



Development of upper limb proprioceptive accuracy in children and adolescents

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Abstract

This study was designed to determine differences in the proprioceptively guided movements of children (8–10 years) and adolescents (16–18 years). Participants were blindfolded and asked to actively match passively determined target positions of the elbow joint under three matching conditions. Overall, children were less accurate than adolescents in all matching tasks and utilized different kinematic strategies for making the matching movements. Specifically, children made larger absolute errors and utilized matching movements which, compared to adolescents, were of shorter duration and less irregular in terms of their velocity profiles. An assessment of limb asymmetry was also performed revealing a non-dominant arm matching advantage but only for children and only in the task requiring interhemispheric transfer of a memory-based model of limb position. The proprioceptive differences observed in this study are likely the result of experience-driven refinement in the utilization of somatosensory feedback throughout childhood and into adolescence.

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1. Introduction

Proprioception provides the basis for knowing where our limbs are in space and is comprised of both static (joint/limb position sense) and dynamic (kinesthetic movement sense) components. Following on the early observations of [Sherrington \(1906\)](#), it has been established that muscle spindles are a major source of proprioceptive feedback to the central nervous system and appear to mediate the conscious perception of movement and limb position ([Clark, Burgess, Chapin, & Lipscomb, 1985](#); [Gandevia, McCloskey, & Burke, 1992](#); [Goodwin, McCloskey, & Matthews, 1972](#); [Matthews, 1982](#); [McCloskey, 1978](#); [Proske, Wise, & Gregory, 2000](#)). Other sources of proprioceptive information, such as cutaneous and joint mechanoreceptors, are also known to contribute in the determination of more distal body segment positions and signaling extreme ranges of motion ([Collins & Prochazka, 1996](#); [Edin, 2001](#); [Edin & Johansson, 1995](#)).

In the production of coordinated movement, proprioceptive feedback has been found to be critical in controlling muscle interaction torques ([Sainburg, Ghilardi, Poizner, & Ghez, 1995](#); [Sainburg, Poizner, & Ghez, 1993](#)), the timing of limb segments during multi-joint movement ([Cordo, Carlton, Bevan, Carlton, & Kerr, 1994](#)), movement trajectories ([Ghez, Gordon, Ghilardi, Christakos, & Cooper, 1990](#)), and providing internal models of limb representation used in acquisition and adaptation of skilled movement ([Kawato & Wolpert, 1998](#)). Given this importance, development of proprioceptive ability in children has been the focus of several studies. The first definitive analyses in this area were provided by [Bairstow and Laszlo \(1981\)](#) and [Laszlo and Bairstow \(1980\)](#) who examined children aged 5–12 years in a variety of tasks requiring kinesthetic judgments in three-dimensional space. In a task that involved discriminating hand heights after encountering ramps of differing steepness, accuracy was shown to improve substantially from the ages of 5 to 7 years with errors becoming stable in 8 to 12 year olds. Other studies have subsequently demonstrated that the ability to utilize proprioceptive information improves dramatically between the ages of 5 and 8 years with only minor improvement occurring during adolescence and adulthood ([Hay & Redon, 1997](#); [Sigmundsson, Whiting, & Loftnes, 2000](#); [von Hofsten & Rosblad, 1988](#)). Taken together, these studies provide evidence that developmental changes in proprioceptive ability are relatively stable by approximately 8 years of age.

In contrast, it has been suggested that proprioceptive ability continues to improve throughout childhood and well into adolescence. [Elliott, Connolly, and Doyle \(1988\)](#) implemented a similar version of the limb height discrimination task used by [Laszlo and Bairstow \(1980\)](#) and showed a near linear increase in proprioceptive accuracy

from the ages of 4 to 13 years. Further, in studies requiring matching of fingertip position with the same finger of the opposite arm, Crowe and colleagues (Crowe, Keessen, Kuus, van Vliet, & Zegeling, 1987; Hearn, Crowe, & Keessen, 1989) found that positional accuracy continues to improve up to 24 years of age.

