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The development of consistency and flexibility in manual pointing during middle childhood

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Abstract

Goal-directed actions become truly functional and skilled when they are consistent yet flexible. In manual pointing, end-effector consistency is characterized by the end position of the index fingertip, whereas flexibility in movement execution is captured by the use of abundant arm-joint configurations not affecting the index finger end position. Because adults have been shown to exploit their system's flexibility in challenging conditions, we wondered whether during middle childhood children are already able to exploit motor flexibility when demanded by the situation. We had children aged 5–10 years and adults perform pointing movements in a nonchallenging and challenging condition. Results showed that end-effector errors and flexibility in movement execution decreased with age. Importantly, only the 9-10-year-olds and adults showed increased flexibility in the challenging condition. Thus, while consistency increases and flexibility decreases during mid-childhood development, from the age of nine children appear able to employ more flexibility with increasing task demands.

1. INTRODUCTION

A major goal of motor development is to acquire consistent yet flexible goal-directed actions. The first stages of the development of goal-directed actions are characterized by highly inconstant attempts that mostly become manifest in end-effector variability. Looking at manual pointing, for instance, we see that an infant's first pointing movements often miss the target (Ekberg et al., 2013). A key component of motor development then is to increase end-effector consistency to facilitate a more successful and reliable performance. Throughout childhood, this is reflected by a decline of errors in reaching the targets of pointing movements (Bard, Hay, & Fleury, 1990; Favilla, 2006; Wilson & Hyde, 2013). However, end-effector consistency is not the only aspect that changes over age in goal-directed actions. Consistent movements also require the efficient and flexible coordination of the multiple degrees of freedom (DoF; e.g., muscles and joint angles) of the neuromotor system (Bernstein, 1967; Latash, Scholz, & Schöner,

2007). Unfortunately, age-related changes in flexibility during movement execution have received less attention in the motor developmental literature. For the purpose of the present study we define flexibility as the exploitation of DoF over repeated trials (c.f., Latash, 2012), given that pointing at one and the same target can be achieved by adapting various joint-angle configurations (i.e., DoF) of the shoulder, elbow, wrist, and finger. Flexibility in movement execution is what makes movements adaptive (c.f., Adolph, Cole, & Vereijken, 2015; Latash et al., 2007; Lee, Farshchiansadegh, & Ranganathan, 2017; Rachwani, Soska, & Adolph, 2017), which is especially relevant when tasks become more challenging, in which circumstances adults have been shown to exploit more flexibility in their joint-angle configurations (e.g., de Freitas, Scholz, & Stehman, 2007). In the study at hand, we focused on how children in middle childhood (5–10 years of age) utilize additional flexibility of their motor system when a manual pointing task becomes more challenging.

Flexible coordination of DoF is possible because humans have an abundant motor system (Gelfand & Latasch, 1998; Latash, 2000; Latash, 2012) in that our bodies are composed of multiple linkages and joints and a great number of muscles that thus yield a higher number of DoF than is required for the successful performance of a motor task (Bernstein, 1967; Latash et al., 2007; Scholz & Schöner, 1999). To illustrate this, imagine sitting at a table while keeping the tip of your index finger at one position on the surface. You will find that you are still able to vary the joint angles of your arm (reflecting joint-angle flexibility) without affecting the position of your finger tip (signifying end-effector consistency). However, there also are joint-angle configurations that do affect the end position of the index finger, leading to increased end-effector variability influencing the end-effector consistency (Latash et al., 2007). For instance, with your finger still on the table, try to extend your elbow joint to the max. You will find that you cannot compensate for this by adjusting your wrist and shoulder, and consequently your index finger will have moved away from its original position. In the present study we applied the uncontrolled manifold (UCM) method to distinguish variability in joint-angle configurations that does not affect the position of the index finger from variability that does affect the position of the index finger (Domkin, Laczko, Djupsjöbacka, Jaric, & Latash, 2005; Latash et al., 2007; Scholz & Schöner, 1999). In a pointing task, the UCM is a manifold that represents the set of joint-angle configurations of the arm with the index fingertip at a specific position. That is, variance within the UCM corresponds to variability in joint-angle configurations that does not affect the mean position of the index finger (V_{ucm}), whereas variance orthogonal to the UCM subspace (the ORT subspace) corresponds to the variability in joint-angle configurations that does elicit a deviation from the mean position of the index finger (V_{ort}).

