were presented via a computer monitor on the top tier of the apparatus whereas proprioceptive stimuli were provided by the position of the unseen left index finger below the digitizing tablet. Participants moved their occluded right hand on top of the tablet to localize visual, proprioceptive, or simultaneous visual-proprioceptive target stimuli as accurately as possible.* ***B.*** *The four target locations (black circles) are shown with respect to the right hand's start position (gray circle).* ***C****. Computation of the variable X-Dev. The x-coordinate end-point position (*EPP_x*) of an incongruent trial was subtracted from the x-coordinate midpoint of the two target positions for that incongruent trial (vertical dashed line). Values were transformed so that a positive X-Dev value indicated the EPP was closer to the visual (V) target whereas a negative value indicated the EPP was closer to the proprioceptive (P) target.*

Procedures

A target localization task was employed, during which participants were instructed to use the available sensory information to localize target positions with their right index finger as accurately as possible. This target localization task was designed to mimic the multisensory-motor processes involved in hand localization, a critical factor for the accurate execution of goal-directed reaching movements (Shadmehr et al., 2005; Vindras et al., 1998). No time constraints were imposed on the movements of the right hand. The goal of the task was to minimize the distance between the target and EP position of their right hand. Based on these constraints, the task involved minimal movement planning, but rather relied on the utilization of available sensory feedback to optimize localization performance. All targets were located in one of 4 positions to the left of the participants' midline (Figure 3.1.B) and were presented in a pseudo-randomized order (e.g., each target was randomly presented once in a 4-target-sequence).

There were 3 experimental conditions, each referred to by the *target* modality during the localization task: visual (V), proprioceptive (P), and visual-proprioceptive (VP). During the *visual* condition, each participant positioned the pen inside a start circle (0.5 cm diameter) and one of four targets (0.5 cm diameter) appeared. The start circle turned green 750 ms after the target appeared, providing a 'GO' signal for movement onset. After the participant moved to the target position and remained stationary for 750 ms, the target disappeared and he/she returned to the start circle to begin the next trial. Importantly, no visual feedback was provided during the experimental conditions. In the visual condition, the index finger of the left hand remained in contact with a cloth dot (0.5 cm diameter) affixed to a wooden board inserted immediately below the lower tier of the apparatus (herein referred to as the left hand start position). The wooden board also served to indicate proprioceptive target locations for the subsequent experimental conditions.

During the *proprioceptive* (P) condition, each participant was instructed to move the digitizing pen attached to his/her right index finger to localize the position of the unseen left index finger below the digitizing tablet (Figure 3.1.A). Prior to each trial, the participant actively moved the left hand from the start position along the wooden board away from his/her body until the left index finger was positioned at the target, demarcated by a felt cloth dot. The position of the left index finger underneath the tablet served as the proprioceptive target. The start circle turned green after 750 ms, at which time the participant moved the unseen right index finger on the tablet to the perceived location of the left index finger under the tablet. Once motionless for 750 ms, the participant placed the left hand in his/her lap and prepared for the next trial. During this time, an experimenter seated behind an opaque cloth inserted a new wooden board with a different target for the next trial. There were four exchangeable boards in total, each corresponding to one of the four proprioceptive target locations. The location of these four proprioceptive targets corresponded to the location of the visual targets presented on the monitor (Figure 3.1.B).

The *visual-proprioceptive* (VP) condition was nearly identical to the P condition. However, once the participant positioned his/her left index finger at the desired proprioceptive target location and their right index finger in the black start circle, a blue target circle appeared on the display monitor. This visual target circle indicated the position of the left index finger located on the underside of the tablet. Thus, during the

VP condition, both visual and proprioceptive information were concurrently available to localize the target.

Practice sessions (10 trials per condition) were given for the three conditions to familiarize the participants with the task and to provide detailed verbal instructions. During the first eight practice trials, EP feedback was provided on the display monitor. No visual feedback of the digitizing pen was provided for the last two practice trials and the subsequent 16 baseline trials (4 per target) for each of the three conditions. The purpose of these baseline phases was to provide an assessment of localization performance for the different target modality conditions. Subsequently, participants completed an additional 32 VP trials. During 16 of these trials (randomly inserted), the position of the visual target did not match the position of the left index finger (i.e. incongruent stimuli). The incongruent trials were manipulated in the lateral direction only. For example, if the visual target stimulus was located at target position 1 (Figure 3.1.B), the proprioceptive target stimulus was located at target position 2, and vice versa. The purpose of the incongruent trials was to place the visual and proprioceptive stimuli in conflict to determine the *relative* weights of the two sensory estimates. The experimental protocol (80 trials, not including practice) took approximately 45 minutes. Trials in which the participant lifted the pen from the tablet were excluded from analysis. Following completion of the protocol, participants completed a brief interview to assess participants' awareness of the incongruent phase. No participant reported any awareness of the perturbation.

Data Analysis

Customized MATLAB^{TM} (Mathworks, Natick, MA USA) scripts were used to apply a dual-pass 8th order Butterworth filter to the time series data (10 Hz cutoff frequency) and to mark movement onset and offset via an interactive algorithm implemented in previous research (Contreras-Vidal et al., 2005). As localization accuracy was emphasized in the instructions to the participants, end-point position (EPP: x/y-coordinates) was the primary measure. End-point error (EPE), defined as the linear distance between EPP and the desired target position, was computed for each condition. It was hypothesized that localization performance, as assessed by EPE during the baseline conditions, would impact the relative weighting of the visual and proprioceptive estimates during the bimodal trials. Therefore, we computed a variable, X-Deviation (Figure 3.1.C), to characterize the relative contributions of each modality to the multisensory estimate when vision and proprioception were in conflict. X-Deviation was computed by subtracting the EPP_x of the incongruent trials from the midpoint of the target locations (x-coordinate only). For example, an incongruent trial with the visual and proprioceptive target stimuli located at target positions 1 and 2, respectively, the EPP_x of the incongruent trial was subtracted from the midpoint between the first and second target positions (dashed line; Figure 3.1.C). This midpoint represents the theoretical EPP_x assuming that the visual and proprioceptive target stimuli were *equally weighted*. An EPP_x shifted towards the visual target stimulus suggests that vision was more heavily weighted whereas an EPP_x shifted towards the proprioceptive target stimulus suggests that proprioception was more heavily weighted. The variable X-Deviation was transformed such that positive values indicated that the EPP of the incongruent trial was shifted to the visual estimate of target position and negative values indicated a shift to the proprioceptive estimate. The x-coordinate was of interest because the target stimuli in the incongruent trials were manipulated only in the x-direction.

Results

To examine the effects of age and baseline localization performance on multisensory-motor integration, we conducted a hierarchical multiple regression with X-Deviation as the dependent variable. The first block included only the participants' ages. The second block included the average EPE scores from each of the three baseline conditions (EPE_V, EPE_P, EPE_{VP}). A forward selection model ($p = 0.05$) was chosen for the second block so that the condition(s) that significantly accounted for variance in X-deviation would be kept in the final model. By inserting age as the first block, we could investigate the effects of baseline localization performance on multisensory-motor integration that were above and beyond the effects of age.

Age accounted for a significant amount of the variance in X-Deviation (Table 3.1; Model 1). Older children exhibited decreased X-Deviation values, suggesting that the proprioceptive estimate of target position contributed more to the multisensory estimate in comparison to young children (Figure 3.2.A). With respect to the role of baseline localization performance, the forward selection process eliminated EPE_V and EPE_{VP} from the final model. EPE_P accounted for a significant amount of variance in X-Deviation *above and beyond* that found for age (Table 1; $F\Delta = 6.62$; $p = 0.015$). Specifically, smaller EPE_P (i.e., better proprioceptive localization performance) was associated with a stronger contribution of the proprioceptive estimate of target position to the multisensory estimate (i.e., decreased X-Deviation) (Figure 3.2.A).

Table 3.1: Experiment 1 Hierarchical Regression

Model	Parameters	β	S.E.	R^2	R^2 Change	F Change	df	Sig. F Change
1[a]	Constant Age	3.21 -0.35	1.33 0.13	0.161	0.161	6.72	1,35	0.014
2[b]	Constant Age EPE_P	1.36 -0.30 0.54	1.43 0.13 0.21	0.298	0.137	6.62	1,34	0.015

[a] *Model 1 represents the first block which included only age as a predictor.* [b] *Model 2 includes the first and second blocks.* EPE_V *and* EPE_{VP} *were excluded through forward selection* ($p > 0.05$).

The main finding of this study is the relationship between proprioceptive localization and multisensory-motor integration after accounting for the effects of age (Figure 3.2.B). The residuals of the first regression block are depicted on the y-axis. Values equal to zero indicate that a model with only age as an independent variable predicted the exact value of X-Deviation. Residual values greater than zero indicate that the mean EPP of the incongruent trials was shifted *more* towards the visual estimate of target position than predicted by age alone. Similarly, the residuals of regressing EPE_P with age are shown on the x-axis. Positive values indicate that EPE_P was larger than that predicted by age. Critically, there is a positive relationship between the X-Dev and EPE_P residuals. This suggests that above and beyond the effects of age, better proprioceptive localization resulted in a shift towards the proprioceptive target position (i.e., decreased X-Deviation) when the unimodal estimates were in conflict. Thus, improvements in proprioceptive functioning resulted in an increased contribution of proprioception to the multisensory estimate of target position in 7- to 13-year-old children.

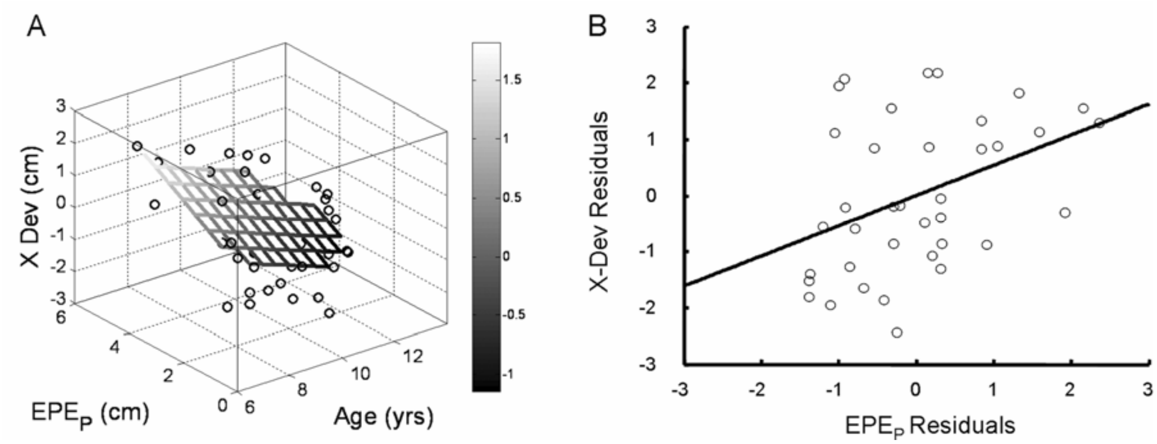

Figure 3.2. Experiment Results ***A.*** *Scatter plot depicting X-Dev as a function of EPE$_P$ and age. Plane and corresponding color bar depict predicted X-Dev values.* ***B****. Partial regression plot depicting X-Dev as a function of EPE$_P$, controlling for the effects of age.*

Discussion

These data indicate that 7- to 13-year-old children utilize information about unimodal estimation to flexibly re-weight redundant sensorimotor inputs. Previous research investigating multimodal localization suggested that 4- to 12-year-old children rely more heavily on vision when target position is provided by both visual and proprioceptive stimuli (von Hofsten et al., 1988). This conclusion was based on the similarity of the children's performance in the visual and visual-proprioceptive conditions. The current study placed the visual and proprioceptive estimates of target position in conflict, allowing us to determine the *relative contributions* of the two sensory modalities. Our data demonstrate that visual information is up-weighted only in the younger children, whereas proprioception appears to be up-weighted in the older children (Figure 3.2). Moreover, above and beyond age-related changes, this up-weighting of proprioception increased as a function of improved proprioceptive localization, demonstrating that changes in multisensory-motor integration are driven by unimodal functioning. This suggests that the CNS in school-age children is capable of acquiring and storing distributions representing the accuracy of unimodal-motor functioning; and, these distributions are utilized in the integration of multisensory-motor information.

The current study demonstrated that multisensory-motor integration in 7- to 13-year old children cannot be explained by a ‘dominant’ sensory modality or by an integration mechanism that weights the two inputs equally. Rather, our results suggest that multisensory-motor integration in children is a flexible process influenced by the functioning of unimodal inputs. In the context of this study, improvements in proprioceptive localization in 7-13 year-old children resulted in an increased contribution of proprioception to the multisensory estimate; and, critically, this finding was independent of age. This result extends the findings of previous research examining multisensory-motor integration in postural control tasks (Bair et al., 2007; Shumway-Cook et al., 1985). In children younger than three years, vision has been considered the dominant modality and the contribution of other sensory inputs (i.e., proprioception) increased with age until approximately 7-10 years (Shumway-Cook et al., 1985). Older children exhibited adult-like multisensory integration, whereas the young children (i.e., 4- to 6-years) were thought to be in a transition period for multisensory integration.

Evidence from a variety of tasks suggests that the adult CNS utilizes *probabilistic* mechanisms to reduce the uncertainty inherent in multisensory-motor processing (e.g., Ernst et al., 2002; Kording et al., 2004b; van Beers et al., 1999; Wolpert, 2007). In a probabilistic framework, available sensory information is differentially utilized, or flexibly ‘re-weighted’, to reduce the uncertainty associated with a multisensory estimate. One such example includes the weighting of sensory inputs based on the inverse of the variability of the unimodal estimates (Bove, 1990; Landy et al., 1995; Searle et al., 1976;

van Beers et al., 1999). Results from the current study suggest that multisensory-motor re-weighting is dependent on unimodal sensory functioning, a finding that is consistent with a probabilistic framework. However, localization distributions for each participant and each experimental condition are necessary to provide definitive evidence that children utilize probabilistic integration mechanisms for hand localization. This would require substantially more trials than employed in the current study. Nonetheless, these data and previous research (e.g., van Beers et al., 1999) suggest that the CNS of both school-age children and adults can acquire and store distributions representing the accuracy of unimodal-motor functioning for hand localization. Moreover, these distributions influence the integration of multisensory-motor information, suggesting that the underlying *mechanisms* are similar across children and adults. This does not imply that these mechanisms are fully developed in school-age children as both the mechanisms and the precision of unimodal-motor functioning are likely to be 'fine-tuned' during development. For example, previous developmental research indicated that *optimal* multimodal integration (i.e., computationally weighting inputs based on their precision) does not develop until approximately 10 years of age (Gori et al., 2008; Nardini et al., 2008). Collectively, our results and the research by Gori and colleagues (Gori et al., 2008) suggest that the accuracy and precision of unimodal estimates influence multisensory integration in children as young as 7 years of age; however, the redundant sensory inputs are not *optimally* integrated until approximately 10 years.

The current study demonstrated that improvements in *proprioceptive* functioning, in contrast to visual functioning, significantly influenced multisensory-motor integration. This is consistent with previous research demonstrating that static visual acuity is developed prior to the age range investigated in the current study (Nelson et al., 1984) whereas proprioceptive acuity continues to improve throughout childhood and adolescence (Goble et al., 2005; Pickett et al., 2009; Visser et al., 2000). While not addressed in this study, future research should attempt to investigate the processes underlying the development of proprioceptive functioning.

Conclusion

Our results indicate that the relative contributions of vision and proprioception to a multisensory estimate are, at least partially, determined by the functioning of individual sensory modalities in 7- to 13-year-old children. Importantly, this finding is above and beyond the effects of age, suggesting that the age-related changes in multisensory integration reported in previous research (Shumway-Cook et al., 1985) may be explained by improvements in unimodal functioning. Future research should probe the influence of these multisensory-motor processes on age-related improvements in sensorimotor performance (Bo et al., 2006; Contreras-Vidal et al., 2005; Hay, 1979; King et al., 2009; Yan et al., 2003).

CHAPTER IV: EXPERIMENTS 2 AND 3: Static and Dynamic State Estimation in Typically-Developing Children

Abstract

Previous developmental research examining sensorimotor control of the arm in school-age children has demonstrated age-related improvements in movement kinematics. A comprehensive, mechanistic explanation of these age-related improvements is not yet known. This research investigated the hypothesis that improvements in sensorimotor performance can be attributed, in part, to developmental changes in state estimation, defined as estimates computed by the central nervous system (CNS) that specify both current and future hand positions and velocities (i.e., hand ‘state’). To achieve this aim, two behavioral experiments (referred to as Experiments 2 and 3) were conducted in which 6- to 12-year-old children and adults executed goal-directed arm movements. Results from Experiment 2 revealed that young children (i.e., approximately 6-8 years) have less precise proprioceptive feedback for static (i.e., stationary) state estimation, compared to older children (i.e., ~10-12 years), resulting in increased variability of target-directed reaching movements. Experiment 3 demonstrated that young children rely on delayed and unreliable state estimates *during* the execution of goal-directed arm movements (i.e., dynamic state estimation), resulting in both increased movement errors and directional variability. Improvements in performance can not be explained by other processes underlying goal-directed arm movements (e.g., the controller). Collectively, this research suggests that improvements in sensorimotor behavior across childhood can be attributed, at least partially, to improvements in state estimation.

Introduction

Adults execute goal-directed arm movements with remarkable consistency and accuracy (e.g., Flash et al., 1985; Morasso, 1981). However, changes in the developing sensorimotor system and in the physical characteristics of the body during childhood can impact the control and coordination of target-directed reaches. Indeed, previous developmental research examining sensorimotor control of the arm in school-age children has demonstrated age-related differences in movement straightness and smoothness, temporal and spatial variability, and movement speed (Bo et al., 2006; Contreras-Vidal, 2006; Contreras-Vidal et al., 2005; Hay, 1979; Jansen-Osmann et al., 2002; King et al., 2009; Pangelinan, Kagerer, Momen, Hatfield, & Clark, 2011; Yan et al., 2000; Yan et al., 2003). Although characterizations of these age-related behavioral differences are pervasive in the developmental literature, a comprehensive and mechanistic explanation has not been identified. The current research investigated the hypothesis that improvements in state estimation, defined as estimates computed by the central nervous system (CNS) that specify both current and future hand positions and velocities (i.e., hand 'state'), underlie the age-related behavioral differences in school-age children.

An accurate and precise estimate of hand state is critical for the successful execution of goal-directed arm movements. To generate an appropriate movement plan that will drive the hand towards a desired target, the CNS estimates the initial position of the hand based on visual and/or proprioceptive feedback (Bullock et al., 1988; Sober et al., 2003; Sober & Sabes, 2005; Vindras et al., 1998). Whereas static visual acuity is relatively stable in school-age children (Nelson et al., 1984), age-related changes in proprioceptive functioning may result in impaired static state estimation in younger children when vision of the hand is absent (Contreras-Vidal, 2006; King, Pangelinan, Kagerer, & Clark, 2010; von Hofsten et al., 1988). Impaired static state estimation, in turn, may underlie the poor sensorimotor performance in younger children, compared to older children or adults, reported in the extant literature.