The conflicting views of when proprioceptive ability matures may largely be explained by differences in the types of proprioceptive tasks employed. For example, most matching studies have used paradigms in which sensory feedback is constantly available as a reference signal throughout the task. This approach, known as the “method of constant stimuli” (Woodworth & Schlosberg, 1954), is clearly useful in determining the ability of individuals to monitor and compare proprioceptive information “on-line” but fails to fully address the ability to create and access primarily memory-based internal models of limb position from proprioceptive feedback. Feedback-dependent internal models of limb position are thought to play a critical role in the programming of limb movements (Kawato, 1999) as well as providing an internal reference for movement error detection and correction (Wolpert, Ghahramani, & Jordan, 1995).

The purpose of this study was to examine differences in proprioceptively guided limb matching movements of 8–10 year old children and 16–18 year old adolescents. This was accomplished using three proprioceptive tasks that were motorically equivalent but varied in their overall complexity. These tasks were chosen since they required various combinations of interhemispheric transfer and generation of memory-based internal models of limb position, both of which are known to provide a processing challenge over the course of development (e.g., Hay & Velay, 2003; Luna, Garver, Urban, Lazar, & Sweeney, 2004). Unlike traditional analyses of proprioceptively guided movement, which have focused only on the accuracy of endpoint matching, this study also addressed the dynamic aspects of such movements. It was hypothesized that, due to a refinement in proprioceptive ability, matching errors would be less in adolescents compared to children.

2. Methods

2.1. Participants

Nine children aged 8–10 years (mean age 9.3 ± 0.5 years; 5 males, 4 females) and nine adolescents aged 16–18 years (mean age 17.6 ± 0.5 years; 5 males, 4 females) participated in the study. Participants were in good general health at the time of testing and showed a strong preference for performing common upper limb activities (e.g., throwing, eating with a spoon) with the right arm as indicated by a 10-item version of the Edinburgh inventory (Oldfield, 1971). Participants were selected as a convenience sample of individuals from the local community and paid a nominal fee for their participation. Experiments were carried out according to the ethical guidelines laid down by the Institutional Review Board of the University of Michigan.

2.2. Experimental design

Participants were seated at an adjustable table with their forearms resting on two instrumented manipulanda designed specifically for measuring angular displacement of the elbow joint in the horizontal plane. Each manipulandum consisted of a horizontal rigid metal support adjusted to the length of the participant's forearm and mounted on a frictionless pivot beneath the elbow joint. The forearms rested comfortably on top of the manipulanda and were held in position by an aluminum cradle. Stabilization of the hand during movement was accomplished by having the participant grasp a vertical handle at the distal end of the support. A standardized start position for the shoulder (60 deg abduction, 30 deg flexion), elbow (115 deg extension) and wrist (neutral) was maintained across participants. A photograph of the experimental setup is shown in Fig. 1.

Prior to data collection, participants were blindfolded and given approximately 5 min to familiarize themselves with three proprioceptive matching tasks. The tasks varied in terms of online vs. memory based feedback of arm position and the need to transfer proprioceptive information from one hemisphere to the other. In Fig. 2 a schematic of these tasks is provided where each task consisted of two phases: (1) generation of a reference position (145 deg extension) by the experimenter and (2) proprioceptively guided movement to this position by the participant with the matching arm. In the first task, *ipsilateral remembered (IR)* matching, the experimenter passively extended the forearm 30 deg from the start position and held it there for



Fig. 1. A photograph of the experimental setup used for the proprioceptive matching tasks. See text for full description.

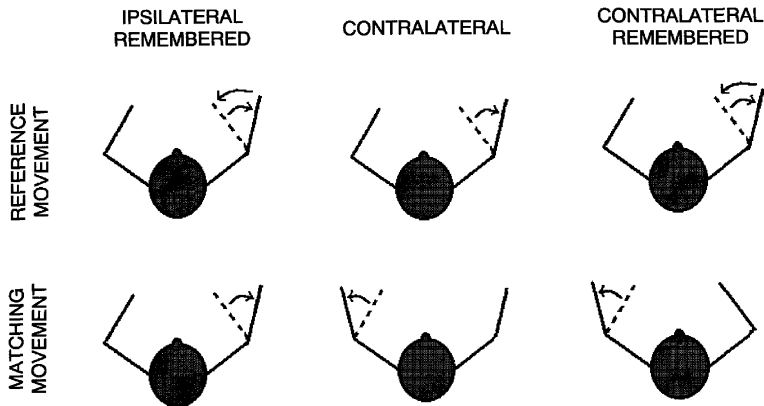


Fig. 2. Schematic of the three proprioceptive matching tasks as viewed from above the participant. For each condition a 30 deg reference movement (upper panels) was made from the start position (dashed line) to the target (solid line). In both remembered conditions, the forearm was returned to the start position. Matching movements (lower panels) were then made by the participant following a verbal cue. Arrows indicate direction of the forearm movement.