As alluded to above, adults have been shown to utilize additional movement flexibility (V_{ucm}) in

demanding situations (e.g., de Freitas et al., 2007; Dutta, Freitas, & Scholz, 2013; Yang, Scholz, & Latash, 2007). When the task became more challenging, V_{ucm} increased, while V_{ort} had only slightly done so (de Freitas et al., 2007; Reisman, Scholz, & Schöner, 2002). Thus, to meet increasing task demands, additional flexibility is exploited by increasing V_{ucm} while keeping V_{ort} as small as possible. This links to the results reported for end-effector consistency that showed no change when task demands increased. Adults, for example exploited their system's flexibility when the target location became more uncertain (de Freitas et al., 2007) or when the support surface of a sit-to-stand movement became narrower (Reisman et al., 2002; Scholz, Reisman, & Schöner, 2001). However, little is known about when children are able to exploit additional flexibility of their motor system.

The main goal of the current study accordingly was to examine if and to what extent children in the ages between 5 and 10 years learn to exploit their DoF to achieve a greater movement flexibility when task demands of a pointing task increase. Of note here is that the flexible use of joint angles (V_{ucm}) can develop independently of end-effector consistency, implying that flexibility and consistency can also change independently of each other with increasing task demands. We therefore decided to also examine age-related changes in movement consistency by looking both at variable errors (VEs; dispersion of endpoint positions of the index finger around the target) and constant errors (CEs; mean deviation from the goal). To create different demanding pointing conditions, we manipulated the certainty of the pointing location as was done by de Freitas et al. (2007). Participants first performed a block of unconstrained pointing movements from a start location to a certain target location (nonchallenging condition), followed by a block in which the target could either switch locations at movement onset or stay in its original location (challenging condition). Studying developmental trends of errors in a simple, non-challenging pointing task in 5 to 10-year-old children, previous research showed constant and variable errors to decrease with increasing age (Favilla, 2006; Ferrel, Bard, & Fleury, 2001; Hay, 1979). To our knowledge, our group (Golenia, Schoemaker, Otten, Mouton, & Bongers, 2018) was the first to investigate the development of flexibility in a nonchallenging pointing condition, showing that both V_{ucm} and V_{ort} decreased with age. In our present study, we will be the first to examine possible changes in flexibility (an increase in V_{ucm}) in 5 to 10-year-old children in response to changes in the constraints of a pointing task.

2. METHOD

2.1 Participants

A statistical a priori power analysis was performed for sample size estimation based on data from Golenia

et al. (2018). With an $\alpha = 0.05$ and power = 0.80, the projected sample size needed to find an interaction effect was $N = 64$ for a between/within group comparison (GPower 3.1). The final study sample consisted of a total of 57, with 42 typically developing right-handed children and 15 right-handed young adults, thus, our sample size of 57 is close to being adequate for the main objective of this study. The included children were aged between 5 and 10 years and recruited from local sport clubs and mainstream elementary schools. Prior to the experiment, children completed the Movement Assessment Battery for children-2nd Edition (MABC-2; Henderson, Sugden, & Barnett, 2007), which provides an indication of motor functioning across fine and gross motor tasks for children aged 3 to 16 years, with typical development being indicated by a score above the 16th percentile. All children included in the study scored above this threshold, signifying typical motor development ($M = 63.8\%$, range = 25–98%). For the analyses, the children were divided into three age groups (see Table 1). The adult participants were aged between 20 and 25 years and were recruited through word of mouth at Groningen University. Adult participants had no motor impairments of the upper extremities.

The ethics committee of the Center for Human Movement Sciences, University Medical Center Groningen, approved the study. The adult participants and the children's parents or legal guardians provided their written informed consent prior to the experiment.