In addition to the localization of hand position *prior* to movement onset, state estimation *during* movement execution is critical for the detection of movement errors and the corresponding trajectory modifications. Relying on sensory afferents to provide state estimates during the execution of rapid, ballistic reaching movements can result in erroneous and inefficient movement trajectories due to the delays in sensory processing. Thus, predicting future states based on efference copies of motor commands can be used as an internal reference to circumvent processing delays, a finding that has been demonstrated in adults (Desmurget et al., 2000; Tseng et al., 2007; Wagner et al., 2008; Wolpert et al., 2001). This prediction can be combined with sensory feedback in order to provide an up-to-date, on-line state estimate (i.e., dynamic state estimation) (Izawa et al., 2008; Vaziri et al., 2006; Wolpert et al., 1995). The development of dynamic state estimation across childhood has not, to our knowledge, been investigated.

The aim of the current research was to investigate the hypothesis that the age-related improvements in goal-directed sensorimotor behavior reported in the extant developmental literature can be explained, at least partially, by improvements in static and dynamic state estimation. To achieve this aim, we conducted two experiments (Experiments 2 and 3) investigating the developmental trajectory of state estimation across 6- to 12-year-old typically-developing (TD) children. Experiment 2 examined the effect of age-related improvements in the accuracy and reliability of proprioceptive feedback for static state estimation on functional sensorimotor behavior. Experiment 3 characterized the effect of age-related changes in dynamic state estimation, above and beyond the effects of static state estimation, on sensorimotor performance.

General Methodology

Participants

Right-handed children (6- to 12-year-olds) and adults (18-22 years) were recruited for these studies. Detailed participant characteristics for each experiment are included in Table 4.1[3]. To ensure typical and healthy development, the parents of the child participants completed a neurological health questionnaire to preclude any neurological deficits or developmental delay (Appendix III). Additionally, the children were screened with the MABC-2 (Henderson & Sugden, 2007). Participants were included in the study if they scored at or above the 25th percentile. Handedness of the children was determined based on MABC criteria: a writing implement was placed on a table in front of the participant's midline. The hand that the participant selected to draw a picture was considered the preferred hand. Adult participants also completed a neurological health questionnaire to ensure no known neurological or motor impairments (Appendix III). Handedness of the adults was determined by the Edinburgh Handedness Inventory (cumulative score > 40; Appendix IV) (Oldfield, 1971). All experimental procedures were approved by the Institutional Review Board at the University of Maryland, College Park. Adult participants and parents or legal guardians of child participants provided informed consent prior to participation (Appendix II). Additionally, informed assent was

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[3] Ten of the child participants and 8 of the adults completed Experiment 3 immediately before completing Experiment 2. The ten child participants were approximately evenly spread out among the different ages (i.e., one 6-year-old, 7-year-old, 8-year-old, and 11-year-old and two 9-year-olds, 10-year-olds and 12-year-olds). Participation in both tasks in the same testing session had no influence on the results for the following reasons. First, participants in both experiments completed familiarization trials and ample practice trials to ensure all individuals were comfortable with the experimental apparatus prior to participation. Second, Experiment 3 did not contain any perturbation (i.e., visual feedback rotation) that would negatively impact performance on Experiment 2.

obtained from the children. Upon completion of the experiment, the children received a small toy prize. Both the children and adults received a modest monetary compensation.

Table 4.1: Experiments 2 and 3 participant characteristics

Group	Gender	Mean Age ± SD (yrs)	Age Range (yrs)	MABC %ile Range	Edinburgh: Mean ± SD
Experiment 2					
Children	19 F; 22 M	9.35 ± 1.84	6.1 – 12.7	25 – 95	N/A
Adults	4 F; 4 M	20.1 ± 0.84	19.2 – 22.0	N/A	71.0 ± 19.1
Experiment 3					
Children	18 F; 22 M	9.40 ± 2.00	5.9 – 12.7	25 - 95	N/A
Adults	7 F; 6 M	20.1 ± 0.89	18.7 – 22.0	N/A	74.4 ± 18.6

Apparatus

Participants were seated in a height-adjustable chair in front of a robotic manipulandum that moved freely in two dimensions (InMotion2; Cambridge, MA) (Figure 4.1). Participants were instructed to use their dominant (right) hand to move the manipulandum (see Procedures for details on the tasks). A vertically-oriented computer monitor provided the task stimuli and, when appropriate, visual feedback of the participants' performance. For Experiment 2, an occluding board was positioned above the manipulandum to prevent the participants from viewing the position of their hand or the manipulandum during task performance. For Experiment 3, the lights in the testing room were turned off and participants were fitted with customized goggles to restrict vision of the participants' limbs. For both experiments, participants were instructed that the goal of the tasks was to move the manipulandum from a start position to a desired target *as fast and as accurately as possible*. The time series of the x/y-coordinates of the manipulandum position was sampled at 200 Hz.

Figure 4.1: Set-up for Experiments 2 and 3. Participants were seated in a height-adjustable chair and were asked to execute arm movements while holding a robotic manipulandum that moves in two dimensions. The occluding board used in Experiment 2 is not shown.

Experiment 2

Procedures

Participants were asked to make 15cm arm movements from one of five starting locations (0.375cm diameter) to a single target (0.625cm diameter) located away from the body and start positions. The target circle was positioned 70°, 80°, 90°, 100°, or 110° with respect to the five different start circles (Appendix V). Prior to each trial, the experimenter held the arm of the robot and moved the manipulandum to the appropriate starting position (i.e., passive arm movements). Note that starting positions were not depicted on the computer monitor viewed by the participant; rather, they represented x/y coordinates that serve as the initial manipulandum position prior to movement onset. Additionally, no visual feedback of the manipulandum's position was provided during the passive movements. The experimental protocol included two conditions: Vision (V) and No Vision (NV). During the V condition, once the manipulandum was moved to the appropriate starting position by the experimenter and the participant remained motionless for a duration that randomly varied between 200 and 400ms, a yellow circle (0.375 cm diameter) appeared that depicted the real-time position of the manipulandum (i.e., visual feedback of current hand position). Simultaneously, a red circle appeared, indicating the desired target position. Once the participant remained motionless for an additional time period (randomly varied between 1000 and 1150ms), the target circle turned green, providing a 'GO' signal for movement onset. This delay period allowed the participants sufficient time to localize the target and starting positions and plan the appropriate movement. If the manipulandum moved outside of a 1.875cm diameter surrounding the center of the start position prior to the appearance of the GO signal, the trial reset and the experimenter returned the manipulandum to the desired start position. The participants were instructed to move to the target as fast and as accurately as possible at any time after the GO signal appeared. Once the manipulandum left the start position, the yellow circle depicting current hand position disappeared; thus, there was no on-line visual feedback of the participants' trajectory to the target circle. Participants were instructed to stop when they felt they reached the target. Once motionless for 500ms, the yellow circle depicting the manipulandum's position re-appeared, providing end-point (EP) visual feedback of the manipulandum. This marked the termination of the trial and the experimenter moved the manipulandum to the appropriate starting position for the next trial. To ensure performance reflected ballistic arm movements as opposed to a target localization task, participants were instructed to complete each movement in less than 1200ms (excluding the 500ms 'hold' period at the conclusion of the movement). If movement duration exceeded this value, instructions prompting participants to speed up were provided on the computer monitor. If the movement was completed in less than 1200ms, the following strategies were employed to maximize motivation and attention: 1) one of four potential 'rewarding' sounds were played on an external laptop computer; 2) a picture depicting two children 'high-fiving' appeared on the monitor; and, 3) 100 performance points were awarded. Participants were instructed that the goal of the experiment was to obtain as many performance points as possible. Critically, in this V condition, participants could utilize visual (provided via the computer monitor) and proprioceptive feedback to estimate the static position of their hand prior to movement onset.

The NV condition was similar to the V condition; however, there was no visual feedback of the manipulandum position *prior* to movement onset in the NV condition. Participants had to rely on the available *proprioceptive* feedback to estimate the static position of the arm. Timelines of sample trials for the two conditions are provided in Appendix VI.

Prior to the experimental protocol, participants completed ten reaching movements (2 per start position) with real-time visual feedback of the manipulandum position. These practice trials allowed the participants to become familiar with the experimental apparatus. The participants then completed one practice cycle of the V condition (10 trials; 2 per starting position; pseudo-randomly selected) and one practice cycle of the NV condition (10 trials; 2 per starting position; pseudo-randomly selected). After the completion of the practice phases, participants alternated between cycles of the V and NV conditions (3 cycles each). The alternating blocked design controlled for potential order effects. Although a random sequence of the two conditions is ideal, our previous studies have indicated that this design is difficult for the youngest children to complete and therefore we employed a blocked design. The experimental protocol consisted of 90 trials in total, including the 30 practice trials, and took approximately 20-35 minutes to complete.

Data Analysis

Customized MATLAB™ (Mathworks, Natick, MA USA) scripts were used to mark movement onset and offset via an interactive algorithm. The time series of two-dimensional (x/y) spatial coordinates were dual-pass filtered with an 8th order Butterworth filter (cutoff frequency = 10Hz). Movement onset was the first sample that the manipulandum reached 10% of its peak velocity. Movement offset was the first sample when the manipulandum was below 2.0 cm/s and remained below this threshold for 150ms. Onset and offset for each trial were visually inspected and, if necessary, manually re-marked.

As the primary difference between the two conditions was the availability of visual feedback of hand position *prior* to a goal-directed arm movement (i.e., static state estimation), the dependent variables of interest were those that reflected movement planning. Directional error (DE) was computed as the difference (measured in degrees) at time of peak velocity between the participant's trajectory and an ideal vector that connects target position and the coordinates of the manipulandum at movement onset. DE means were computed for each individual and experimental condition (collapsed across the three cycles). The standard deviation of DE (Var DE) for each condition and individual was also computed and used to assess each individual's variability of movement planning. Data were analyzed with the following linear regression:

$$Y = (\beta_o + \gamma_0 C) + ((\beta_1 + \gamma_1 C) * (age)) + e \qquad \text{(Eq. 1)}$$

Where Y = dependent measure (i.e., DE or Var DE)

β_0, β_1 = estimated fixed effects for the V condition

γ_0, γ_1 = adjustments to the β parameters for the NV condition

C = 1 if NV condition; 0 otherwise

e = residuals

The parameter β_1 provides an assessment of the age-related changes (i.e., the slope) of the dependent variables (DE and Var DE) for the V condition whereas γ_1 assesses the *difference* in the age-related changes between the two conditions. With this parameterization, the sum of β_1 and λ_1 is equal to the age-related changes for the NV condition. The adult participants were not included in the regression analyses described above. Rather, their data were compared to the performance of the 11-12 year-olds to determine if age-related improvements continue beyond the oldest children tested in the current study.

Results

No age-related differences in mean directional errors

Mean DE for the V (top panel) and NV (middle panel) conditions are shown in Fig 4.2 and analyzed with Eq. 1. Neither the β_1 parameter nor the sum of the β_1 and γ_1 parameters were significant ($p > 0.05$), indicating that there were no age-related differences in mean DE *within* either of the conditions. [Note that the sum of β_1 and γ_1 is the age-based slope for the NV condition.] The λ_1 parameter, representative of the difference in the age-based slopes *between* the two conditions, was also not significant. These results suggest that the movement trajectories of the young children (e.g., 6-7 years) were as accurate, on average, as the trajectories of the old children (e.g., 11-12 years) for both the V and NV conditions. Similarly, results of the 2 (condition) by 2 (group) ANOVA revealed no significant differences between the 11-12 year-old children and the adult participants ($p > 0.05$).

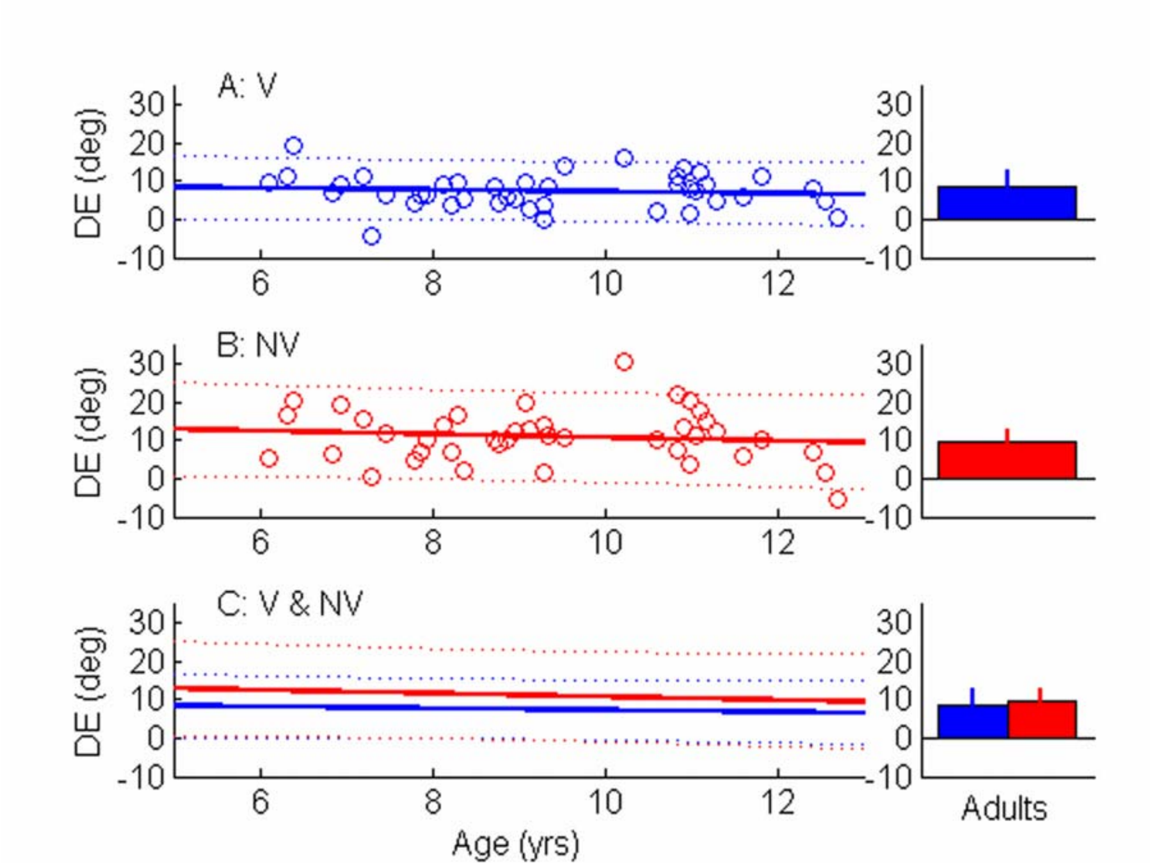

*Figure 4.2. Experiment 2: Mean Directional Error (DE) for the V condition (**A**) and NV condition (**B**) are depicted as a function of age. To make comparison between the two conditions, estimated age-based trajectories for both V (blue) and NV (red) are superimposed in the bottom panel (**C**). Dotted lines represent 95% prediction intervals. Mean values for the adults are shown in the bar graphs to the right.*

Removal of visual feedback of initial hand position disproportionately affects the variability of reaching trajectories in young children

Individual variability of DE is depicted for the V and NV conditions in Figure 4.3. Both the β_1 and the $(\beta_1+\gamma_1)$ parameters were statistically significant ($\beta_1 = -0.37$, SE = 0.15 p = 0.02; $\beta_1+\gamma_1 = -0.80$, SE = 0.19, p = 0.001). This indicates that Var DE significantly decreased as a function of age in both experimental conditions. Moreover, the γ_1 parameter was also significant ($\gamma_1 = -0.43$, SE = 0.19, p = 0.033), demonstrating that the age-based slope for the NV condition was greater (in magnitude) than the age-based slope for the V condition (Figure 4.3C). This finding indicates that removal of visual feedback of initial hand position disproportionately affected the variability of reaching movements in the younger children, as compared to the older children, suggesting that the less precise proprioceptive feedback for static state estimation in the younger children results in decreased sensorimotor performance.

To determine if these age-related decreases in directional variability persist into adolescence, we conducted a 2 (condition) by 2 (group: 11-12 year-olds / adults) ANOVA. The condition main effect was significant ($F_{(1,15)} = 39.7$, $p < 0.001$), however, the group main effect and the condition by group interaction were not. Although directional variability was larger in the NV condition for both groups, the lack of a significant group effect or interaction demonstrates that the directional variability of 11-12 year-olds was similar to that of the adults.

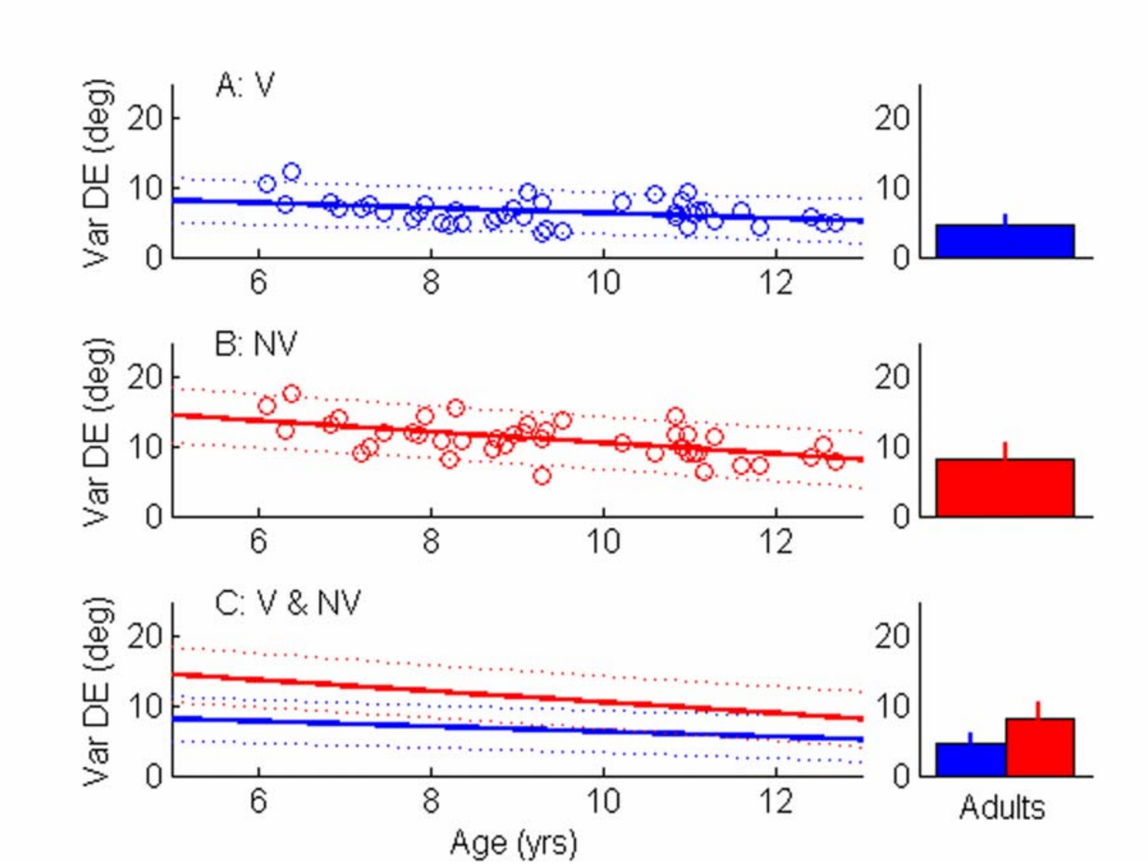

*Figure 4.3. Experiment 2: Directional Error Variability (Var DE) for the V condition (**A**) and NV condition (**B**) are depicted as a function of age. To make comparison between the two conditions, estimated age-based trajectories for both V (blue) and NV (red) are superimposed in the bottom panel (**C**). Dotted lines represent 95% prediction intervals. Mean values for the adults are shown in the bar graphs to the right.*

Experiment 3

Procedures

Participants were asked to make discrete reaching movements from a single start circle (0.75cm diameter) to one of five target positions (0.75cm diameter) located 15cm away from the body and start circle. The target circles were positioned 20°, 55°, 90°, 125°, and 160° with respect to the start circle (Appendix VII). Prior to each trial, the participant positioned the robotic manipulandum in the start position, the locations of which were depicted on the computer monitor. The cursor diameter depicting the manipulandum's position was 0.25cm. Once the manipulandum was motionless in the start position for a duration that randomly varied between 200 and 400ms, a red target circle appeared. Participants were instructed to not initiate movement until both the target and start circles turned green, which occurred after the participant remained motionless for an additional time period that randomly varied between 200 and 350ms. [This hold period for Experiment 3 is less than that in Experiment 2 because participants did not need additional time to localize initial hand location as they actively moved their hand to the starting position prior to each trial.] The color change of start and target circles provided a 'GO' signal for movement onset; and, participants were instructed to move as soon as possible after the circles turned green. If the manipulandum moved outside of the start position prior to the GO signal, the trial reset and the participant returned to the start position. Once the participant exited the start position and moved toward the target circle, the visual feedback depicting current hand (e.g., manipulandum) position disappeared, effectively removing any on-line visual feedback of the participants' movement trajectories. Participants were instructed to stop and hold still when they felt they reached the target circle. Once motionless for 500ms, the yellow circle depicting the manipulandum's position re-appeared, providing EP visual feedback of the participants' movements. This marked the termination of the trial and the participants returned to the start position for the next trial. Participants were instructed to complete each movement in between 300 and 1200ms (excluding the 500ms 'hold' period at the conclusion of the trial). If the movement was not completed in time, the same prompt as employed in Experiment 2 appeared informing participants to speed up. To maximize motivation and attention, the same rewarding stimuli as used in Experiment 2 were provided if the movement was completed within this time window.