approximately 2 s before returning it to the start position. The participant then used a primarily memory-based internal model to guide reproduction of the reference position after a delay of approximately 1 s. In the second task, *contralateral (C)* matching, the experimenter moved the participant's forearm 30 deg and held this reference position. The participant was then asked to match the position with the contralateral arm. In this task, proprioceptive feedback from the reference arm was available "online" throughout the task to assist in the generation of an internal model for matching. This information, however, had to be transferred across cerebral hemispheres in order to perform the matching task with the contralateral arm. Lastly, in the *contralateral remembered (CR)* matching task, the forearm was passively extended 30 deg, held for approximately 2 s and returned to the start position. The participant was then asked to produce the same movement with the contralateral arm. In this case, generation of an internal model without online feedback about the reference position as well as interhemispheric transfer was necessary for accurate performance of the task.

In order to determine whether limb dominance influenced proprioceptive ability, active matching of the reference position was performed by both the dominant and non-dominant arms. Thus, each task was comprised of two limb conditions: dominant arm matching and non-dominant arm matching. For a given matching task and limb condition, three trials were completed using a block design with random presentation of the arm used to create the reference position. A concerted effort was made to ensure that participants were engaged throughout the testing procedure including minimizing testing time (~20 min), visually monitoring participant behavior and presenting the tasks to children in the form of a game. In the few rare cases where a participant was unsuccessful in performing a trial to the best of his or her ability, the trial was repeated.

2.3. Data acquisition and analysis

Elbow joint rotation was recorded as voltage output from precision potentiometers mounted beneath the pivot point of the manipulanda. The analog signal was sampled at 50 Hz, filtered (fourth order Butterworth, zero phase lag, 6 Hz) and saved to a laptop computer. Custom software created using LabVIEW (National Instruments, Plano Texas, USA) acquired and converted the voltage signals to angular displacements for each arm using linear calibration coefficients.

As shown in Fig. 3, three dependent variables were calculated: (1) absolute end-point error, (2) movement time and (3) the number of velocity peaks as a measure of movement smoothness. Absolute error was chosen as the preferred measure of end-point accuracy given the number of trials within a condition, and a lack of consistency in the direction of error (i.e. constant error) between groups, limbs or task. Movement time was calculated utilizing onset and offset values that were 2 standard deviations greater than the averaged signal of a 200 ms pre-movement baseline calculated from the differentiated position (i.e. angular velocity) record. The number of velocity peaks was determined based on the number of zero crossings in the double differentiated (angular acceleration) position record divided by 2 (Brooks, Cooke, & Thomas, 1973).

Statistical analysis of all dependent variables was conducted using separate $2 \times 3 \times 2$ repeated measures analyses of variance (ANOVA) for the main effects of age group (children vs. adolescents), matching task (IR vs. C vs. CR) and limb used for matching (dominant vs. non-dominant), as well as any interaction between these variables. Decomposition of significant factors was accomplished utilizing paired *t*-tests. Statistical significance was set at the level of $p \leq 0.05$ for all analyses.

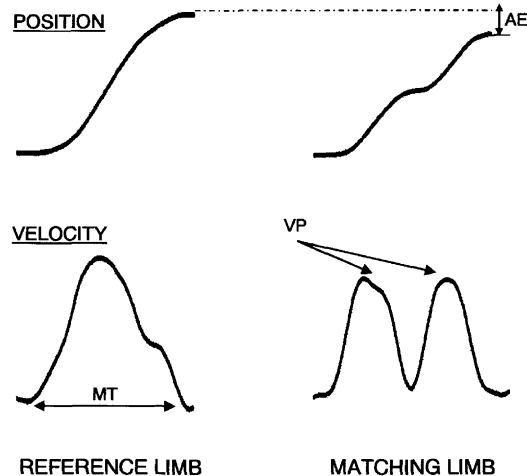


Fig. 3. Schematic showing the dependent measures (absolute error [AE], movement time [MT], velocity peaks [VP] as a measure of movement smoothness) calculated for this study.