2.2 Experimental setup

To examine the position of the index finger and the joint-angle configurations of the arm, 3D position data of all segments of the right arm were collected (with a sampling of frequency 100 Hz) using two Optotrak 3020 system sensors (Northern Digital, Waterloo, Canada). In total, six rigid bodies (each with three LED markers) were attached to the participant's right arm and trunk (van Andel, Wolterbeek, Doorenbosch, Veeger, & Harlaar, 2008). The first rigid body was attached to the index finger such that it splinted the finger to prevent motion of the interphalangeal joints given that the finger was considered as one segment in the analysis. The other five rigid bodies were triangular shaped and attached to the dorsal surface of the hand, the lower arm, the upper arm, the acromion, and the sternum (Figure 1). Nineteen anatomical landmarks were digitized using a standard pointer and linked to the positions of the rigid bodies (van Andel et al., 2008). This allowed extraction of the position of the fingertip and the computation of nine joint angles of the shoulder, elbow, wrist and finger.

The task was performed at a black table (height = 72 cm) with a large television screen (Panasonic, 62*111 cm) integrated into the tabletop on which the trials were presented using Presentation (Neurobehavioral systems, Berkeley, CA). Participants were seated in a chair (Tripp Trapp, Stokke, Sweden) adjusted to their height facing the middle of the longer side of the screen. Their trunks were

stabilized with a crossover harness of the upper body that was tied to the chair (Greve, Hortobágyi, & Bongers, 2015; Valk, Mouton, & Bongers, 2016; Van der Steen & Bongers, 2011). This was done to prevent major movements of the torso. During data analysis we saw that movements of the sternum were indeed small, which was indicated by an average difference between the position of the sternum in the anterior and posterior direction at movement initiation and termination of 2.0 cm ($SEM = 4.65$). Note that the strap allowed for free movements of the shoulder and elbow joints. An elbow rest was placed at table height on the right side of the participant to keep the start posture of the upper extremity similar over trials. The start location was a circular-shaped pressure sensor (2-cm diameter) located halfway along the longer side of the screen (2 cm away from the edge of the table). The circular (2-cm diameter) center target was displayed 25 cm away from the start location. We had opted for 25 cm to ensure that for all participants the targets were within arm's reach while still providing ample opportunity to correct the pointing movements in the double-step trials (i.e., prior to the initial target being reached). The index of difficulty (ID) for the pointing movement was 3.2 as calculated using Fitts' law. At the start of each trial the experimenter seated next to the participants ensured that their posture was such that their trunks were aligned to the vertical midline of the screen at a 10-cm distance from the start location, with the tip of the right index finger placed on the start location and the elbow resting on an arm rest. See Figure 1 for a schematic representation of the participants' start posture.

2.3 Procedure and design

Pointing movements were first performed in a non-challenging and then in a challenging condition. In the nonchallenging condition, the participants performed 30 pointing movements to the same, fixed target position (center target). Each trial started as soon as they had adopted the start posture. Participants initiated the pointing movement at their own convenience after hearing a beep that was emitted at a random interval of 1.0–1.5 s after the target location

had appeared on the display. They were instructed to perform a pointing movement with the tip of the index finger from the start location to the target as fast and as accurately as possible, where the tip of the index finger had to move unconstrained through 3D space using joint rotations of the whole arm. Note that the elbow needed to be lifted from the elbow rest to perform the movement. The trial ended with holding the finger on its reached end position for a short period of time. This implies that children could see whether they reached the target or not. No additional knowledge of the results was provided.

After the nonchallenging block, participants performed 120 more challenging trials in which the target location was uncertain. As in the nonchallenging condition, the center target was presented on the screen

but now, upon movement initiation, either remained there or unexpectedly “jumped” to a new location 10 cm to the left or right of the center target on a 25-cm radius (with the new targets also being 2-cm diameter circles). The procedure and instructions were the same as in the non-challenging condition with the difference that lifting the index finger to start the movement caused the target to either remain in place or change location, where the “jump” occurred randomly 0, 50 or 100 ms after movement onset. Trials were divided into three blocks of 30 trials, with each block containing 10 constant-target trials and 20 “jumping target” trials (10 to each side) presented in a pseudorandomized order. Short breaks were allowed between blocks.