The experiment contained two conditions: single and double-step (Appendix VII). The single-step condition was exactly as described in the preceding paragraph. A target appeared and the participants executed a rapid arm movement towards the target. For the double-step condition (25% of the total number of trials; randomly inserted), the target circle 'jumped' to one of the adjacent target locations at the time of movement onset. Participants were instructed to modify their movement trajectory as fast as possible in order to reach the displaced target.

Prior to the experimental protocol, participants completed 30 practice single-step trials; the first 15 provided real-time visual feedback of the manipulandum position during the reaching movement. These practice trials allowed the participants to become familiar with the experimental apparatus. Data from the practice trials were not analyzed. Participants subsequently completed 80 experimental trials; 20 randomly selected trials were the double-step condition. Participants were told a priori that the targets may switch positions and they should attempt to hit the new target as fast as possible. The experimental protocol consisted of 110 trials in total, including the 30 practice trials, and took approximately 20-35 minutes to complete.

Data Analysis

Initial data processing, including marking movement onset and offset, was identical to Experiment 2. Additionally, the time at which the participants generated a corrective movement to the displaced targets (double-step trials only) was marked as the local minima of the velocity profile after peak velocity of the movement towards the initial target (see Appendix VIII for details). Each marking was visually inspected and manually re-marked if necessary.

The dependent variables for the single-step condition (and for the initial movements of the double-step trials) were directional error (DE), intra-individual variability of DE (Var DE) and reaction time (RT). DE and Var DE were computed as described for Experiment 2. RT was the duration between the GO stimulus and movement onset. Means for DE and Var DE and medians for RT were computed for each individual. RT medians, as opposed to means, were computed to minimize the influence of large single-trial values that can potentially be attributed to lapses in attention. Child data from the single-step condition and the movements to the initial targets in the double-step trials were analyzed with the following age-based linear regression.

$$Y = \beta_o + (\beta_1 * age) + e \qquad \text{(Eq. 2)}$$

Where Y = dependent measure

β_0, β_1 = estimated fixed effects for the single-step condition e = residuals

A statistical test of the β_1 parameter assesses the magnitude of the age-related changes in DE, Var DE and RT for the single-step condition and the initial movements of the double-step trials.

For the movements to the displaced targets in the double-step condition, the dependent variables were directional error of the secondary movement (DE_{DS}), intra-individual variability of DE_{DS} and time-to-correction (TTC). The time at which the participant initiated a corrective movement towards the displaced target was marked and herein referred to as COR (Appendix IX). The variable TTC is the duration between the time at which the target is displaced and COR. DE_{DS} is computed as the difference (measured in degrees) between the participant's corrective movement to the displaced target and an ideal vector that connects manipulandum position at COR and the target (Appendix IX). Similar to DE, DE_{DS} was computed at the time of peak velocity of this secondary movement. An examination of the DE_{DS} values revealed a systematic bias, especially in the younger children, depending on whether the target was displaced to the right or to the left. For example, a visual inspection of the double-step movement trajectories of the *young* children in Figure 4.2 reveals that the participants' movement trajectories were predominantly directed counter-clockwise (CCW) with respect to the target when the target was displaced from left to right. However, the trajectories were predominantly directed clockwise (CW) with respect to the target when the target was displaced from right to left. Since DE_{DS} was computed by the equation $DE = \theta_{mov} - \theta_t$, where θ_{mov} is the direction of the actual movement and θ_t is the direction of the desired target position, DE_{DS} values in the younger children were predominantly positive or negative when the target was displaced to the right or left, respectively. To adjust for this bias, DE_{DS} values were transformed by multiplying by the constant (-1) if the target was displaced to the left. Thus, positive DE_{DS} values are indicative of an 'overshoot' of the displaced target position, as depicted by the average movement trajectories of the young children in Figure 4.2. The standard deviation of each individual's transformed DE_{DS} scores (Var DE_{DS}) assessed the directional variability of the corrective movements. Means for DE_{DS} and Var DE_{DS} and medians for TTC were computed for each individual for the double-step trials.

These dependent variables specific to the double-step trials were initially analyzed with Eq. 1 above. However, to assess the effects of dynamic state estimation *above and beyond* the influence of other processes such as static state estimation and/or the controller, analyses of the double-step corrective movements also consisted of semipartial linear regressions (i.e., single-step performance was partialed out of double-step performance). For example, TTC was initially analyzed with a linear regression with RT as the independent variable. The residuals from this model were then analyzed with a second linear regression with age as the independent variable. With this semipartial linear regression, the age-related effects on the time it takes to respond to a stimulus during movement execution (i.e., TTC) that are above and beyond differences in RT can be investigated. DE_{DS} and Var DE_{DS} are analyzed with similar semipartial linear regressions; however, the first independent variable block was DE and Var DE, respectively. The semipartial regressions allow us to differentiate age-related changes in dynamic state estimation, as probed by the corrective movements to the displaced targets, from differences in both static state estimation and controller, as any differences in these underlying processes are also present in the analysis of the single-step trials (i.e., DE and Var DE). Similar to Specific Aim 2, adult participants were not included in the regression analyses. Their data were statistically compared with t-tests to the performance of the 11-12 year-old children to determine if the performance of these older children can be considered adult-like.

Results

Average movement trajectories during single- and double-step trials for a group of young children (n=6; mean age = 6.3 years), old children (n=6; mean = 12.2 years) and adults (n=6; mean = 20.5 years) are depicted in Figure 4.4. The six adults were randomly selected from the full sample whereas the young and older child groups consist of the six youngest and oldest child participants, respectively. During single-step trials, movement paths of the three groups were relatively straight. Although the young children appear to have increased movement variability, the three groups performed relatively similarly in the single-step condition. Conversely, there appears to be substantial age-related improvements in performance in the double-step condition. The young children were more variable and consistently 'overshot' the displaced target position. The movements by the adults, and to a lesser extent the older children, were more accurate and consistent. Detailed statistical analyses of performance are included in the subsequent sections.

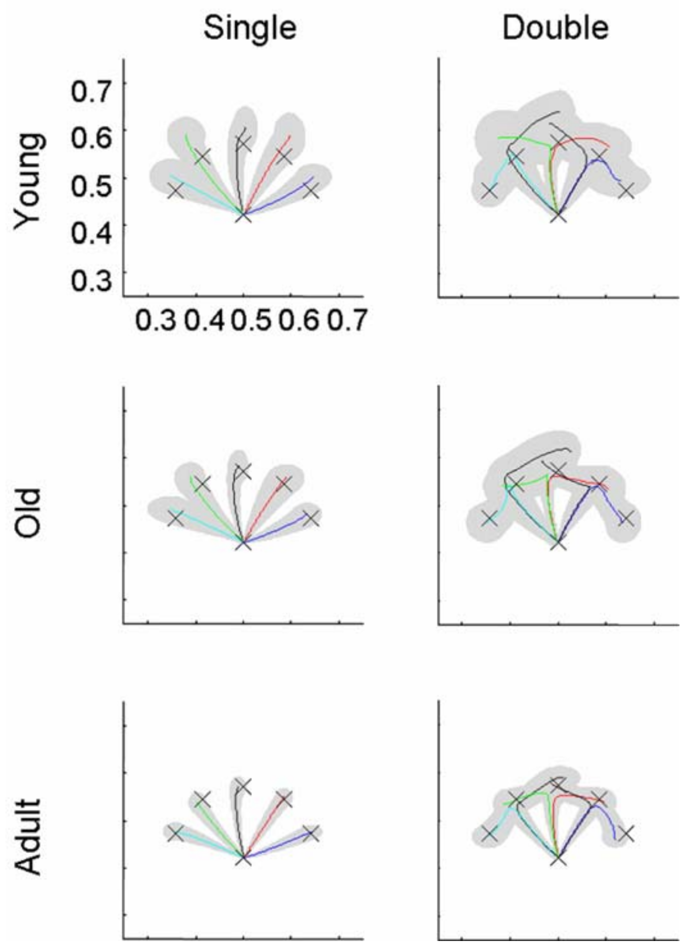

Figure 4.4. Experiment 3: Movement trajectories. Solid lines depict average trajectories for a group of young children (n = 6; mean age = 6.3 years), old children (n = 6; mean age = 12.2 years) and adults (n=6; mean age =20.0 years). Gray shaded regions represent 1 sd. Black Xs depict target positions. Units = m.

Younger children moved at similar peak velocities as older children

Since the purpose of this experiment was to examine age-related improvements in *dynamic* state estimation (i.e., during movement execution), it is critical to verify that there were no age-related differences in movement velocity across the child participants. Slower movement speeds may depend more on static, as opposed to dynamic, state estimation. Importantly, there were no age-related differences in peak velocity for the single-step and the initial movements of the double-step trials (Appendix X; $p > 0.05$). There were also no age-related differences in PV for the corrective movements in the double-step condition (Appendix X; $p > 0.05$). Last, the adult participants moved at similar speeds as the 11-12 year-old children for both the single-step trials and the corrective movements of the double-step trials ($p > 0.05$).

Age-related differences in the time to correct to the target perturbation are accounted for by differences in RT

Age-related differences in median RT for the single-step trials and the initial movements of the double-step trials are depicted in Figure 4.5A. The slope of this age-based regression was significant ($\beta_1 = -15.50$; $p < 0.001$), indicating that RT decreased as a function of age in the child participants. Age-related decreases in median TTC (Figure 4.5B) for the double-step trials were also significant ($\beta_1 = -17.8$; $p < 0.01$). This suggests that older children (i.e., 11-12 years), as compared to younger children (i.e., 5-7 years), responded faster to the displaced target position. To determine if these age-related differences in TTC can be attributed to delays in dynamic state estimation, as opposed to age-related processing delays that are independent of dynamic state estimation, we conducted a semipartial linear regression. Specifically, we regressed RT on TTC and then examined age-related differences in the TTC residuals. If the TTC residuals significantly decreased as a function of age, this would indicate that the age-related decreases in TTC are above and beyond any general age-related processing delays that were also evident in the analysis of RT. The slope of the age-based regression on TTC Resids (Figure 4.5C) was not significant ($\beta_1 = -6.03$; $p = 0.24$), suggesting that the age-related differences in TTC can simply be explained by age-related processing delays[4].

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[4] To verify that the results presented in the main text were not due to analyzing median values, we also computed *mean* RT and TTC values. Analyses of the means were consistent with those of the medians (see Appendix XI for details).

To determine differences between the oldest group of children (11-12 years) and the adult participants, we conducted two-sample t-tests on both median RT and TTC. Median RT of the adults was substantially faster than that of the 11-12 year-old children (t=2.72; p = 0.013), indicating that age-related reductions in RT persist through adolescence. Median TTC was not statistically different among the adults and 11-12 year-old children (p > 0.05), demonstrating that the older children responded to the target perturbation as fast as the adults.

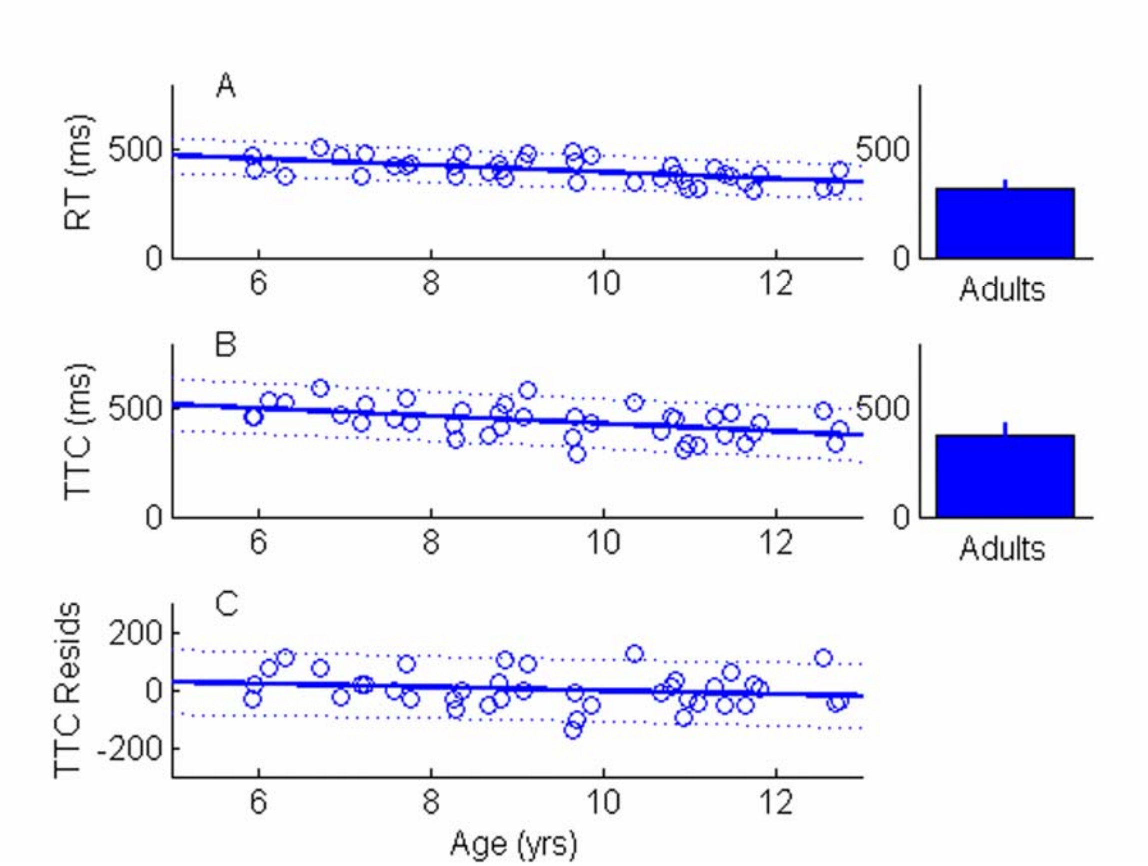

*Figure 4.5. Experiment 3: Temporal measures. Median RT (**A**), TTC (**B**) and TTC Resids (**C**; residuals based on linear regression with RT as a predictor) are depicted as a function of age. Dotted lines represent 95% prediction intervals. Median values for the adults are shown in the bar graphs to the right.*

Dynamic state estimation in younger children, as compared to older children and adults, is delayed and unreliable

There were no age-related differences in DE ($p > 0.05$) for the single-step and the initial movements of the double-step trials (Figure 4.6A), indicating that, on average, the trajectories of the 5-6 year-olds were as accurate as the older children. Interestingly, there were significant age-related decreases in DE_{DS} ($\beta_1 = -2.59$; $p = 0.038$); the older children were able to accurately modify their movement trajectory towards the displaced targets whereas the younger children demonstrated large positive errors (Figure 4.6B). Positive DE_{DS} values are indicative of an 'overshot' of the displaced target positions (see movement trajectories of the young children in Figure 4.4). This systematic overshot can be interpreted as relying on *delayed* sensory feedback in order to estimate hand state during movement execution. Specifically, the direction of the secondary movements in the younger children *would* be directed exactly, on average, towards the displaced target position assuming the estimate of hand state prior to the corrective movement was actually an estimate at some time point in the past. The estimates of hand state at the time of correction appear to be out-of-date in the younger children. Conversely, the direction of the secondary movements in the older children and adults were directed exactly, on average, towards the displaced target position (i.e., $DE_{DS} \sim 0$), suggesting that the hand state estimate prior to the corrective movement was accurate despite the fact the hand was moving towards the initial target position. In summary, the pattern of errors demonstrated by the children suggests that younger children relied on delayed sensory feedback for dynamic state estimation whereas the older children and adults utilized an up-to-date estimate, presumably the result of state prediction. To ensure that the age-related differences in DE_{DS} can be attributed to improvements in dynamic state estimation and not other underlying processes such as static state estimation or the controller, we conducted a semipartial linear regression. We initially regressed DE on DE_{DS} and subsequently regressed age on the residuals. There was a significant age-related decrease in DE_{DS} residuals ($\beta_1 = -2.61$; $p = 0.029$), demonstrating that the improvements in DE_{DS} can be attributed to improvements in dynamic state estimation. There were no significant differences between the 11-12 year-old children and the adults in DE or DE_{DS} ($p > 0.05$), demonstrating that these older children were as accurate as the adults for both single- and double-step movements.