3. Results

All participants were successful in completing the entire testing procedure. Reference arm movements made by the experimenter were highly consistent across all trials with mean arm displacement amplitude of 29.7 ± 1.3 deg and mean movement duration of 2.3 ± 0.5 s.

3.1. Absolute error

Overall, children were less accurate in matching than adolescents across all task and limb conditions, $F(1,16) = 26.1$, $p < 0.001$, with a mean absolute error of 6.2 deg for children and 3.7 deg for adolescents. Matches made by children were also more variable and ranged from 0.1 to 20.8 deg compared to adolescents where errors ranged from 0.0 to 14.1 deg. In Fig. 4, the mean absolute error values for each proprioceptive task (IR, C, CR) and arm matching condition (dominant, non-dominant) are presented for the two age groups. In the adolescent group, the level of error was consistent across all matching tasks regardless of the arm used to make the matching movement. For the 8–10 year old group, a similar trend in performance was observed in both the IR and C conditions. However, in the CR condition, absolute matching errors were significantly greater, $t(8) = 2.4$, $p < 0.05$, when the non-dominant arm was used as the reference and matching was performed by the dominant arm.

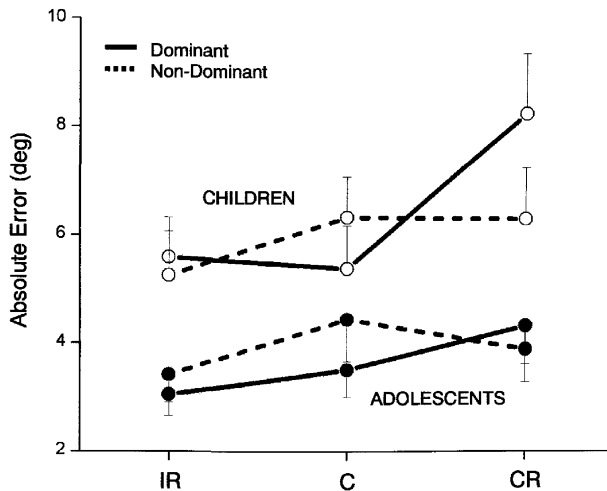


Fig. 4. Mean absolute error values for children (open circles) and adolescents (filled circles) in each of the matching tasks. Data are shown for tasks in which the dominant and non-dominant arm performed the matching movement. Error bars represent standard error of the mean.

3.2. Movement time

The amount of time taken to move the arm from the start position to that of the target was significantly longer, $F(1, 16) = 11.9$, $p < 0.01$, for adolescent participants than for children. On average, adolescents took 2.7 s to make matching movements whereas children required an average of 2.1 s. Mean movement time values for the three matching tasks and two limb conditions are shown in Fig. 5. In children there were no differences in the time taken to perform any of the matching tasks regardless of the arm used. Similar results were seen in the adolescent group.

3.3. Movement smoothness

Age-related differences in movement dynamics are shown in Figs. 6 and 7. In Fig. 6 representative velocity profiles associated with three matching movements made by a 9 and a 17 year old participant using the dominant arm in the CR task are contrasted. In general, movement irregularities (i.e. indicating a lack of movement smoothness) were more prevalent in the velocity profiles associated with movements made by the adolescents compared to children. This observation was validated in the analysis of movement smoothness, as estimated by the number of velocity peaks seen during a trial, where significant differences, $F(1, 16) = 17.4$, $p < 0.001$, between age groups were revealed. Matching movements made by adolescents were characterized by 2.7 velocity peaks compared to 2.2 velocity peaks seen in movements made by children. As shown in Fig. 7, no significant differences in movement smoothness due to matching task or arm dominance were observed in either age group.