2.4 Data analysis

For all analyses, customized data-analysis programs were developed in Matlab (MathWorks; Natick, Massachusetts). It is relevant to note here that we only entered the 30 “non-jump” trials from the challenging condition into our analyses to allow a comparison of similar pointing movements, where those executed in the challenging condition only differed from those in the non-challenging condition due to the target uncertainty. To determine the initiation and termination of the pointing movements, a backward (movement initiation) and forward (movement termination) search was performed from the maximum in the tangential velocity profile of the tip of the index finger with the threshold being set at 5 cm/s. The first point below this threshold was taken to reflect the initiation and the termination of the pointing movement. To verify that both points were determined correctly, each trial was checked visually. All variables were analyzed at movement termination.

2.4.1 Variable and constant errors

Target consistency was based on the difference vector between the center of the target position and fingertip position at movement termination. The VE (within-subject standard deviation of the difference) was calculated to characterize the dispersion of the endpoint positions around the target. In addition, we calculated the CE (mean deviation from the target).

2.4.2 Joint angle configurations

Nine joint angles of the arm were calculated at movement termination as proposed in the International Society of Biomechanics (ISB) standardization proposal for the upper extremity by Wu et al. (2005): shoulder plane of elevation, shoulder elevation, shoulder inward–outward rotation, elbow flexion–extension, elbow pronation–supination, wrist flexion–extension, wrist abduction–adduction, index finger flexion–extension, and index finger abduction–adduction. Variability in joint configurations was

examined with the UCM method at movement termination as previously described in the literature (Domkin et al., 2005; Latash et al., 2007; Scholz & Schöner, 1999; Tuitert et al., 2017; Verrel, 2011). The joint angles of the arm were the elemental variables and the performance variable was the position of the index finger. The relations between changes in elemental variables and changes in the performance variable were computed using multiple regressions (de Freitas & Scholz, 2010; Krishnamoorthy, Scholz, & Latash, 2007; Tuitert, Valk, Otten, Golenia, & Bongers, 2018) and united in a Jacobian matrix (Domkin et al., 2005; Verrel, 2011). The null space of the Jacobian matrix was used as a linear approximation of the UCM. V_{ucm} and V_{ort} were computed by projecting the total variance in joint space onto the linear approximation of the UCM (V_{ucm}) and the orthogonal complement (V_{ort}), respectively. Note that, although our interest is primarily in V_{ucm} , we also present V_{ort} to give an indication of the variability in joint angles that led to end-effector displacement. To correct for non-normal data distribution, V_{ucm} and V_{ort} were log transformed prior to the statistical analysis (Verrel, 2010). Figure 2 and 3 display the values before log transformation.

2.5 Statistical analysis

Repeated measures ANOVAs on VE, CE, V_{ucm} and V_{ort} were performed using SPSS version 20.0 (IBM, Armonk, New York). Pointing condition (nonchallenging, challenging) was the within-subject factor and age group (5-6, 7-8, and 9-10-year-olds, and adults) the between-subjects factor. Post-hoc tests were performed with Bonferroni correction. If the assumption of sphericity was violated, the Greenhouse–Geisser correction was applied. The level of significance was set at $\alpha < 0.05$. Generalized eta-squared, η^2_G , (Bakeman, 2005) was used to calculate effect sizes and interpreted according to Cohen's recommendation of 0.02 for a small effect, 0.13 for a medium effect, and 0.26 for a large effect (Cohen, 1988). For the t -tests, measures of effect size (r) were used.

3. RESULTS

We removed 544 of the total of 3,420 trials from the dataset, with trials being excluded when at least one variable could not be determined because of the occlusion of rigid bodies (mostly markers on the rigid body of the sternum that were obscured by the children's chins) or when the task was performed incorrectly (e.g., movements initiated before the beep). This left 2,876 (84%) trials for our analyses.

3.1 Constant and variable error

The repeated measures ANOVA on VE revealed a significant age group effect, $F(3,53)=13.83, p<0.001, \eta^2_G=0.32$ (Figure 2a). Post-hoc tests showed that the VEs of all children groups were significantly larger than those of the adult group ($p's < 0.002$). The repeated measures ANOVA on CE also only demonstrated a significant effect of age group, $F(3,53) = 13.18, p < 0.001, \eta^2_G = 0.36$ (Figure 2b). Post-hoc tests showed that CEs of all children groups were significantly larger than those of the adult group ($p's < 0.009$) and that the CEs were larger for the 5-6-year-olds compared to those for the 7-8-year-olds ($p = 0.049$).