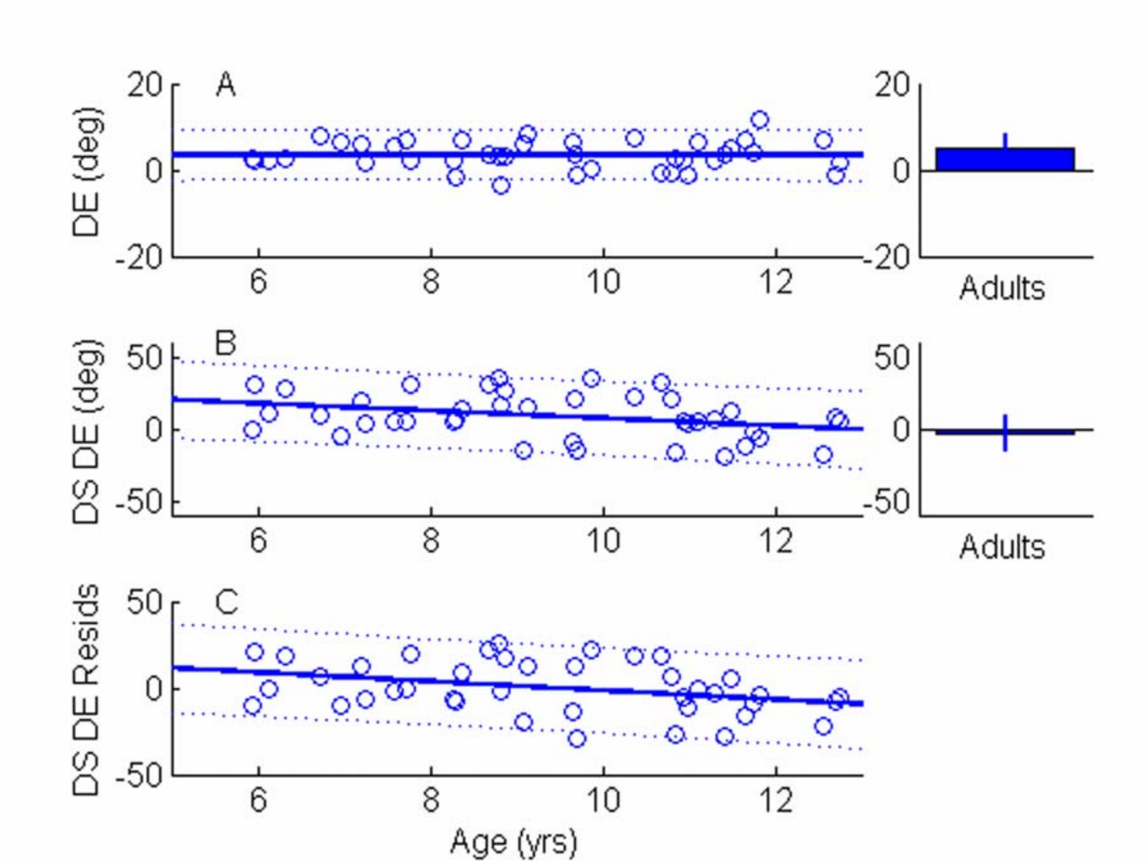

*Figure 4.6. Experiment 3: Directional Error (DE). Mean DE (**A**)), DE_{DS} (**B**) and DE_{DS} Resids (**C**; residuals based on linear regression with DE as a predictor) are depicted as a function of age. Dotted lines represent 95% prediction intervals. Mean values for the adults are shown in the bar graphs to the right.*

Directional variability was examined by computing the standard deviation of each individual's DE and DE_{DS} scores (Figure 4.7). Consistent with previous research, there were significant age-related differences in Var DE for the single-step and initial movement of the double-step trials ($\beta_1 = -0.35$; $p = 0.036$). Significant age-related decreases in Var DE_{DS} ($\beta_1 = -1.45$; $p < 0.01$) were also revealed, indicating that the secondary movements to the displaced targets were less consistent in the younger children as compared to the older children. This increased variability can be interpreted as a less reliable dynamic state estimate prior to the corrective movement. To verify that the age-related decreases in Var DE_{DS} can be attributed to dynamic state estimation as opposed to other underlying processes, we again conducted a semipartial linear regression; we first partialed out Var DE from Var DE_{DS} and then regressed the residuals with age. The age-related decrease in the Var DE_{DS} residuals was significant ($\beta_1 = -1.18$; $p = 0.015$), providing further evidence for increased dynamic state estimation variability in the younger children (i.e., 5-6 years). The 11-12 year-old children were significantly more variable than the adults in their movements to the initial targets, as indicated by larger Var DE ($t=2.17$; $p = 0.042$). However, there were no significant differences between the older children and the adults in Var DE_{DS} ($p > 0.05$), suggesting that these older children were as consistent as the adults in the corrective movements to the displaced targets.

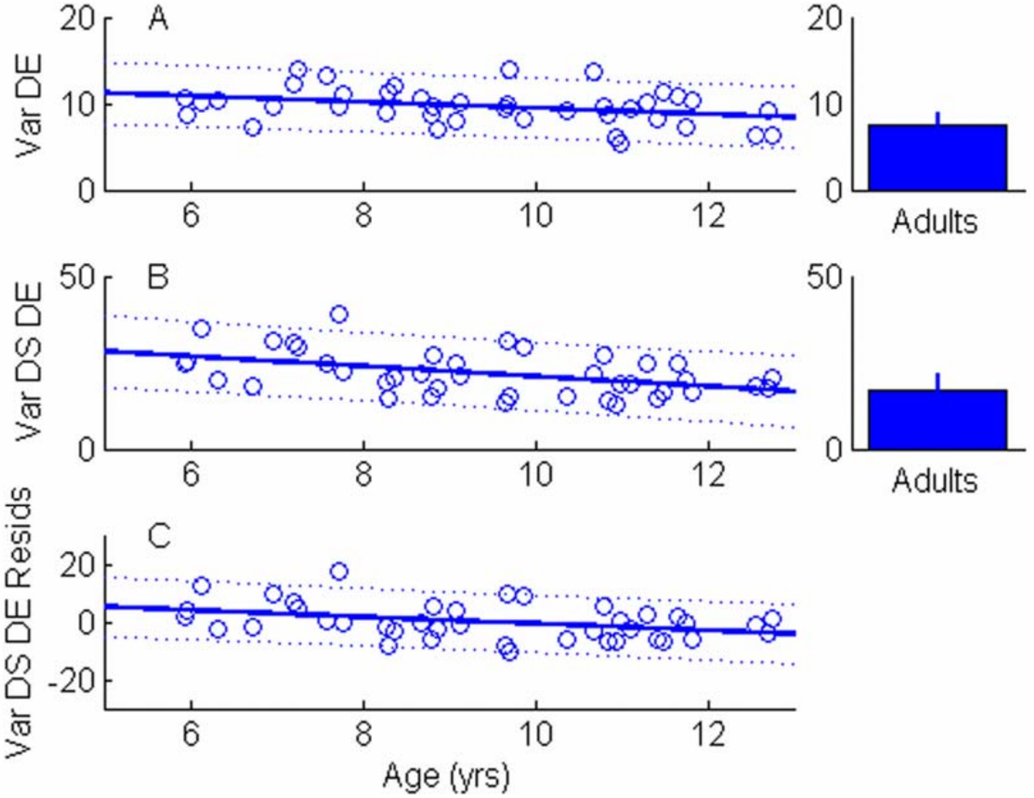

*Figure 4.7. Experiment 3: Directional Error Variability (Var DE). Mean Var DE (**A**)), Var DE_{DS} (**B**) and Var DE_{DS} Resids (**C**; residuals based on linear regression with Var DE as a predictor) are depicted as a function of age. Dotted lines represent 95% prediction intervals. Mean values for the adults are shown in the bar graphs to the right.*

Summary

The results from Experiment 3 demonstrated significant age-related differences across 5- to 12-year-old children in both directional errors (DE_{DS}) and directional variability (Var DE_{DS}) in a double-step reaching task. Since both these measures depend on the accurate localization of the hand *during* movement execution, these results suggest that dynamic state estimation is a rate-limiter in the development of sensorimotor control of the arm. Importantly, these differences were above and beyond the influence of static state estimation and the controller, as any differences in these underlying processes were also present in the single-step trials and the initial movements of the double-step trials.

Moreover, the older children performed nearly identical to the adults, suggesting that dynamic state estimation is adult-like by 11-12 years.

Discussion

The current research examined the effects of static and dynamic state estimation on sensorimotor performance in 5- to 12-year-old children. Results revealed two key findings: 1) young children (i.e., approximately 6-8 years) have less precise proprioceptive feedback for static state estimation, compared to older children (i.e., ~10-12 years), resulting in increased movement trajectory variability; and, 2) young children, as compared to older children, rely on delayed and unreliable state estimates during the execution of ballistic, goal-directed arm movements, resulting in increased movement errors and directional variability. Collectively, these results suggest that age-related improvements in static and dynamic state estimation underlie, at least partially, age-related improvements in sensorimotor performance.

Poor proprioceptive functioning for localization of initial hand position in the younger children increases directional variability of reaching movements

Results from Experiment 2 revealed that the age-related improvements in directional variability in the NV condition were significantly different from the age-related improvements in the V condition (i.e., significant γ_1 parameter in Eq. 1). The critical difference between the two conditions was that the NV condition required participants to utilize proprioceptive feedback to localize initial hand position whereas participants could use vision *and* proprioception in the V condition. Thus, the difference in the age-related improvements between the two conditions can be explained by improved proprioceptive functioning for hand localization in the older children, an interpretation that is consistent with previous research (Contreras-Vidal, 2006; King et al., 2010; Pickett et al., 2009; Visser et al., 2000).

Importantly, the differences in the age-related improvements between the conditions can *not* be explained by age-related improvements in other processes involved in goal-directed reaching movements such as the controller (e.g., inverse internal representation). The function of the controller is to transform desired movement trajectories into the appropriate motor commands. But, in Experiment 2, any influence of the controller remained constant across the two experimental conditions.

Significant age-related decreases in directional variability in the V condition, when both visual and proprioceptive estimates of hand position were available, were also revealed in Experiment 2. Assuming static visual acuity is developed prior to the ages investigated in this study (Ellemberg et al., 1999; Leat, Yadav, & Irving, 2009; Nelson et al., 1984), decreases in movement variability in the V condition can not be attributed to improvements in visual functioning for static state estimation. Interestingly, research by Sabes and colleagues suggests that when both the visual and proprioceptive systems provide estimates of hand position, proprioception contributes more to the state estimate that is used to transform a spatial difference vector between initial and desired positions into the appropriate joint-based motor commands (Sober et al., 2003). Thus, age-related improvements in proprioceptive functioning for hand localization may also explain the age-related decreases in directional variability even when visual information of hand position was provided, a result demonstrated in the current study and in previous research (Contreras-Vidal et al., 2005; King et al., 2009; Pangelinan et al., 2011).

On-line movement corrections in younger children are dependent on delayed and unreliable state estimates

The primary finding from Experiment 3 was older children (~10 to 12 years) and adults, as compared to the younger children (~6 to 8 years), were more accurate and less variable in their corrective movements to displaced targets. The pattern of errors demonstrated by the younger children suggests that their corrective movements were based on delayed and unreliable state estimates. These age-related improvements in performance can be attributed to improvements in *dynamic* state estimation that are above and beyond the effects of static state estimation and the controller. The influence of static state estimation and the controller were consistent across reaches to both the initial *and* the displaced targets. By employing hierarchical regressions, we differentiated age-related improvements in dynamic state estimation from other processes. These findings suggest that the development of a *forward* internal representation, responsible for predicting future states of the system based on the current state and descending motor commands, is a rate-limiter for the development of sensorimotor control of the arm. The development of the forward representation is likely to depend on sufficient, task-specific experience that fine-tunes the input/output relationships.

The age-related improvements in dynamic state estimation demonstrated in the current research may potentially be attributed to developmental changes in the underlying neural substrates. Optimal dynamic state estimation is thought to be the result of combining state predictions with delayed sensory feedback (Gritsenko et al., 2009; Izawa et al., 2008; Wolpert et al., 1995), a process that is dependent on the posterior parietal cortex (PPC) and cerebellum (Bastian, 2006; Miall et al., 2008; Miall et al., 2007; Shadmehr et al., 2008). Previous research has demonstrated structural changes in both the parietal cortex and cerebellum across the age range examined in the current study (Giedd et al., 1999; Tiemeier et al., 2010). Future studies should attempt to reveal the relationship between these structural changes and age-related improvements in state estimation and sensorimotor performance.

Age-related decreases in the time to initiate corrective movements

Results from Experiment 3 demonstrated that the dependent variable TTC, defined as the duration between target displacement and the initiation of the corresponding corrective movement, significantly decreased as a function of age across childhood. However, this finding can be explained by age-related improvements in RT, and is *not* specific to on-line trajectory modifications. Specifically, after RT was partialed out, the age-related decreases in the time it takes to initiate a corrective movement during movement execution were not significant. The assessment of RT, in the context of the current study, provided an estimate of the time it took to detect the GO signal and send the pre-selected motor commands to the appropriate muscles (i.e., a simple RT paradigm). Conversely, the assessment of TTC provided an estimate of the time it took to detect the target jump, select or compute the appropriate motor commands that will move the hand to the new target position and send these commands to the periphery. The critical distinction is that the movements to the initial target were cued and the participants had a hold period lasting over 1000ms to plan the movement. Conversely, in the double-step condition, participants did not know *if* or *where* the target was going to jump and had to compute the appropriate motor commands once they detected the target jump. The results of the semipartial regression suggest that the time it took to complete this additional processing step (e.g., computation of the appropriate commands) did not significantly change as a function of age.

Age-related, not age-determined, improvements

It should be emphasized that the improvements in state estimation and sensorimotor performance demonstrated in the current study are age-related, *not* age-determined. We simply used age as a proxy to represent the developmental process. Despite the significant findings, an examination of our results reveals substantial inter-individual variability that is not accounted for by age (i.e., many 7-8 year-old children performed better than 9-10 year-olds). The improvements reported in this research are likely to be a function of the task-specific experiences specific to each individual and are not the result of maturational processes that simply unfold as a function of age. Future research should examine what specific experiences are considered sufficient to drive age-related changes in state estimation and sensorimotor behavior.

Conclusion

The experiments in the current research demonstrated age-related improvements in sensorimotor performance in two goal-directed reaching tasks. Based on the experimental designs and the statistical analyses employed, these improvements in performance are attributed to improvements in static and dynamic state estimation. We suggest that age-related improvements in state estimation are responsible, at least partially, for the age-related improvements in sensorimotor control of the arm frequently reported in the extant literature. Future research should investigate the development of the neural structures underlying static and dynamic state estimation and the influence of these developmental processes on sensorimotor behavior.

CHAPTER V: EXPERIMENT 4: The Effects of a State Estimation Perturbation on Sensorimotor Performance in Adults

Abstract

The current research sought to examine the relationship between dynamic state estimation and sensorimotor performance by exposing adult participants to a visual feedback perturbation that simulated the delayed and unreliable dynamic state estimates previously demonstrated in young children. If dynamic state estimation is indeed a rate-limiter in sensorimotor development, a visual feedback perturbation that makes dynamic state estimation as equally inaccurate and unreliable in adults and young children would theoretically eliminate or minimize the previously demonstrated differences between the two age groups. However, results indicated that the perturbation had no substantial effects on the performance of the adults. This suggests that the adults down-weighted or ignored the visual feedback perturbation and instead estimated hand state based on available proprioceptive feedback and/or predictions of hand state generated by a developed and stable forward model.

Introduction

The results from Experiments 2 and 3 suggested that age-related improvements in sensorimotor performance across childhood can be attributed to improvements in static and dynamic state estimation. Specifically, compared to the older children and adults, the poor performance demonstrated by young children in a double-step reaching task was the result of delayed and unreliable state estimates during the execution of rapid, goal-directed arm movements. If dynamic state estimation is indeed a rate-limiter in sensorimotor development, then any age-related improvements in performance should be minimized *if* the accuracy and reliability of dynamic state estimates are similar across different age groups.

To investigate the relationship between dynamic state estimation and sensorimotor performance, we *exposed adults to a visual feedback perturbation that attempted to simulate the delayed and variable dynamic state estimation evident in young children.* Thus, the perturbation sought to make state estimation equally inaccurate and unreliable in adults as in young children. It was hypothesized that this visual feedback perturbation would cause adults to perform nearly identical to young children in Experiment 3. Ideally, results would provide a causal link between age-related improvements in dynamic state estimation and age-related improvements in sensorimotor performance.

Methodology

Participants

Nine adults between the ages of 18 and 23 years participated in this study. Inclusion criteria were identical to Experiments 2 and 3. Adult participants completed a neurological health questionnaire to ensure no known neurological or motor impairments (Appendix III). Handedness of the adults was determined by the Edinburgh Handedness Inventory (cumulative score > 40; Appendix IV) (Oldfield, 1971). The performance of the adults in the current study was compared to the youngest children (5 to 7 years of age) in Experiment 3 (see Chapter IV for inclusion criteria). Detailed participant characteristics for both groups are provided in Table 5.1. All experimental procedures were approved by the Institutional Review Board at the University of Maryland, College Park. Informed consent was obtained prior to participation (Appendix II). Upon completion of the experiment, participants received a modest monetary compensation.

Table 5.1: Experiment 4 participant characteristics

Group	Gender	Mean Age ± SD (yrs)	MABC %ile Range	Edinburgh: Mean ± SD
Young children	4F; 7M	6.9 ± 0.7	25 - 91	N/A
Adults	7F; 2M	21.0 ± 1.6	N/A	80.9 ± 17.6

Procedures

The same experimental apparatus used in Experiments 2 and 3 was used for this experiment (Figure 4.1). Participants were appropriately positioned in the adjustable chair and instructed that the goal of the task was to move the manipulandum from a start position to a desired target *as fast and as accurately as possible*. Relevant task stimuli were available via the vertically-oriented computer monitor. During the experimental protocol, the lights in the testing room were turned off to restrict vision of the participants' limbs.

There were two conditions in this experiment: baseline and perturbed. The order in which the participants completed the two conditions was counterbalanced to minimize fatigue or practice effects. The protocol for the baseline condition was nearly identical to Experiment 3. Participants were asked to make discrete reaching movements from a start circle to one of five target positions located 15cm away. The target circles were positioned 20°, 55°, 90°, 125°, and 160° with respect to the start circle (Appendix VII). Following 30 practice trials, participants completed an additional 80 experimental trials, 20 of which were the double-step condition described in the preceding chapter (i.e., target jumped at movement onset). The critical difference between the procedures in Experiment 3 and the baseline condition in Experiment 4 was that on-line visual feedback of the manipulandum's position was provided in the current experiment.

Similar to the baseline condition, the perturbed condition consisted of eighty experimental trials (25% double step; 75% single step) following a practice phase of 30 single step trials. However, during the perturbed condition, the visual feedback displayed on the computer monitor was spatially and temporally manipulated. The parameters of this perturbation were ‘yoked’ to the performance of the youngest children in Experiment 3. Results from this previous experiment revealed that the younger children relied on delayed and spatially variable sensory feedback to estimate hand state during the execution of rapid arm movements. Specifically, hand state estimates in the younger children appeared to be delayed by approximately 50ms. Moreover, the standard deviation of the directional errors during the single-step trials was approximately 9.75 degrees[5]. The perturbation in Experiment 4 consisted of temporal and spatial distortions that attempted to simulate these performance characteristics displayed by the younger children. Specifically, the visual feedback was delayed 50ms and unpredictably rotated on a trial-to-trial basis (mean rotation = 0 degrees; standard deviation = 9.75). This perturbation was present throughout the duration of the perturbed condition, even the 30 practice trials.

The purpose of this visual feedback perturbation was to systematically disrupt dynamic state estimation in the adult participants. By increasing variability and inserting a temporal delay into the visual feedback, the magnitudes of which were based on the performance of 5- to 7-year-old children, the perturbation would theoretically create an environment that precluded accurate and reliable dynamic state estimation. Ideally, this perturbation would make dynamic state estimation in the adults equally inaccurate and unreliable as the younger children, allowing us to directly assess the relationship between dynamic state estimation and sensorimotor control.

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[5] See Appendix 12 for details on the computation of the parameter estimates for the spatial and temporal perturbations.