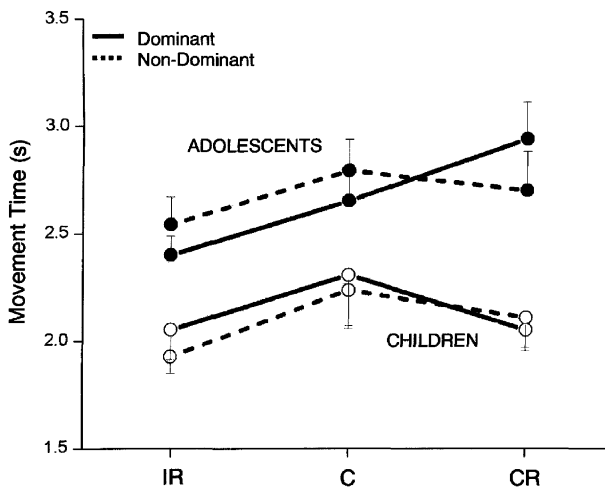


Fig. 5. Mean movement time values for children and adolescents in each of the matching tasks. Data are shown for tasks in which the dominant and non-dominant arm performed the matching movement. Symbols and error bars as in Fig. 4.

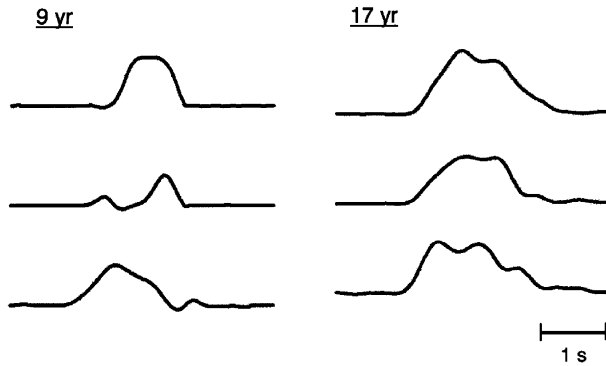


Fig. 6. Representative velocity profiles associated with movements made by a 9 year old and a 17 year old for three consecutive matching trials made by the dominant arm in the contralateral remembered condition.

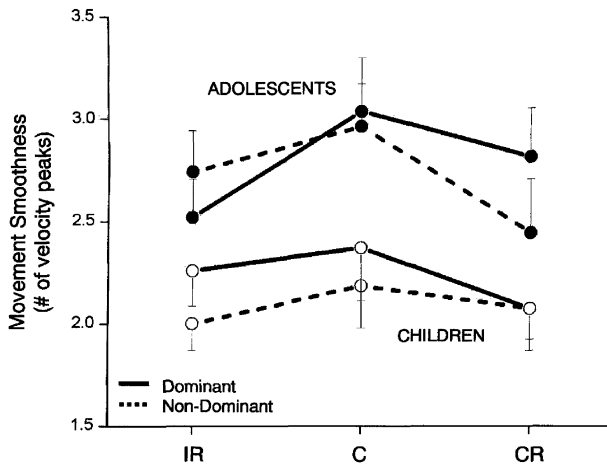


Fig. 7. Mean number of velocity peaks as an indicator of movement smoothness for children and adolescents in each of the matching tasks when either the dominant or non-dominant limb performed the matching movement. Symbols and error bars as in Fig. 4.

4. Discussion

This study examined the differences in proprioceptively guided limb matching movements of 8–10 year old children and 16–18 year old adolescents. Specifically, participants performed a series of upper limb matching tasks that varied in complexity and that utilized both the dominant and non-dominant arms as the proprioceptive reference and matching arms. Significant age differences were observed in both the accuracy of arm position matching and in the dynamics of the matching movements. Additionally, a task-specific difference related to limb dominance was evident

demonstrating a left arm advantage in the matching accuracy of children during the CR task.

The results of this study provide strong evidence that the control of proprioceptively guided movements continues to be refined from childhood well into adolescence with an almost 50% reduction in matching error occurring in 16–18 year olds as compared to 8–10 year old children. Adolescent matching errors of 3.7 deg observed in this study are comparable to errors observed in young adults performing similar proprioceptive tasks. For example, mean elbow matching errors associated with ipsilateral (Darling, 1991) and contralateral (Inglis, Frank, & Inglis, 1991) matching in young adults averaged between 3 and 4 deg. Thus, the findings reported here indicate that, for the upper limb, peak proprioceptive ability is reached by late adolescence. Previously, Hearn et al. (1989) indicated that proprioceptive ability continues to improve through the mid-twenties. However, their data revealed only marginal changes in matching error beyond 18 years of age, and statistically significant age effects were only seen at the $p < 0.10$ level.