3.2 Joint angle configurations

3.2.1 V_{ucm}

The repeated measures ANOVA on V_{ucm} revealed a significant main effect of age group, $F(3,53) = 39.56, p < 0.001, \eta^2_G = 0.67$, showing that V_{ucm} decreased with age. Post-hoc test showed that V_{ucm} was significantly different for most age groups ($p's < 0.049$) except for the 7-8 and the 9-10-year-olds. A significant main effect of condition, $F(1,53) = 18.41, p < 0.001, \eta^2_G = 0.02$, showed that V_{ucm} was higher in the challenging condition ($M = 0.007, SEM = 0.001$) compared to the non-challenging condition ($M=0.006, SEM=0.001$). Importantly, an interaction between age group and condition was found for V_{ucm} , $F(3,53) = 6.95, p < 0.001; \eta^2_G = 0.03$. Interestingly, post-hoc tests showed that V_{ucm} in the nonchallenging and challenging condition was not different for the 5-6 ($p = 0.45$) and the 7-8-year-olds ($p = 0.46$), whereas V_{ucm} was higher in the challenging condition for both the 9-10-year-old children, $t(14) = 4.13, p < 0.001, r = 0.74$, and the adults, $t(14) = 8.36, p < 0.001, r = 0.91$ (Figure 2c). To further test this interaction effect, we focused on the condition-specific differences between the 7-8 and the 9-10-year-olds. Results of these two independent t -tests were non-significant for both the non-challenging ($p = 0.095$) and the challenging condition ($p = 0.251$).

Showing the data of V_{ucm} for all individual participants, Figure 3a provides more insight into the interaction effect between pointing condition and age. Visual perusal of these data reveals that the increase of V_{ucm} in the challenging condition is systematic at the individual level both in the 9-10-year-old and the adult participants, with 14 and 12 out of 15, respectively, showing an increased V_{ucm} . Looking at the magnitude of the difference between these two groups in the two experimental conditions, we see that only two of the 9-10-year-olds (the two youngest children in this age group, as Figure 3a shows) have the same difference magnitude as the adults. However, this effect is masked due to the scale of the axes since

the axes for the child data cover a larger range than those for the adults. When we take into account the V_{ucm} levels in the nonchallenging condition, the relative difference in the 9-10-year-olds and the adults is similar. The V_{ucm} increase in the children in the challenging condition should therefore also be looked at in terms of this relative difference. Nonetheless, the interaction effect could still mostly result from the two children in this age group in whom V_{ucm} increased more than in their age peers. Having conducted the repeated measures ANOVA again while excluding these two children from the analysis, we found that the interaction effect between condition and age group was still significant ($p = 0.001$).

3.2.2 V_{ort}

The repeated measures ANOVA on V_{ort} demonstrated a significant main effect of age group, $F(3,54) = 54.33$, $p < 0.001$, $\eta^2_G = 0.63$, showing that V_{ort} decreased with age (Figure 2d). Post-hoc testing showed that V_{ort} was significantly different for most age groups ($p's < 0.011$) but not for the 7-8 and the 9-10-year-old children. The main effect for pointing condition was small but significant, $F(1,54) = 5.51$, $p = 0.023$, $\eta^2_G = 0.04$, showing that V_{ort} had slightly increased in the challenging condition ($M = 0.0013$, $SEM = 0.0001$) compared to the nonchallenging condition ($M = 0.0018$, $SEM = 0.0001$). The condition-age interaction effect was not significant ($p = 0.417$). For completeness, individual data of V_{ort} are presented in Figure 3b.