Data Analysis

Initial data processing (marking movement onset, offset and time of correction) was identical to Experiment 3. Each marking was visually inspected and manually re-marked, if necessary. The dependent variables for the single-step condition (and for the initial movements of the double-step trials) were directional error (DE), intra-individual variability of DE (Var DE) and reaction time (RT). For the double-step condition, the dependent variables were directional error of the secondary movement to the displaced target (DE_{DS}), intra-individual variability of DE_{DS}, and time-to-correction (TTC). Means for DE, Var DE, DE_{DS}, and Var DE_{DS} and medians for RT and TTC were computed for each individual. RT and TTC medians, as opposed to means, were computed to minimize the influence of large single-trial values that can potentially be attributed to lapses in attention.

The overarching hypothesis of this experiment was that the perturbation of dynamic state estimation would cause the adults to perform similar to the young children, effectively eliminating the differences between the two groups that were present in Experiment 3. To investigate this hypothesis, we conducted multiple planned contrasts. First, t-tests were conducted comparing the performance of the adults in baseline condition of Experiment 4 to the performance of the young children (5 to 7 years) in Experiment 3. Consistent with Experiment 3, results were expected to show substantial group differences. To examine the effects of the dynamic state estimate perturbation on sensorimotor performance, we conducted t-tests comparing the performance of the adults in the perturbed condition of Experiment 4 to the performance of the young children in Experiment 3. Consistent with our primary hypothesis, no group differences were expected as perturbation to dynamic state estimation would cause the adults to perform similarly to the young children. To quantify the effect of the perturbation on adult performance, we compared the perturbed and baseline conditions in Experiment 4. It is important to note that we employed multiple planned contrasts, as opposed to an omnibus ANOVA, because the same adult participants completed both conditions in Experiment 4, whereas the younger children only completed the one (baseline) condition in Experiment 3.

Results

Average movement trajectories for the adults during the baseline (top panel) and perturbed (middle) conditions of Experiment 4 and the young children from Experiment 3 (bottom) are depicted in Figure 5.1. During single-step trials, movement paths from the different groups and conditions were relatively straight. The young children appear to have increased movement variability compared to both the baseline and perturbed conditions completed by the adults; however, the increased variability around the target positions can be explained by the lack of on-line visual feedback in Experiment 3. As discussed in the preceding chapter, the young children were more variable and overshot the displaced target positions in the double-step condition. Interestingly, the perturbation appears to have little to no effect on the performance of the adults, an observation that was statistically examined in the subsequent sections.

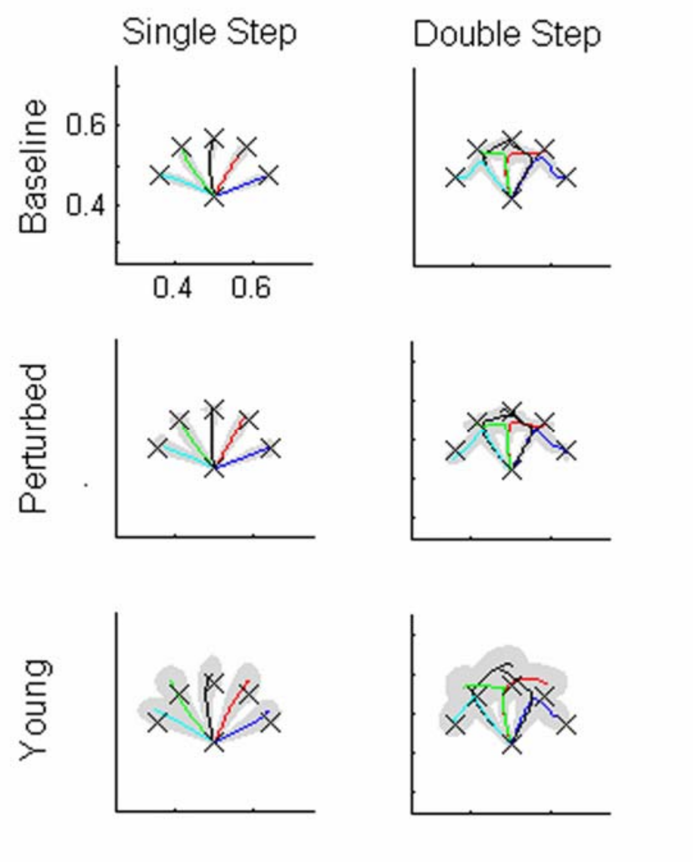

Figure 5.1. Experiment 4: Movement trajectories. Solid lines depict average trajectories for the adults during the baseline (top panel) and perturbed (middle) conditions. Bottom panel shows trajectories from the younger children in Experiment 3. Gray shaded regions represent 1 sd. Black Xs depict target positions. Units = m.

The primary conclusion from Experiment 3 was that the younger children relied on delayed and unreliable sensory feedback to estimate hand state during the execution of rapid arm movements. This result was based on the pattern of directional errors (DE_{DS} and Var DE_{DS}) when moving to the displaced target positions. Figure 5.2 depicts DE_{DS} and Var DE_{DS} for the young children in Experiment 3 and the adults in Experiment 4 (both conditions). Both DE_{DS} and Var DE_{DS} during the adult baseline condition were significantly different than in the young children (DE_{DS}: $t = 4.24$, $p < 0.001$; Var DE_{DS}: $t = 7.70$, $p < 0.001$), a result that is consistent with Experiment 3. These group differences were still present when comparing the adult perturbation condition and the young children (DE_{DS}: $t = 4.06$, $p < 0.001$; Var DE_{DS}: $t = 7.64$, $p < 0.001$), suggesting that the perturbation to dynamic state estimation did not cause the adults to perform similarly to the young children. A comparison of the adult baseline and perturbation conditions revealed no differences in either DE_{DS} or Var DE_{DS} ($p > 0.05$). Collectively, these results indicate that the perturbation had no influence on the performance of the adults, as assessed by DE_{DS} or Var DE_{DS}.

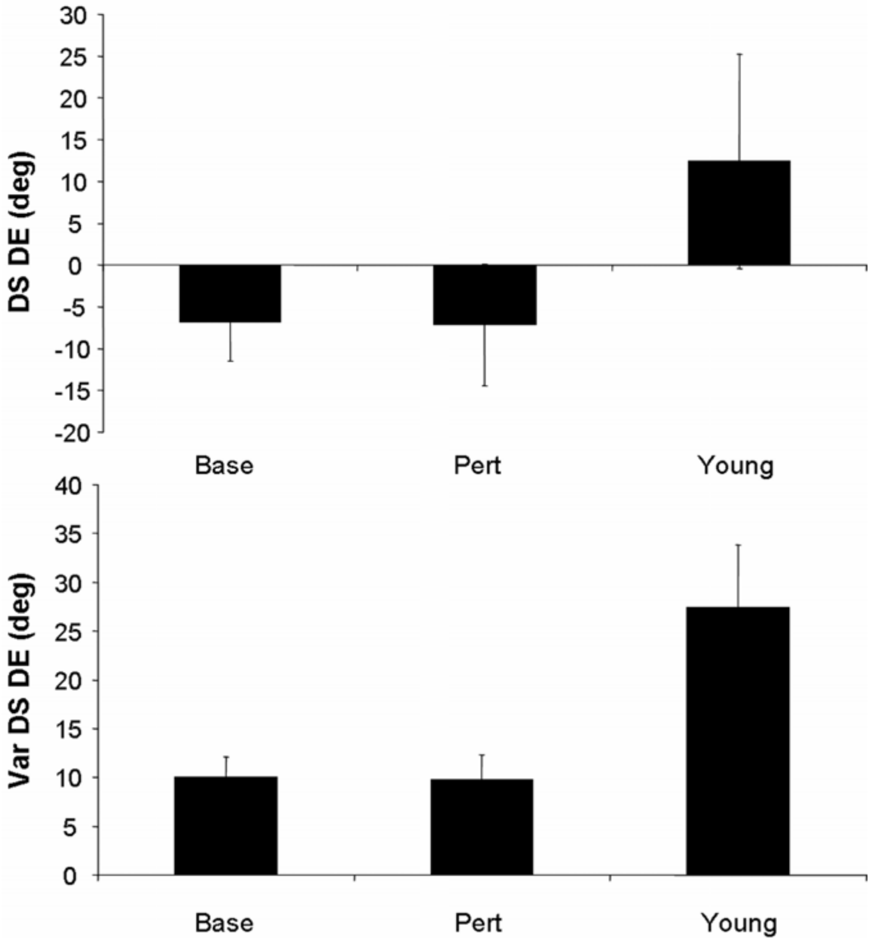

*Figure 5.2. Experiment 4: Spatial Measures. (**A**) DE_{DS} and (**B**) Var DE_{DS} are shown for the adults in the baseline and perturbed conditions relative to the young children from Experiment 3.*

Other dependent measures of interest, summarized in Table 5.2, demonstrated nearly identical trends[6]. The perturbation did not cause the adults to perform similarly to the young children; and, more importantly, it did not substantially affect sensorimotor performance in the adult participants. The only measure that was altered during the perturbed condition was TTC ($t = 16.7$, $p = 0.003$; Figure 5.3A); although TTC during the perturbed condition was still less than in the young children ($t = 3.77$, $p = 0.001$). Similar to Experiment 3, the differences in TTC between the young children and the adults can likely be attributed to group differences in RT (Figure 5.3B).

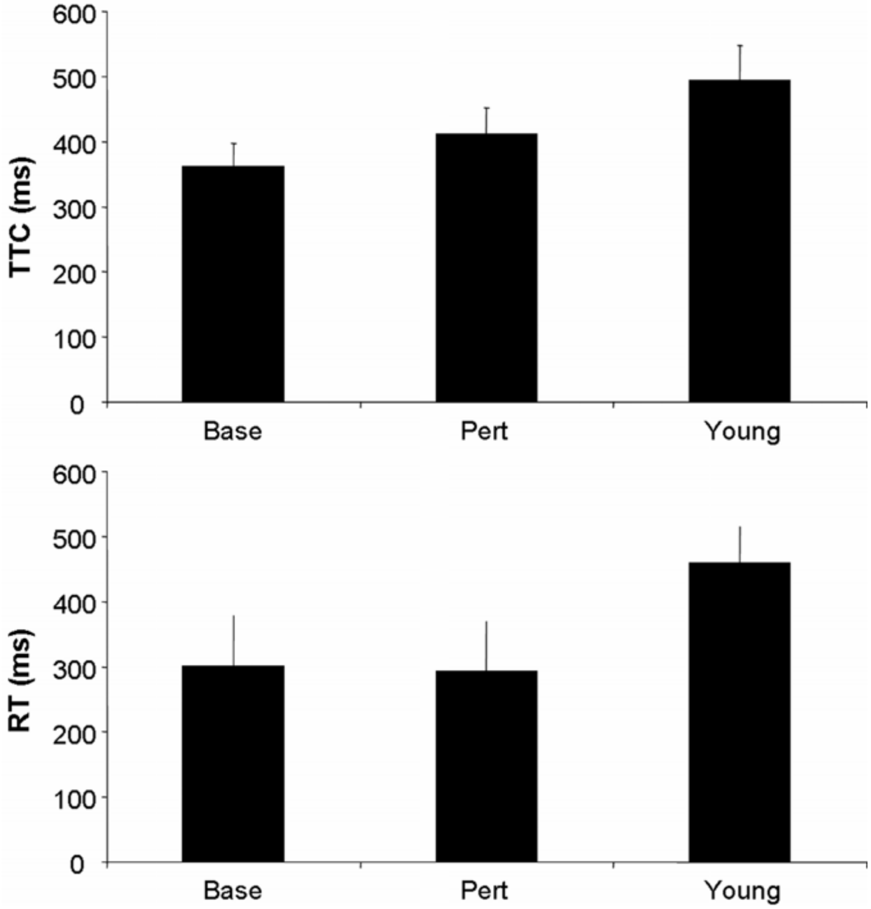

*Figure 5.3. Experiment 4: Temporal Measures. (**A**) TTC and (**B**) RT are shown for the adults in the baseline and perturbed conditions relative to the young children from Experiment 3.*

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[6] Figures depicting other dependent measures are in Appendix XIII.

Table 5.2: Experiment 4 statistical contrasts

	Contrasts		
Variable	Base vs. Young	Pert vs. Young	Base vs. Pert
RT	$t=5.29; p<0.001$	$t=5.61; p<0.001$	$F=1.26; p=0.29$
TTC	$t=6.27; p<0.001$	$t=3.77; p=0.001$	$F=16.69; p=0.003$
PV	$t=1.93; p=0.07$	$t=2.72; p=0.014$	$F=2.02$ $p=0.19$
DE	$t=1.58; p=0.13$	$t=2.08; p=0.052$	$F=1.12; p=0.32$
Var DE	$t=6.14; p<0.001$	$t=5.73; p<0.001$	$F=0.03; p=0.87$
DE_{DS}	$t=4.24; p<0.001$	$t=4.06; p<0.001$	$F=0.05; p=0.83$
Var DE_{DS}	$t=7.70; p<0.001$	$t=7.64; p<0.001$	$F=0.04; p=0.85$

Discussion

The current experiment attempted to probe the relationship between dynamic state estimation and sensorimotor performance in adults by exposing participants to a perturbation that simulated the delayed and unreliable dynamic state estimates evident in young children. The primary results of this experiment were: 1) consistent with Experiment 3, the decreased sensorimotor performance in the young children can be attributed, at least partially, to deficits in dynamic state estimation (see Column 2, labeled as ‘Base vs. Young in Table 5.2); 2) exposing adults to a visual feedback perturbation, the parameters of which attempted to simulate dynamic state estimation in the young children, did not result in the adults performing similarly to the young children (see Column 3, labeled as ‘Pert vs. Young in Table 5.2); and, 3) the perturbation had little to no influence on the adults’ performance (see Column 4, labeled as ‘Base vs. Pert in Table 5.2). The remainder of this discussion will offer potential explanations as to why the perturbation had little influence and provide suggestions for future research.

Stability of Dynamic State Estimation

The visual feedback perturbation employed in the current study had no influence on dynamic state estimation or sensorimotor performance, a result that speaks to the stability of dynamic state estimation in adults. Adults have extensive experience over their lifetimes executing goal-directed arm movements. These experiences allow for the fine-tuning of sensorimotor functioning and facilitate the development of a forward model that can be used to accurately and reliably predict the consequences of descending motor commands. The visual feedback perturbation employed in this research was not sufficient to degrade the CNS' ability to estimate hand state during the execution of ballistic arm movements. This interpretation is supported, at least anecdotally, by the participants' responses in a debriefing session following completion of the experimental protocol. Participants consistently claimed the perturbed condition appeared to be 'slower' and resulted in increased movement errors, functions of the temporal delay and rotated visual feedback, respectively. The participants noted that the errors were not systematic (i.e., consistent across a series of trials) and considered the visual feedback to not be an accurate reflection of their own performance. When probed about their strategy for minimizing the errors while staying within the speed constraints imposed by the experimental protocol, the majority of participants claimed they did nothing different because they attributed the errors to the computer as opposed to their own performance. This suggests that the participants ignored the visual feedback perturbation, instead relying on proprioceptive feedback and/or state predictions generated by a developed forward model.

We hypothesized that dynamic state estimation in 11-12 year-old children, although similar to the adults as demonstrated in Experiment 3, may not be as stable and may be disrupted by the perturbation employed in the current study. A group of three right-handed, 11-12 year-old children (mean age = 11.8 years) completed the experimental protocol described above. Interestingly, the perturbation had no influence on performance in this small sample

Previous research has used a minimum of 1000 trials for participants to learn distributions of either imposed forces or the uncertainty of visual feedback (Kording et al., 2004a; Kording et al., 2004b). It could be argued that the perturbed condition in the current study (110 trials) was not long enough to trigger changes in dynamic state estimation. Pilot data from an experimental protocol similar to the one employed in this study suggested that the number of exposure trials had no influence on the results. Following a baseline phase, the pilot participant completed 660 trials, spread across three experimental sessions and two days of testing, with unpredictable, trial-to-trial rotations of visual feedback (no temporal delay). Results demonstrated no substantial changes in sensorimotor performance as a function of perturbation exposure.

Role of Proprioception

Previous research (Jones, Wessberg, & Vallbo, 2001) demonstrated that proprioceptive estimates of hand position were down-weighted during a visuomotor adaptation task. The authors suggested that this strategy was adopted by the CNS in order to resolve the visuo-proprioceptive conflict inherent in the adaptation paradigm. This strategy is intuitive given that the goal of the adaptation task was to move a *visual* cursor, representing the position of the end effector, to a *visual* representation of a target. In other words, the goal of the task was specified in visual coordinates; employing a strategy that down-weights the proprioceptive estimate of hand location will result in the highest likelihood of success. This finding served as the basis for the visual feedback perturbation employed in the current study, which also created a mismatch between visual and proprioceptive estimates of hand position. Since the goal of the task was to move the cursor specifying the manipulandum's position to the desired (visual) target circle, it was hypothesized that participants would down-weight proprioception and rely on visual feedback in order to perform the task. Conversely, results suggested that participants predominantly ignored the perturbed visual feedback provided on the monitor, a finding that differs from the results presented in Jones et al. (2001).

One potential explanation for the participants' downweighting or ignoring the visual feedback in the current study is that the perturbation created unpredictable movement errors. On any given trial, the visual feedback was rotated clockwise, counterclockwise, or not at all. This lack of systematic errors simply made the visual estimate of hand state noisy or unreliable. The participants appeared to up-weight the proprioceptive estimate of hand state as it was considered to be more reliable for this specific task, a result that has been demonstrated in the extant literature (Bove, 1990; Ernst et al., 2002; Searle et al., 1976; van Beers et al., 1999). Conversely, in a visuomotor adaptation task (e.g., Jones et al., 2001), the visual feedback rotation creates systematic, as opposed to unpredictable, movement errors. This visuo-proprioceptive conflict is solved by down-weighting proprioception.

Future Directions

The visual feedback perturbation employed in the current study had no influence on sensorimotor performance in adults or a small sample of 11-12 year-old children. Presumably, the participants estimated hand state based on available proprioceptive feedback and/or state predictions generated by a forward model. In order to experimentally manipulate dynamic state estimation in the future, the perturbation should simultaneously impair visual and proprioceptive estimates of hand state. Two techniques have previously been used to disrupt proprioception: tendon vibration (Hay et al., 2005; Pipereit, Bock, & Vercher, 2006) and repetitive transcranial magnetic stimulation (rTMS) applied over the somatosensory cortex (Balslev et al., 2004). Both of these techniques, however, introduce additional methodological issues. Most importantly, it is not clear how the parameters (i.e., frequency) of the vibration or rTMS would be selected. A strength of the perturbation employed in the current study was that the parameters were yoked to the performance of the young children. This approach sought to make state estimation as equally inaccurate and unreliable in the adults as in the young children. It is not clear how the vibration or rTMS techniques can be appropriately parameterized to simulate dynamic state estimation in the young children.

Conclusions

The current study sought to probe the relationship between dynamic state estimation and sensorimotor performance in adults by exposing participants to a perturbation that simulated the delayed and unreliable dynamic state estimates evident in young children. However, results indicated that the perturbation had no substantial effects on the performance of the adults. This suggests that the participants predominantly ignored the visual feedback perturbation and instead estimated hand state based on available proprioceptive feedback and/or predictions of hand state generated by a developed and stable forward model. Future research aimed at systematically manipulating dynamic state estimation should simultaneously perturb visual and proprioceptive estimates of hand state.