Maturation of peripheral somatosensory pathways is thought to be relatively complete by 12 months (Boor & Goebel, 2000), and so the continued improvement in proprioceptive ability observed here no doubt reflects changes in central sensorimotor processes including increased myelination of fiber tracts (Benes, Turtle, Khan, & Farol, 1994; Paus et al., 1999), and experience-dependent strengthening of synaptic connections (Black, Isaacs, Anderson, Alcantara, & Greenough, 1990; Nudo, 2003). Delayed maturation of the corpus callosum and the dorsolateral frontal cortex relative to sensorimotor cortical development may also contribute to age-related changes in proprioceptive ability. For instance, in proprioceptive tasks involving contralateral matching, the corpus callosum is involved in interhemispheric transfer of sensory information. As a result of myelogenesis, the corpus callosum continues to increase in size throughout childhood and well into adolescence (Schaefer et al., 1990; Giedd et al., 1996). This increase appears specific to posterior areas of the corpus callosum (Giedd et al., 1999; Giedd et al., 1996) that link, among other cortical areas, the posterior parietal cortex. This area is involved primarily with visuospatial aspects of motor coordination so it is unclear to what extent maturation of the posterior corpus callosum may be involved in purely proprioceptively guided movement.

The dorsolateral prefrontal cortex is one of the last brain regions to mature and plays a critical role in cognitive processes such as working memory and sensory attention (Casey, Giedd, & Thomas, 2000; Goldman-Rakic, 1987), both of which are essential in proprioceptive ability studies. The ability to cognitively attend to proprioceptive feedback mediating limb position awareness, as well as generate and remember an internal model of limb position, depends heavily on executive functions typically ascribed to the prefrontal cortex. Thus, developmental changes in proprioceptive ability most likely reflect maturation of more general cognitive abilities as well as experiential enhancement of sensorimotor processing.

Another factor to consider when interpreting the results of this study concerns the need to recalibrate an internal body schema in response to physiologic growth. Although growth rates during childhood are relatively stable, pubertal growth is a dynamic period of development marked by rapid changes in body size, shape and

composition. This period of growth occurs between 11–15 years in females and 13–17 years in males (Rogal, Clakr, & Roemmich, 2000). It is possible that in our adolescent male participants the presence of a growth spurt may have impacted proprioceptive matching of body space. However, given that their performance was comparable to that seen in healthy young adults, it is unlikely that any growth-induced perturbation of an internal body schema was a confounding factor in this study.

Most studies of proprioceptive ability have focused solely on static measures related to end-point, limb positional errors with little or no attention paid to the dynamic aspects of the matching movements themselves. This is in marked contrast to the number of studies that have focused on arm trajectory formation during visually guided movements. Trajectories associated with such goal-directed movements are typically characterized by smooth, single-peaked velocity profiles in which the times spent accelerating and decelerating the arm are approximately equal (Abend, Bizzi, & Morasso, 1982; Flash & Hogan, 1985). These temporal characteristics, which are relatively invariant across different task conditions, have been documented for both single-joint movements similar to those produced in the present study (Berardelli et al., 1996; Brown & Cooke, 1981, 1990) and multi-joint movements made in three-dimensional space (Lacquaniti & Soechting, 1982; Todorov & Jordan, 1998). Smooth, time symmetric velocity profiles are thought to reflect optimization of motor execution (Nakano et al., 1999), and have been increasingly used to provide a sensitive measure of movement quality, particularly in clinical populations (Brown, 1996; Brown & Cooke, 1990; Cirstea & Levin, 2000; Hurvitz, Conti, & Brown, 2003; Woldag & Hummelsheim, 2003). In healthy individuals, secondary velocity peaks associated with sub-movements may occur during, for example, learning of a visually-guided novel task or during tasks requiring a high degree of terminal accuracy in which error corrections are generated (Crossman & Goodeve, 1983; Keele & Posner, 1968; Milner, 1992).