CHAPTER VI: GENERAL DISCUSSION

Although previous research examining goal-directed reaching movements in school-age children had demonstrated age-related improvements in movement accuracy, speed and variability, a comprehensive, mechanistic explanation of these improvements has not been established. This dissertation hypothesized that improvements in performance can be attributed, in part, to developmental changes in state estimation. To this end, this dissertation characterized a developmental trajectory of state estimation across 5- to 12-year-old children, and demonstrated that state estimation is a rate-limiter for the development of sensorimotor control of arm movements. A summary of this developmental trajectory is depicted in Figure 6.1. Improvements in proprioceptive functioning, around 7 years of age on average, resulted in changes in multisensory-motor integration. Specifically, as proprioceptive functioning improved, it contributed more to the multisensory estimate of hand position when both vision and proprioception were available (Experiment 1). These improvements in proprioceptive functioning resulted in more precise estimates of static hand position *prior* to the execution of a goal-directed reach, effectively decreasing the directional variability of reaching movements (Experiment 2). The age-related improvements in static state estimation, investigated in the first two specific aims, also contributed to the accuracy and reliability of estimating hand state *during* movement execution as dynamic estimation is dependent on both sensory feedback and the output of a forward model that predicts future hand states based on copies of descending motor commands. Results from Experiment 3 demonstrated that dynamic state estimation also improved as a function of age; and, these improvements in dynamic state estimation, in turn, contributed to age-related improvements in functional sensorimotor behavior.

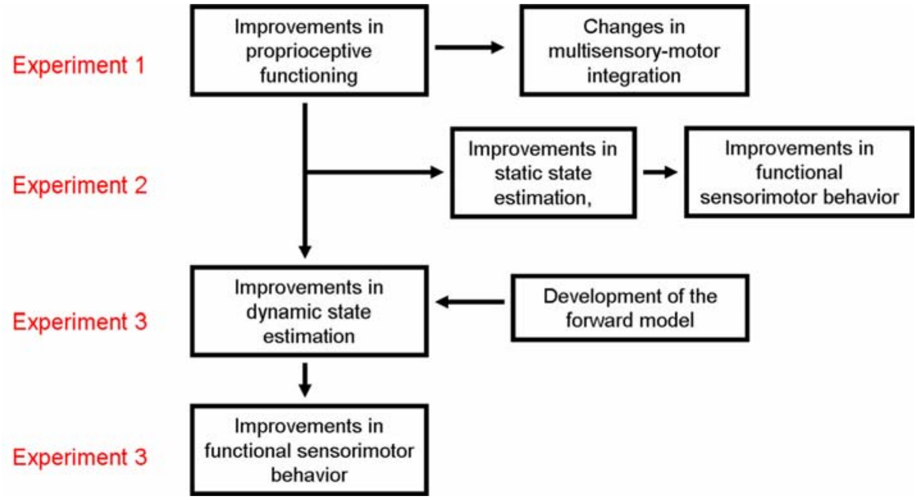


Figure 6.1: Developmental Trajectory of State Estimation and its effects on sensorimotor performance.

It should be emphasized that the improvements in state estimation and sensorimotor performance demonstrated in the current research are age-related, *not* age-determined. We simply used age as a proxy to represent the developmental process. Despite the significant findings, our results revealed substantial inter-individual variability not accounted for by age (i.e., some 7-8 year-old children performed better than 9-10 year-olds). The improvements reported in this research are likely to be a function of the task-specific experiences specific to each individual and are not the result of maturational processes that simply unfold as a function of age. Future research should examine what specific experiences are considered sufficient to drive age-related changes in state estimation and sensorimotor behavior.

Although several explanations of the age-related improvements in performance have been posited in previous research, two of the most pervasive in the developmental literature are: 1) improvements in sensorimotor performance are the result of changes in the underlying control (i.e., feedforward vs. feedback) mechanisms employed by children; and, 2) improvements in sensorimotor performance are the result of the fine-tuning of acquired internal representations that specify the relationships between (sensory) input and (motor) output. We propose that our interpretation of the results in this research, namely that state estimation underlies the development of sensorimotor control, expands on this previous research and provides a comprehensive and unifying explanation of the age-related improvements reported in the extant literature.

Research by Hay and colleagues suggested that the improvements in sensorimotor behavior across school-age children can be explained by shifts in the relative contributions of feedforward and feedback control (Bard et al., 1990; Hay, 1979; Hay et al., 1991; Hay, 1978). Specifically, the execution of reaching movements by 7- 8 year-old children was considered to be feedback-dependent. Conversely, the performance of younger children (i.e., 5-6 year-olds) was thought to be feedforward-dependent and the performance of older children (i.e., approximately 10-12 years) was thought to be a combination of the two strategies. These findings were based predominantly on experiments that removed *visual* feedback of hand position during the execution of goal-directed reaches. End-point accuracy was substantially reduced in the 7-8 year-old children, suggesting that these children rely on the visual feedback of hand position to perform reaching movements (Bard et al., 1990; Hay, 1978). Moreover, 7-8 year-old children had the longest movement times and the smallest peak velocities and accelerations compared to both the younger and older children, providing further evidence for an increased reliance on sensory feedback (Bard et al., 1990; Hay et al., 1991). We suggest that the results of this research provide a more comprehensive and mechanistic explanation for the findings by Hay and colleagues. For example, the 7-8 year-old children are considered feedback-dependent because they incorporate the more reliable and accurate proprioceptive feedback, as compared to the 5-6 year-olds, into the planning and execution of goal-directed arm movements. Conversely, the 10- to 12-year-old children are thought to utilize both feedforward and feedback control strategies because they can accurately and reliably predict future states of the system, rather than relying on delayed sensory feedback. In summary, developmental changes in state estimation provide an explanation for the non-monotonic shifts in the relative contributions of feedforward and feedback control reported in previous research (Bard et al., 1990; Hay, 1979; Hay et al., 1991; Hay, 1978).

It has also been posited that the progressive fine-tuning of acquired inverse internal representations (e.g., the controller) across childhood contributes to the age-related improvements in sensorimotor performance (Bo et al., 2006; Contreras-Vidal et al., 2005; Jansen-Osmann et al., 2002; King et al., 2009). These inverse internal representations approximate the motor commands necessary to achieve a task given the current state of the system and the desired future states (Shadmehr et al., 2005; Wolpert et al., 1998). This explanation is consistent with the findings in the current research. A comparison of sensory feedback and predicted sensory consequences, a function of the forward model, is thought to serve as an error signal that drives motor learning (Davidson et al., 2005). Sensory prediction errors have been shown to be critical for updating inverse internal representations in order to adapt to externally-imposed manipulations (Tseng et al., 2007). Thus, the development of the predictive forward model, examined in

Specific Aim 3, may actually drive the age-related improvements in the fine-tuning of the inverse internal representations reported in previous research.

This dissertation also highlights several questions to be addressed in future research. First, the relationship between age-related improvements in state estimation and the development of the underlying neural substrates and networks should be investigated. Optimal dynamic state estimation is thought to be the result of combining state predictions with delayed sensory feedback (Gritsenko et al., 2009; Izawa et al., 2008; Wolpert et al., 1995), a process that is dependent on the posterior parietal cortex (PPC) and cerebellum (Bastian, 2006; Miall et al., 2008; Miall et al., 2007; Shadmehr et al., 2008). Previous research has demonstrated structural changes in both the parietal cortex and cerebellum across the age range examined in the current study (Giedd et al., 1999; Tiemeier et al., 2010). Future studies should attempt to reveal the relationship between these structural changes and age-related improvements in state estimation and sensorimotor performance.

Second, the current research examined the role of state estimation in the control of goal-directed arm movements and predominantly ignored the controller or inverse internal representation, which function to transform relevant sensory information (i.e., target and hand localization) into the appropriate motor commands. Recent research has indicated that well-learned, goal-directed arm movements in adults are best explained by an optimal feedback control policy (OFC) (Todorov et al., 2002; Todorov, 2004). By comparing the real-time current and desired states of the system and considering associated rewards and risks of the task, the controller is able to control movements as they are executed by operating under the principle of minimal intervention - movement errors are corrected only if they have a systematic effect on the performance or task variable. This approach is similar to that of the uncontrolled manifold (Latash et al., 2007; Scholz et al., 1999) which posits that the CNS partitions movement variability into task-relevant and task-irrelevant variability. It has been argued by Todorov (2002; 2004) that this minimal intervention principle is based on the fact that corrective movements come at a cost: 1) they generate additional noise in the system which can increase movement variability (Harris et al., 1998); and 2) there is increased energy expenditure associated with corrective movements that could potentially result in unwanted effects such as fatigue. Using minimal intervention and a forward model that is able to predict next states of the system, the OF controller can control movements in real time. Critically, OFC assumes that the forward model is able to accurately and reliably predict next states of the system in order to control movements as they are being executed, as assumption that is not valid in young children as demonstrated in Experiment 3. Future research should address how age-related improvements in state estimation influence the control policy employed in children.

Last, the research in the current study should be extended to children with movement difficulties such as Developmental Coordination Disorder (DCD). Previous research has indicated that these children have deficits in both proprioceptive functioning (Mon-Williams et al., 1999; Sigmundsson et al., 1997) and the execution of rapid on-line trajectory modifications (Hyde et al., 2011a; Hyde et al., 2011b). Both of these behavioral deficits potentially suggest impairments in the accuracy and reliability of state estimation. An increased understanding of these developmental motor impairments will lead to the design and implementation of interventions that will improve not only motor functioning, but will also have academic (e.g., Cantell et al., 1994), socio-emotional (e.g., Skinner et al., 2001), and physical health implications for children with DCD (e.g., Faught et al., 2005).

In summary, this dissertation characterized the development of state estimation in typically-developing children and demonstrated that age-related improvements in state estimation are at least partially responsible for improvements in sensorimotor control of the arm. This line of research is significant as it provides novel insights into mechanisms underlying sensorimotor development of children. Future research should probe the underlying neural correlates of state estimation, the influence of age-related improvements in state estimation on the control policy, and the role of state estimation in the impaired sensorimotor performance in children with movement difficulties, such as DCD.

APPENDICES

Appendix I: Experiment 1 Consent Form

Permission Form 14 for **child** participant (localization)

PERMISSION FORM

University of Maryland, Cognitive-Motor Behavior Laboratory

Identification of Project	Project Title: Development of visuomotor coordination and adaptation
Statement of Age of Participant	You are over 18 years of age and are the parent or legal guardian of the child who is between 4 and 16 years of age. Your child is invited to participate in a research project conducted by Dr. Jose L. Contreras-Vidal & Dr. Jane Clark at the Department of Kinesiology, University of Maryland, College Park.
Purpose	The purpose of the research is to investigate the way typically-developing children and children with developmental coordination disorder control arm movements under changing movement conditions. The experiment is designed in a way that makes it possible to determine the influence of different task conditions, such as movement direction and distance, on movements.
Procedures	The study will consist of either 1 or 2 sessions. During the first session your child will complete a standardized motor skill assessment (Movement Assessment Battery for Children – MABC). This assessment will take approximately 30 minutes to 1 hour to complete and will consist of 8 different tasks in the areas of manual dexterity, ball skills, and balance. For example, your child may be asked to use a pen to trace a shape, catch/throw a ball, or stand on one leg. During the assessment, your child may be video recorded for “coding” purposes. This assessment will determine your child’s eligibility for an additional testing session. For the second session, your child will sit comfortably in a chair with his/her hand resting on a table and perform point-to-point arm movement with the dominant hand using a special "computer pen". Movements between two points, in different direction, will be performed on the horizontal plane over the table. At some stage, your child will either 1) hear auditory stimuli, and will point in the direction where he/she thinks the sounds are coming from while he/she wears opaque goggles, or 2) move to the targets without visual feedback of the pen trace. A computer will store information about the position of their hand and arm during the movement task. This task will require approximately 45 minutes to complete. Again, your child will be video recorded for “coding” purposes. Upon completion of the first experimental session, your child will be able to choose a small toy prize. A report of your child’s performance on the motor

skill assessment will be provided to you upon request. Upon completion of the second session, your child will receive $12.00 dollars. If you want, your child may be re-assessed with the movement task approximately one week later. For each additional 30-minute session your child will receive $6.

Confidentiality

All information collected in the study is strictly confidential except as you specify on the signed permission form for video and image illustrations, and your child's name will not be identified at any time. The data your child provides will be grouped with data others provide for reporting and presentation. Data will be stored in a locked file cabinet in the Cognitive-Motor Behavior Laboratory. Only the principal investigator and his collaborators will have access to this locked file.

Your child’s information may be shared with representatives of the University of Maryland, College Park or governmental authorities if you or someone else is in danger or if we are required to do so by law.

Risk

As a result of your child's participation in this study, he/she may experience a modest degree of fatigue from the concentration required during the performance of the test but there are no other known risks and no known long-term effects associated with participation in this study.

Benefits, Freedom to Withdraw and to ask questions

Your child’s participation is completely voluntary. The experiment is not designed to help your child specifically, but it may have substantial impact on understanding how the brain controls visually-guided movement. You are free to ask questions or to withdraw permission for your child's participation at any time without penalty. You could have a signed copy of this permission form and the investigators will provide you with the results of this study upon request. The University of Maryland does not provide any medical or hospitalization insurance coverage for participants in the research study nor will the University of Maryland provide any compensation for any injury sustained as a result of participation in this study except as required by law.

Principal Investigator

Dr. Jose L. Contreras-Vidal (PI),
Dr. Jane Clark (Collaborator),
Department of Kinesiology, 2363 SPH Bldg
University of Maryland, College Park, MD 20742
(301)405-2495

Informed Consent Requirements

"You are voluntarily making a decision whether or not to permit the participation of your child in the research study described above. Your signature indicates that you have read the information provided above, have had all of your questions answered, and have permitted your child to participate in this study. Further, your child has agreed to participate in this study. You will be given a copy of this consent form to keep."

Name of Participant: ____

Participant's Birth date: ____

Signature of Participant's Parent/Guardian (if minor): _____________________

Today's Date: ____

If you have questions about your child's rights as a research subject or wish to report a research-related injury, please contact: Institutional Review Board Office, University of Maryland, College Park, Maryland, 20742; (email) irb@deans.umd.edu; (telephone) 301-405-0678

Appendix II: Experiments 2-4 Consent Forms

Permission Form 1 – for **child** participant (IM2)

PERMISSION FORM

University of Maryland, Cognitive-Motor Behavior Laboratory

Identification of Project	Project Title: Development of Visuomotor Coordination and Adaptation Using a Robotic Manipulandum
Statement of Age of Participant	You are over 18 years of age and are the parent or legal guardian of this child who is between 4 and 17 years of age. Your child is invited to participate in a research project conducted by Dr. Jose L. Contreras-Vidal & Dr. Jane Clark at the Department of Kinesiology, University of Maryland, College Park.
Purpose	The purpose of this research is to investigate the way children who are normally developing and those with developmental coordination disorder control arm movements under changing movement conditions. The experiment is designed in a way that makes it possible to determine the influence of different task conditions, such as movement direction, distance, and velocity, on movements.
Procedures	Prior to coming to the lab, you will complete a phone interview to discuss your child's neurological health and to provide you with the details of the study. The purpose of this questionnaire is to ensure typical neurological development of your child. The study will consist of either 1 or 2 tasks. For the first task your child will complete a standardized motor skill assessment (Movement Assessment Battery for Children – MABC). This assessment will take approximately 30 minutes to 1 hour to complete and will consist of 8 different tasks in the areas of manual dexterity, ball skills, and balance. For example, your child may be asked to use a pen to trace a shape, catch/throw a ball, or stand on one leg. During the assessment, your child will be video recorded for "coding" purposes. This assessment will determine your child's eligibility for a second testing session. Upon completion of the first experimental session, your child will be able to choose a small toy prize. A report of your child's performance on the motor skill assessment will be provided to you upon request.
	For the second task, your child will be asked to complete between one to three experimental sessions. During each session, your child will sit comfortably in a chair with his/her hand resting a table. Your child will be secured to a chair using a shoulder-strap and seatbelt which are adjusted for his/her comfort. He/she will perform arm movements with the dominant hand while holding a robotic manipulandum. A computer will store information about the position of their hand and arm during the movement task and again your child may be video recorded for "coding" purposes. Non-invasive markers will be placed on the arms and the torso of your child. These markers will allow cameras to record your child's movements. The first session will require approximately 60

minutes to complete. Each subsequent session will require approximately 30 minutes.

Confidentiality All information collected in the study is strictly confidential except as you specify on the signed permission form for video and image illustrations and your child's name will not be identified at any time. The data your child provides will be grouped with data others provide for reporting and presentation. Data will be stored in a locked file cabinet and/or on a password protected computer in a secured university laboratory facility. Only the principal investigator and his collaborators will have access to this locked file.

Your child's information may be shared with representatives of the University of Maryland, College Park or governmental authorities if you or someone else is in danger or if we are required to do so by law.

Risk As a result of your child's participation in this study, he/she may experience a modest degree of fatigue from the concentration required during the performance of the test but there are no other known risks and no long-term effects associated with participation in this study.

Benefits, Freedom to Withdraw and to ask questions Your child's participation is completely voluntary. The experiment is not designed to help your child specifically, but it may have substantial impact on understanding how the brain controls visually-guided movement. You are free to ask questions or to withdraw permission for your child's participation at any time without penalty. You could have a signed copy of this permission form and the investigators will provide you with the results of this study. The University of Maryland does not provide any medical or hospitalization insurance coverage for participants in the research study nor will the University of Maryland provide any compensation for any injury sustained as a result of participation in this study except as required by law.

Principal Investigator
Dr. Jose L. Contreras-Vidal (PI),
Dr. Jane Clark (Collaborator),
Department of Kinesiology, 2363 HHP Bldg
University of Maryland, College Park, MD 20742
(301)405-2495

Informed Consent Requirements "You are voluntarily making a decision whether or not to permit the participation of your child in the research study described above. Your signature indicates that you have read the information provided above, have had all of your questions answered, and have permitted your child to participate in this study. You further understand that your child has agreed to participate in this study. You will be given a copy of this consent form to keep."

Name of Participant:____

Participant's Birth date: ____

Signature of Participant's Parent/Guardian (if minor): ________________________

Today's Date: ____

If you have questions about your rights as a research subject or wish to report a research-related injury, please contact: Institutional Review Board Office, University of Maryland, College Park, Maryland, 20742; (email) irb@deans.umd.edu; (telephone) 301-405-0678

Consent Form 2 - for **adult** participant (IM2)

CONSENT FORM

University of Maryland, Cognitive-Motor Behavior Laboratory

Identification of Project	Project Title: Development of Visuomotor Coordination and Adaptation Using a Robotic Manipulandum
Statement of Age of Participant	You are an adult over 18 years of age and willing to participate in a research project being conducted by Dr. Jose L. Contreras-Vidal & Dr. Jane Clark at the Department of Kinesiology, University of Maryland, College Park.
Purpose	The purpose of current research is to investigate how a person controls arm movements under changing movement conditions. The experiment is designed in a way that makes it possible to determine the influence of different task conditions, such as movement direction, distance, and velocity, on movements.
Procedures	You will be asked to complete between one to three experimental sessions. At the initial session, you will complete a neurological health questionnaire and a handedness inventory. The purpose of these questionnaires is to ensure typical neurological development and to assess hand dominance. During each session, you will sit comfortably in a chair with your hand resting on a table. You will be secured to a chair using a shoulder-strap and seatbelt which are adjusted for your comfort. You will perform arm movement with the dominant hand while holding a robotic manipulandum. A computer will store information about the position of your hand and arm during the movement task. Non-invasive markers will be placed on your arms and your torso. These markers will allow cameras to record your movements. The first session will require approximately 60 minutes to complete. Each subsequent session will require approximately 30 minutes. During the experiment, you will be video recorded for “coding” purposes.
Confidentiality	All information collected in the study is strictly confidential except as you specify on the signed consent form for video and image illustrations and your name will not be identified at any time. The data you provide will be grouped with data others provide for reporting and presentation. Data will be stored in a locked file cabinet in the Cognitive-Motor Behavior Laboratory. Only the principal-investigator and his collaborators will have access to this locked file. Your information may be shared with representatives of the University of Maryland, College Park or governmental authorities if you or someone else is in danger or if we are required to do so by law.
Risk	As a result of your participation in this study, you may experience a modest degree of fatigue from the concentration required during the performance of the test but there are no other known risks and no long-term effects associated with participation in this study.
Benefits,	Your participation is completely voluntary. The experiment is not designed to

Freedom to Withdraw and to ask questions	help you specifically, but it may have substantial impact on understanding how the brain controls visually-guided movement. You are free to ask questions or to withdraw permission for your participation at any time without penalty. You could have a signed copy of this permission form and the investigators will provide you with the results of this study. The University of Maryland does not provide any medical or hospitalization insurance coverage for participants in the research study nor will the University of Maryland provide any compensation for any injury sustained as a result of participation in this study except as required by law.
Principal Investigator	Dr. Jose L. Contreras-Vidal (PI), Dr Jane Clark (Collaborator), Department of Kinesiology, 2363 HHP Bldg University of Maryland, College Park, MD 20742 (301)405-2495
Informed Consent Requirements	"You are voluntarily making a decision whether or not to participate in the research study described above. Your signature indicates that you have read the information provided above, have had all of your questions answered, and have decide to participate in this study. You will be given a copy of this consent form to keep"

Name of Participant (please print): ____

Participant's Signature: ____

Participant's Birth date: ____

Today's Date: ____

If you have questions about your rights as a research subject or wish to report a research-related injury, please contact: Institutional Review Board Office, University of Maryland, College Park, Maryland, 20742;
(email) irb@deans.umd.edu; (telephone) 301-405-0678

Appendix III: Neurological Health Questionnaires

Adult Neurological Health Questionnaire

Participant ID ____
Sex___________ Age___________ Date of Birth___________
Preferred Hand _____________________________

Have you ever…(Please circle yes or no)

1) been seen by a neurologist or neurosurgeon? Yes No
if yes, please explain___________________________________

2) had a head injury involving unconsciousness? Yes No
if yes, how long?______________________________________

3) required overnight hospitalization for a head injury? Yes No
if yes, please explain?______________________________________

4) had any illness that caused a permanent decrease in memory or cognition? Yes No
if yes, please explain___________________________________

5) had a seizure? Yes No
if yes, please explain___________________________________

6) had any illness that caused a permanent decrease in motor ability (including speech)? Yes No
if yes, please explain___________________________________

7) had difficulty using your hands? Yes No
if yes, please explain___________________________________

8) been diagnosed with a learning disability (dyslexia, ADHD)? Yes No
if yes, please explain___________________________________

if yes, are you currently taking any medications for these disabilities? Yes No
if yes, please list the medications, dosage, and duration of treatment below:
Medication: ______________________________
Dosage: _________________________________
Duration of Treatment: _____________________

Pediatric Neurological Health Questionnaire

Participant ID ____
Gender__________ Age_____________ Date of Birth______________
Preferred Hand ___________________

Past Medical History

Please list any prior major illnesses and/or injuries:

Birth History:
1) Any problems with the pregnancy? Yes No
if yes, what?____
2) Was your child born full term? Yes No
if no, how early?_____________________________________
3) Medical problems at birth? Yes No
if yes, what?____

Hospitalization/Surgery/Injury:
4) Except at birth, has your child been hospitalized? Yes No
if yes, list age(s) and reason_____________________________
5) Has your child ever had surgery? Yes No
if yes, list age(s), and reason____________________________
6) Has your child ever had a head injury involving unconsciousness? Yes No
if yes, how long?_____________________________________
7) Has your child had any illness that caused a permanent decrease in memory or cognition? Yes No
if yes, please explain___________________________________
8) Had your child any illness that caused a permanent decrease in motor ability (including speech)? Yes No
if yes, please explain___________________________________

Review of Neurological Systems

Please circle yes or no to the following. Has your child experienced or been diagnosed for the following:
9) Any neurological problems (seizure disorder, tics)? Yes No
if yes, please explain ____
10) Developmental delay? Yes No
if yes, please explain ____
11) Speech delay? Yes No
if yes, please explain ____
12) Learning disabilities (dyslexia, ADHD)? Yes No
if yes, please explain ____
13) Movement difficulties? Yes No
if yes, please explain ____

14) If you responded “Yes” to questions 9 -12 above, is your child currently taking any medications for these disabilities? Yes No

if yes, please list the medications, dosage, and duration of treatment below:
Medication: ______________________________
Dosage: _________________________________
Duration of Treatment: _____________________

Appendix IV: Edinburgh Handedness Inventory

Subject ID: ______________

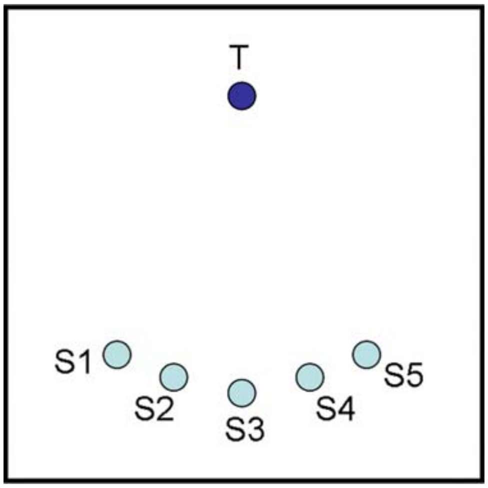
Edinburgh Handedness Inventory (for Adults)

Please indicate your preferences in the use of hands in the following activities *by putting + in the appropriate column.* Where the preference is so strong that you would never try to use the other hand unless absolutely forced to, *put* ++. If in any case you are really indifferent *put + in both columns.*

Some of the activities require both hands. In these cases the part of the task, or object, for which hand preference is wanted is indicated in brackets. Please try to answer all of the questions, and only leave a blank if you have no experience at all of the object or task.

		Left	**Right**
1	Writing		
2	Drawing		
3	Throwing		
4	Scissors		
5	Toothbrush		
6	Knife (without fork)		
7	Spoon		
8	Broom (upper hand)		
9	Striking match (match)		
10	Opening box (lid)		
i.	Which foot do you prefer to kick with?		
ii.	Which eye do you use when using only one?		

Appendix V: Experiment 2 task stimuli.



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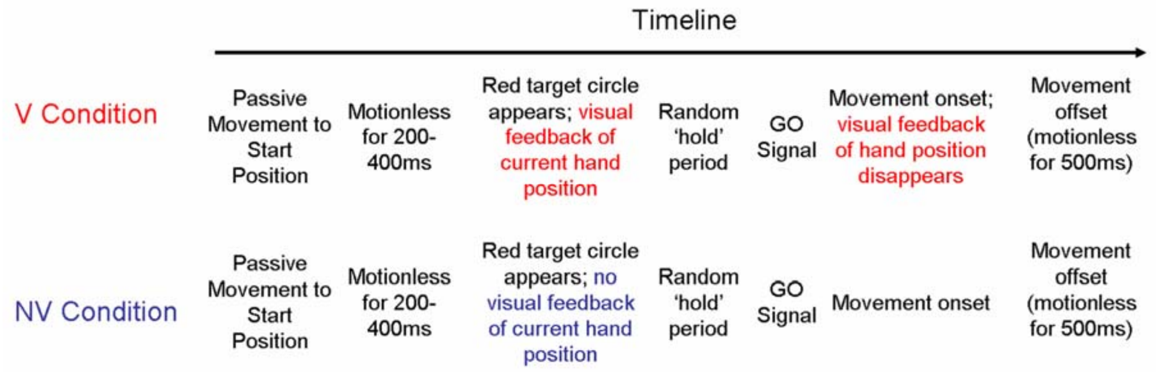
Appendix 5 Figure. Experiment 2 Task stimuli. Participants moved from one of five potential start position (S1–S5) to a single target (T). The experimenter passively moved the robotic manipulandum to the appropriate starting position. Note that the start positions were not provided on the computer monitor viewed by the participants.

Appendix VI: Timeline of Trial in Experiment 2

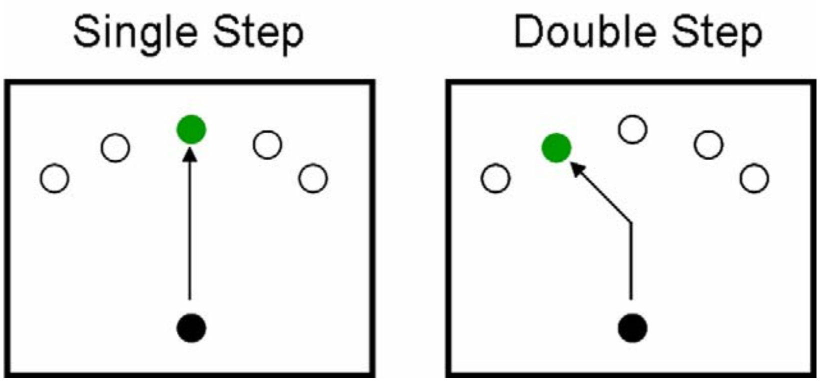


Timeline

V Condition	Passive Movement to Start Position	Motionless for 200-400ms	Red target circle appears; visual feedback of current hand position	Random ‘hold’ period	GO Signal	Movement onset; visual feedback of hand position disappears	Movement offset (motionless for 500ms)
NV Condition	Passive Movement to Start Position	Motionless for 200-400ms	Red target circle appears; no visual feedback of current hand position	Random ‘hold’ period	GO Signal	Movement onset	Movement offset (motionless for 500ms)

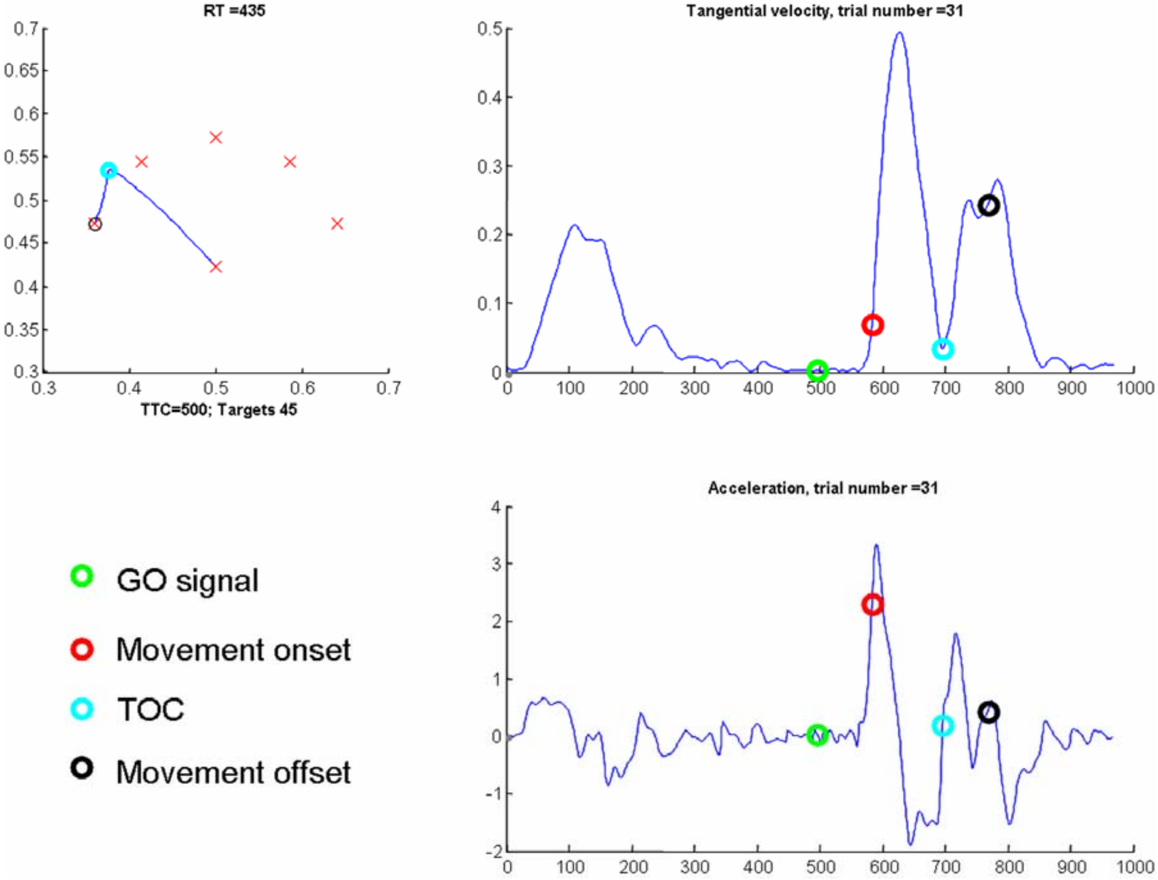
Appendix 6 Figure. Trial timeline in Experiment 2. Items specific to the V and the NV conditions are shown in red and blue, respectively. Items in black font are consistent across the two conditions. The critical difference between the two conditions is the presence or absence of visual feedback of hand position prior to movement onset.

Appendix VII: Experiment 3 task stimuli.



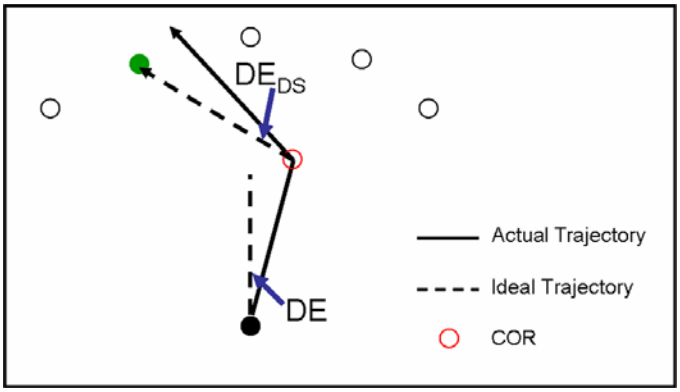
Appendix 7 Figure. Experiment 3 task stimuli. Participants moved from a start circle (black) to one of five targets (Single-Step). On certain trials, the target location 'jumped' to an adjacent target location at movement onset (Double Step). In the figure below, the middle target was initially displayed; the desired target then jumped to the left at movement onset. Participants needed to modify their movement trajectory to reach the displaced target. Note that the black arrows are shown to highlight the two tasks. On-line visual feedback of hand position was not provided during the experimental protocol.

Appendix VIII: Determining Time of Correction (TOC)



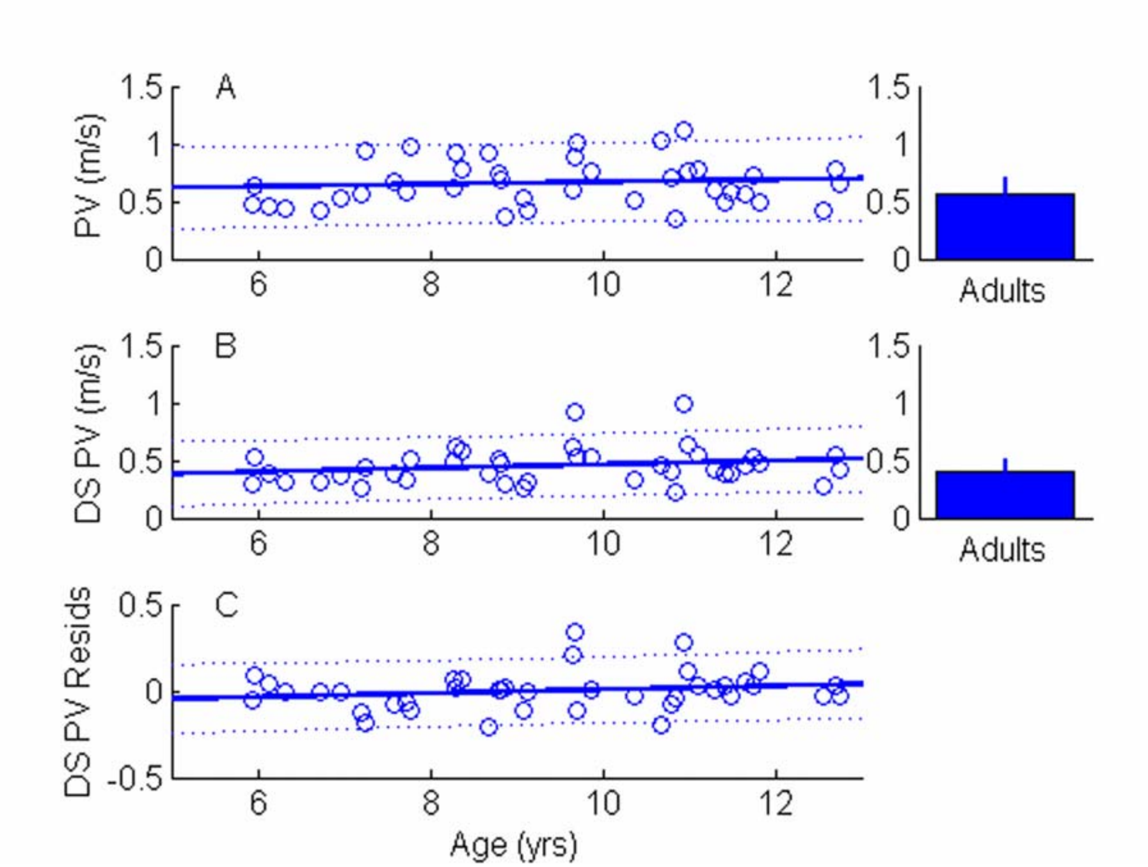
Appendix 8 Figure. Computing time of correction (TOC). Top left panel depicts the movement trajectory (x/y coordinates) relative to the start position and the five potential target locations. In this particular trial, the target was initially at position 4 (2nd from left) and jump to position 3 (middle) at movement onset. The top right and bottom right panels depict the corresponding velocity and acceleration profiles. Time of correction (TOC), defined as the time the participant initiated a corrective movement to the displaced target position, is shown as cyan circles in the three panels below. ***TOC was computed as the local minima in the velocity profile after peak velocity after the movement to the initial target.*** *Each trial was visually inspected and manually remarked if necessary (< less than 5% of all double-step trials).*