The proprioceptively guided movements that were freely chosen by children and adolescents in this study were substantially different from one another. Movements made by children were both faster and had a smaller number of movement discontinuities compared to adolescents. This is in contrast to the only known developmental study examining velocity characteristics of proprioceptively guided movements (Hay & Redon, 1997). In this study, trajectory irregularities decreased in 11 year old children and adults compared to 5–9 year olds. These conflicting findings may largely be explained by differences in experimental design involving different levels of sensory processing. In the Hay and Redon study a vibration technique was employed, which degraded the amount of proprioceptive information available to the participant. In addition, the position target remained visible throughout the movement while, in the present study, the target was proprioceptively generated. The ability to integrate both visual and somatosensory information, as would be required when target information is visually provided, may be experience driven and thus explain the age-related improvement in trajectory characteristics as reported by Hay and Redon. In the present study in which only proprioceptive information about target location was provided, an increase in movement irregularities accompanied by

greater time spent making the movement in the adolescent group may have reflected an improved ability to monitor actual position with available or remembered proprioceptively generated reference information. In contrast, children may have utilized more of a feedforward strategy, resulting in smoother trajectories and shorter movement durations but with increased end point errors.

Beyond the developmental differences in proprioceptive ability shown in this study, a handedness effect was found but only during contralateral remembered matching and only in children. In this condition, matching accuracy worsened when the non-dominant arm served as the reference arm and matching occurred with the dominant arm. This is in contrast to previous developmental studies in which improved matching performance occurred with the dominant compared to the non-dominant arm (Crowe et al., 1987; Hearn et al., 1989), and studies which found no differences between right and left limb matching (Laszlo & Bairstow, 1980; Sigmundsson et al., 2000). These conflicting results may be partially explained by differences in matching paradigms. Previous investigations have utilized a method of constant stimuli where a reference position signal was available throughout the matching task. In the present study, matching error worsened considerably when proprioceptive feedback arising from the non-dominant arm provided the reference information for the generation of an internal model of limb position and subsequent matching by the dominant arm. It is possible that, in children, arm differences in proprioceptive ability during contralateral remembered tasks may be experience driven. In other words, the ability to utilize proprioceptive feedback, particularly when such information must be retained in memory, may be dependent on repetitive activation of relevant sensorimotor pathways as would occur more frequently with the dominant compared to the non-dominant arm. For example, it is now well established that the size of cortical representation, particularly in sensory and motor areas, is not static but can be modified as a result of limb usage (Kaas, Merzenich, & Killackey, 1983; Nudo, Plautz, & Frost, 2001; Plautz, Milliken, & Nudo, 2000) and level of motor skill (Recanzone, Merzenich, Jenkins, Grajski, & Dinse, 1992). While it is possible that differences in the direction of interhemispheric transfer may have also contributed to limb asymmetries seen during contralateral remembered matching, such differences were not observed when the reference signal was constantly available throughout the matching task.

It is of interest to note that the time course associated with the development of proprioceptive ability extends beyond what has been described for skilled motor function. While studies have indicated that the age at which adult-like movement patterns emerge may depend upon task requirements (Kuhtz-Buschbeck, Stolze, Joehnk, Boczek-Funke, & Illert, 1998; Schneiberg, Sveistrup, McFadyen, McKinley, & Levin, 2002; Shumway-Cook & Woollacott, 1995), it is generally assumed that mature patterns of motor coordination are present in the majority of children by approximately 10 years of age (Seefeldt & Haubenstricker, 1982). Given the interaction between somatosensory and motor pathways during skilled movement, it may be naive to assume that significant improvement in motor ability does not occur throughout adolescence.

The results of the present study provide new information regarding the normal development of the proprioceptive system and may also be of importance in the study of pediatric onset motor disability. Proprioceptive deficits have been shown in many such conditions including hemiplegic cerebral palsy (Lewis, Goble, Hurvitz, & Brown, 2004; Opila-Lehman, Short, & Trombly, 1985; Van Heest et al., 1993) and developmental coordination disorder (Sigmundsson, Whiting, & Ingvaldsen, 1999a; Sigmundsson, Whiting, & Ingvaldsen, 1999b; Smyth & Mason, 1998). Sensory feedback, including proprioception, plays a role in the development of movement patterns, and sensory deficits have been shown to affect, for example, grasp formation in children with hemiplegia (Gordon & Duff, 1999). Since rehabilitation of sensory function has been shown to be effective in some populations (Smania et al., 2003), the current findings are relevant to the development and assessment of more effective sensorimotor intervention programs.

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