Appendix IX: Experiment 3 dependent measures



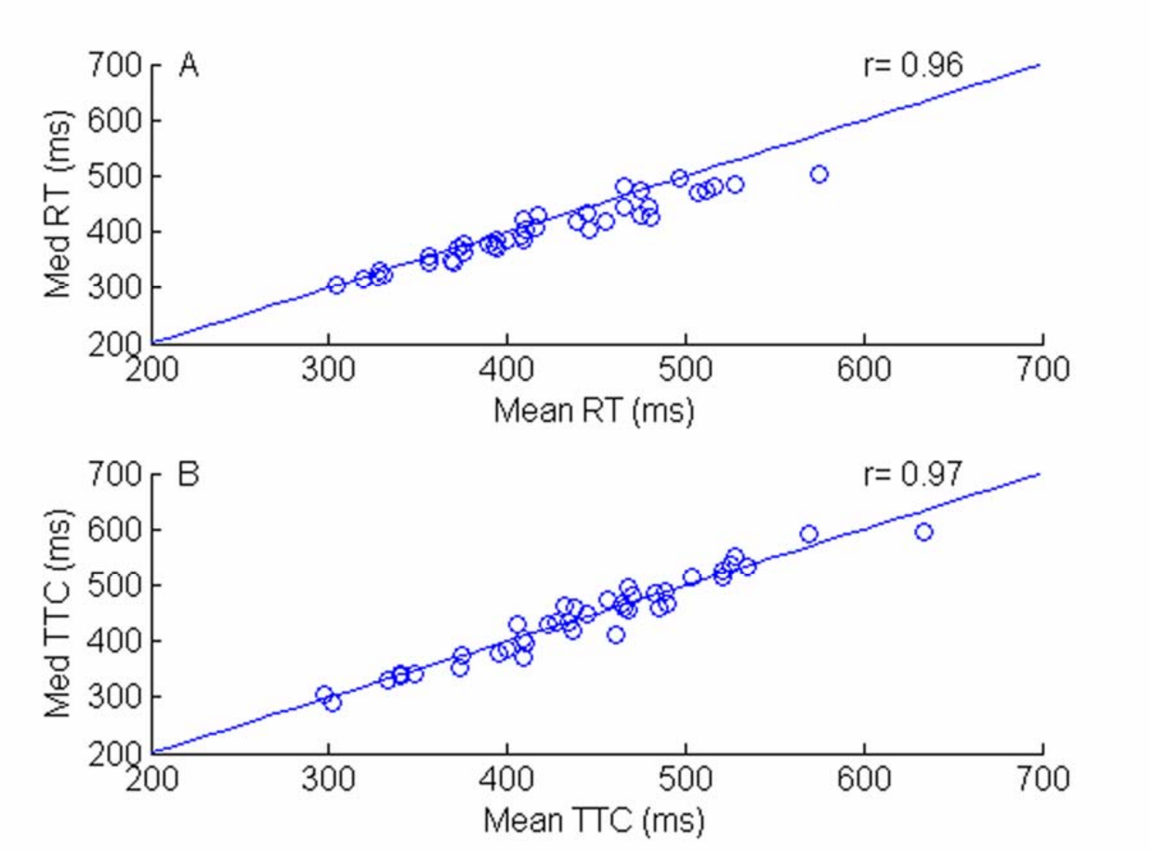
Appendix 9 Figure. Experiment 3 dependent measures. Figure depicts variables for double-step trials that were initially directed towards the center target position; target was then displaced to the left. DE is the directional deviation between the ideal and actual trajectories (dotted and solid lines, respectively) computed at peak velocity of the initial movement. COR represents the time, and the corresponding spatial coordinates, at which the participant initiated a corrective movement towards the displaced target. DE_{DS} *was the directional deviation between the participant's corrective movement and an ideal vector that connects manipulandum position at COR to the target.*

Appendix X: Experiment 3 peak velocity

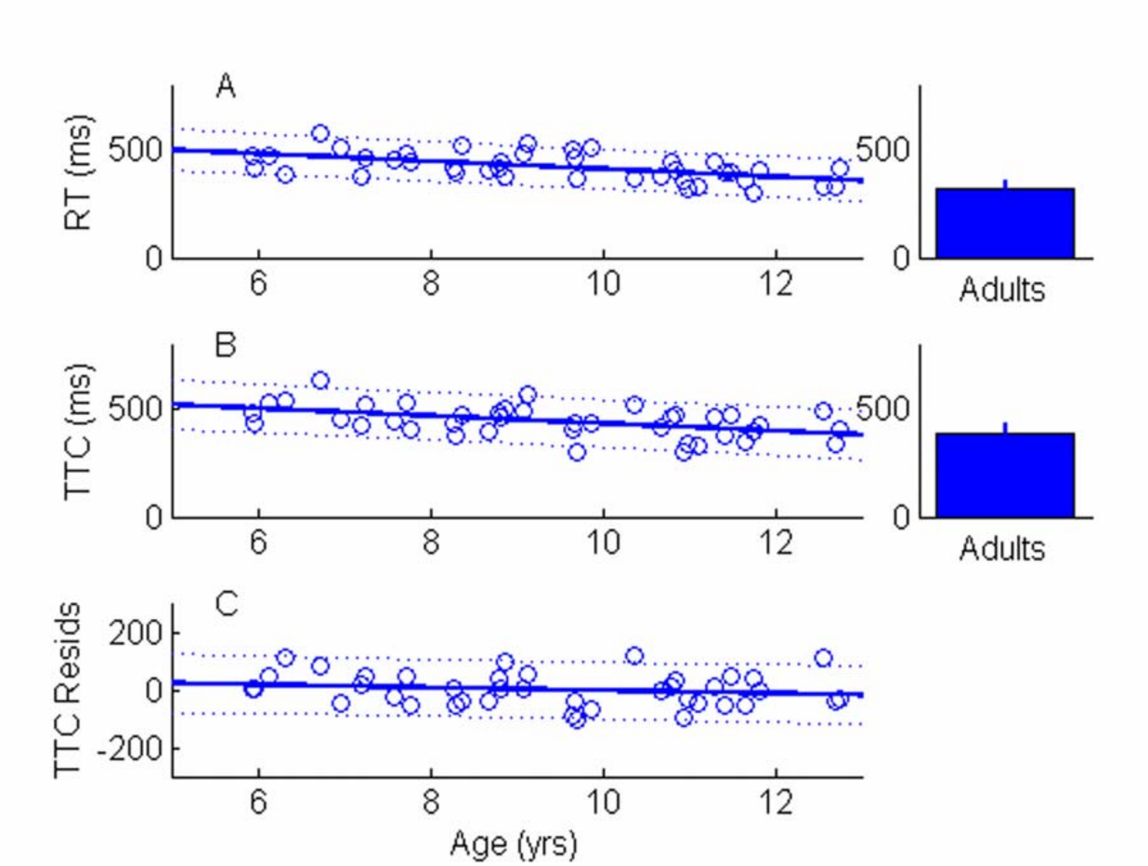


*Appendix 10 Figure. Experiment 3 peak velocity. Mean PV (**A**)), DS PV (**B**) and DS PV Resids (**C**; residuals based on linear regression with PV as a predictor) are depicted as a function of age. Dotted lines represent 95% prediction intervals. Mean values for the adults are shown in the bar graphs to the right. Results indicate that there are no age-related differences in peak velocity (all* $p > 0.05$*).*

Appendix XI: Relationship between mean and medians values for RT and TTC



*Appendix 11 Figure 1. Correlations between mean and median temporal measures. Relationships between mean and median RT (**A**) and TTC (**B**) values. Correlations are positive and high, demonstrating minimal differences between the two descriptive statistics.*



*Appendix 11 Figure 2. Experiment 3 Mean RT and TTC. Mean RT (**A**)), TTC (**B**) and TTC Resids (**C**; residuals based on linear regression with RT as a predictor) are depicted as a function of age. Dotted lines represent 95% prediction intervals. Mean values for the adults are shown in the bar graphs to the right. Results are consistent with the median values presented in the main text. Specifically, the slopes of the age-based regressions for RT ($\beta_1 = -15.79$; $p<0.001$) and TTC ($\beta_1 = -17.20$; $p < 0.01$) were both significant. The slope of TTC Resids was not significant ($\beta_1 = -8.56$; $p = 0.09$).*

Appendix XII: Experiment 4 Perturbation Parameters

Spatial Perturbation:

Results from Experiment 3 revealed that the standard deviation of the directional errors in the 5- to 7-year-old children had a mean value of 9.75 degrees. To simulate this increased variability in the perturbed condition of Experiment 4, we unpredictably rotated the visual feedback provided on the computer on a trial-to-trial basis. Visual feedback was rotated clockwise (positive value) and counterclockwise (negative value); the mean and standard deviation of the rotation were 0 and 9.75 degrees, respectively.

Temporal Perturbation:

Based on the data from Experiment 3, it was concluded that dynamic state estimation in young children was delayed (i.e., the estimates used to make on-line trajectory modifications were from some time instant in the past). This finding was based on the pattern of directional errors when moving to the displaced target positions. We estimated that the mean delay, average across 5- to 7-year-old children, was approximately 50ms. This estimate was based on the computation described below.

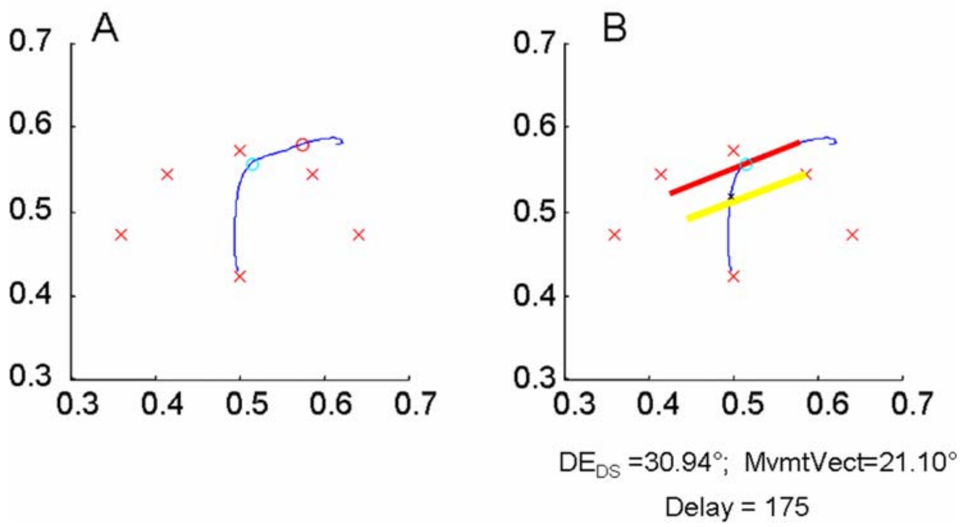
Panel A in Figure 1 below depicts an exemplar movement trajectory of a double-step trial. Red x's represent target locations; cyan and red circles depict hand positions at time of correction (TOC) and peak velocity of the secondary movement (PV2), respectively.

1. The angle of the vector connecting the spatial coordinates at TOC and PV2, herein referred to as the movement vector, was computed. The movement vector is shown as the thick red line in Panel B and the corresponding angle was 21.10° above the horizontal. Since the ideal vector between the spatial coordinates at TOC and the desired target was 9.84° below the horizontal, this resulted in a DE_{DS} value of 30.94°.

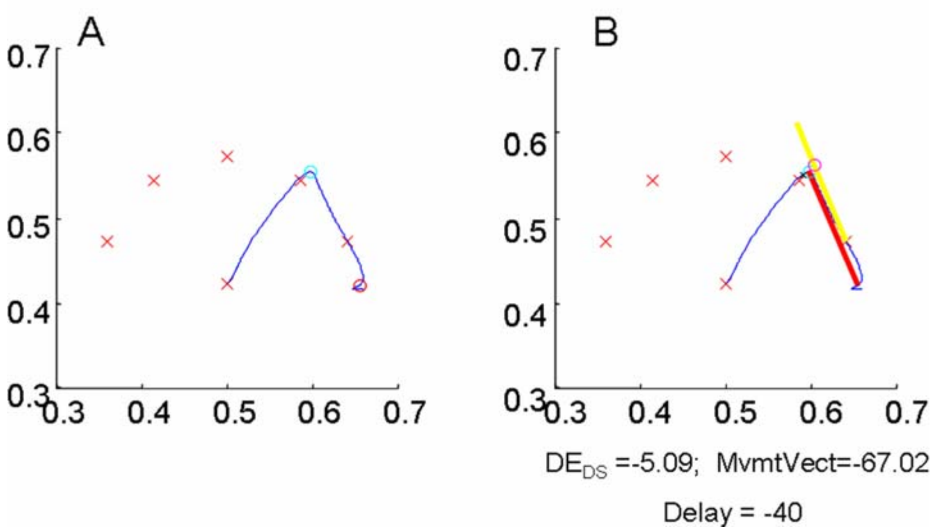
2. The movement vector was then linearly translated such that it passed through the desired target position (shown as the yellow line in Panel B of Figure 1). The intersection of this translated vector (yellow line) and the actual movement trajectory (thin blue trace) represents the participants' *estimate* of hand location at TOC. [The cyan circle represents that participant's *actual* hand location at TOC; thus, the participant's estimate of hand state at TOC, in this example, can be considered delayed or out-of-date]. The translated vector represents an *ideal movement vector* that connects the participant's estimate of hand state at TOC and the target position.
    a. In some instances, the translated vector (yellow) and the actual movement trajectory do not intersect (see Figure 2 below). This results when DE_{DS} was negative and suggests the participant's estimate of hand state was at some point in the future (i.e., predictive). In this case, the movement vector connecting the spatial coordinates at TOC and PV2 is extended to create a hypothetical intersection point (pink circle in Figure 2).
3. The duration between the participant's estimate of hand state at TOC and actual hand state at TOC was computed. This value represents the magnitude of the delay in dynamic state estimation. In the example shown in Figure 1 below, this delay was equal to 175ms.
    a. In the instance that DE_{DS} was negative (Figure 2 below), the distance (referred to as *d*) between the spatial coordinates at TOC (cyan circle) and the hypothetical intersection point of the translated vector and extended movement trajectory (pink circle) was computed. We then made the

assumption that the time it would take the participant to travel distance *d* from the spatial coordinates at TOC (cyan circle) to the hypothetical interaction point (pink circle) was equal to the time it would take to travel distance *d* as the participant approached the TOC – as assumption that is valid if movement velocity at TOC was equal to zero. Thus, the point along the actual movement trajectory that was distance *d* from the spatial coordinates of TOC was identified. The duration between this point and TOC was estimated to be the 'delay'. Note that this delay would be negative, indicating the hand state estimate at TOC was a time point in the future (i.e., predictive). In the example shown in Figure 2 below, this delay was equal to -40ms.

4. This computation was done for each double-step trial. Individual means were computed and then average across all 5- to 7-year-old participants. The estimated average delay was equal to 50ms.

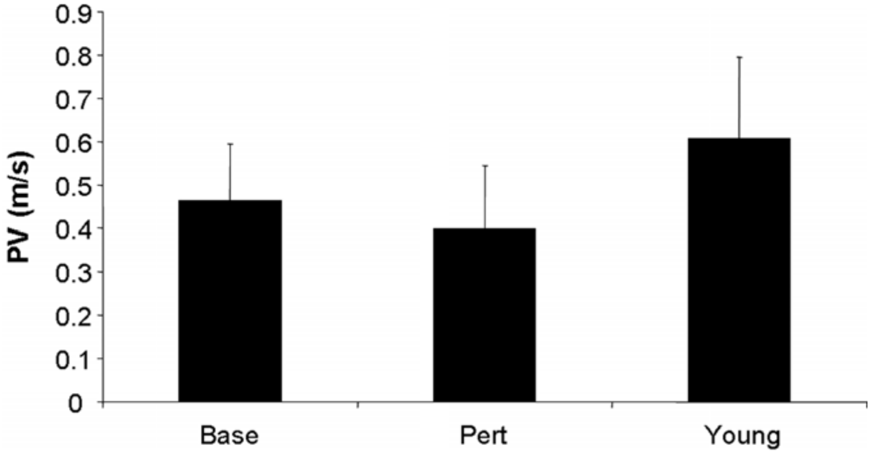


Appendix 12 Figure 1. Experiment 4 estimate of temporal delay (positive value). Units are in m.

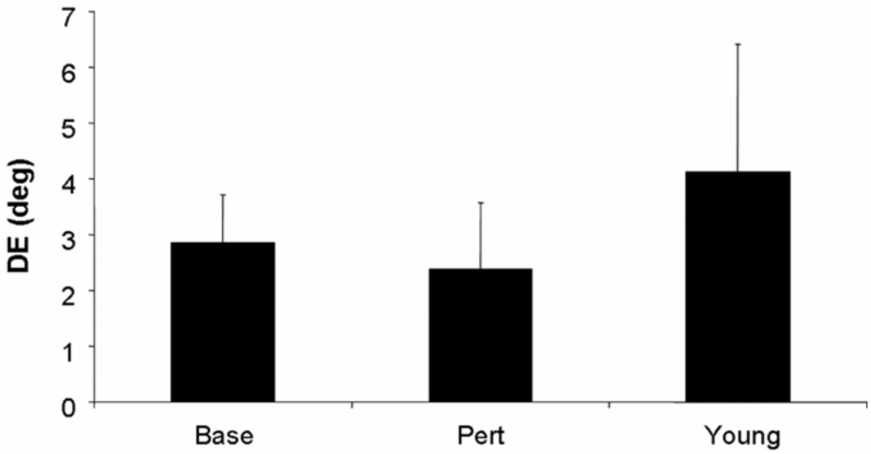


Appendix 12 Figure 2. Experiment 4 estimate of temporal delay (negative value). Units are in m.

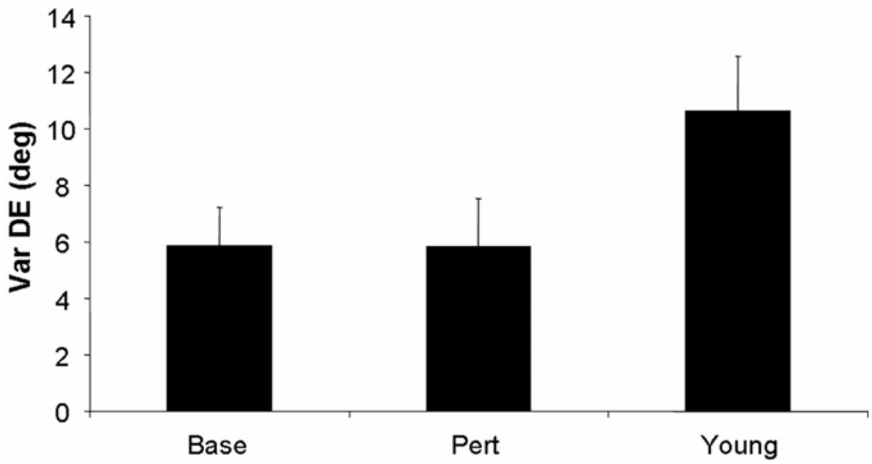
Appendix XIII: Experiment 4 Additional Figures



Appendix 13 Figure 1. Experiment 4 Peak Velocity. PV is shown for the adults in the baseline and perturbed conditions relative to the young children from Experiment 3. The perturbation did not significantly decrease peak velocity in the adults; however, PV during the perturbed condition was significantly less than in the young children.



Appendix 13 Figure 2. Experiment 4 Directional Error. DE is shown for the adults in the baseline and perturbed conditions relative to the young children from Experiment 3. The perturbation had no influence on DE in the adults.



Appendix 13 Figure 3. Experiment 4 Variability of Directional Error. Var DE is shown for the adults in the baseline and perturbed conditions relative to the young children from Experiment 3. The perturbation had no influence on Var DE in the adults.

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