4. DISCUSSION

Goal-directed actions become truly functional and skilled when they are consistent yet flexible (c.f., Adolph et al., 2015; Adolph & Robinson, 2015; Black, Smith, Wu, & Ulrich, 2007; Rachwani et al., 2017; Vereijken, 2010). To explore the development of motor flexibility and consistency, we had 5-10-year-old children and adults perform a pointing task while manipulating the target location (certainty versus uncertainty). Movement flexibility was reflected in the usage of multiple arm-joint configurations that did not affect the position of the index finger (V_{ucm}) and end-effector consistency by variable and constant error. We found a main interaction effect between pointing condition and age group for V_{ucm} , where the children in the 9-10-year group and the adults showed higher V_{ucms} in the challenging condition whereas the other two age groups (5-6 and 7-8 years) showed no such condition-specific differences. V_{ort} (joint angle variability affecting the position of the index finger) on the other hand, showed no interaction between condition and age although it was marginally larger in all age groups in the challenging

condition, with target errors being rather similar across conditions, indicating that the challenging condition had not affected end-effector consistency. The developmental trends for condition were similar for V_{ucm} and V_{ort} as both measures were highest in the 5-6-year-olds, decreasing in the 7-8-year-olds, plateauing in the 9-10-year-olds and further decreasing until adult level. Overall, the children made more errors than the adult participants. The results thus revealed general developmental changes in consistency and flexibility during middle childhood: the children's end-effector movements became more consistent while their movement execution became less flexible. Most notably, from the age of 9 years the children in our sample showed that they were able to exploit their DoF by showing more flexibility with increasing task demands.

Our question whether the use of flexibility was age-dependent was prompted by the results of previous studies in adults, who used additional flexibility when demanded by the situation (e.g., de Freitas et al., 2007; Dutta et al., 2013; Reisman et al., 2002; Yang et al., 2007). The results we found for our adult participants were in line with the findings by de Freitas et al. (2007): when the task became more challenging, V_{ucm} increased, while V_{ort} only marginally increased. Also, their end-effector consistency remained similar across conditions and was thus not affected by task difficulty. This underscores the suggested advantages of increased flexibility (c.f., Latash, 2000; Latash, 2012; Reisman et al., 2002). Like Freitas et al. (2007), we pose that increasing flexibility appears to facilitate motor performance under challenging conditions. As it were the older children (12 of the 15 9-10-year-olds) only that, similar to the adults, showed increased V_{ucm} without substantially increasing V_{ort} when challenged, we suggest that the ability to exploit more flexibility does not develop until the age of 9–10 years. Developing the ability to increase V_{ucm} without substantially increasing V_{ort} is important, because the increased employment of joint angle configurations reflects additional flexibility. It also shows that they tailored the flexibility in their motor behavior to changing task constraints (Adolph et al., 2015; Rachwani et al., 2017). Crucially, their movement execution became more flexible without their end-effector consistency being negatively affected, which, arguably, may even reflect an enhanced control strategy. That is, the employment of more joint angle combinations that do not affect task success might reduce the influence of perturbations that occur due to the uncertainty about the target location. In doing so, the 9 and 10-year-olds and the adults took advantage of the available motor abundance.

A secondary finding was the age-related change in the general level of flexibility and consistency, where, significantly, flexibility was higher in younger children, with the decline in V_{ucm} going hand in hand with a decrease in V_{ort} and errors. These developmental trends are in line with the trends we observed in our

earlier nonchallenging pointing task (Golenia et al., 2018). Also, the adult V_{ucm} and V_{ort} values are in line with those found in other studies (de Freitas et al., 2007; Tuitert et al., 2017; Yang et al., 2007), showing that the high V_{ucm} and V_{ort} values we recorded in the children are actually higher than those generally reported for adults. But what do these higher values in children reflect? Because the developmental trend for V_{ucm} and V_{ort} was alike, we need to consider both indices for a plausible interpretation of the developmental trend in flexibility we observed. As we suggested previously (Golenia et al., 2018), an increased V_{ort} in younger children may be related to changes in the general stability of their neuromotor system. Throughout middle childhood, the whole body is continuously changing, where, for example, body proportions such as length and mass fluctuate (Malina, Bouchard, & Bar-Or, 2004), postural control accompanying pointing movements develops (van der Heide, Otten, van Eykern, & Hadders-Algra, 2003), and neurological changes occur (Kandice Mah & Lee Ford-Jones, 2012). All these developmental dynamics may then result in a less stable system, thereby explaining the high V_{ort} . To compensate for this V_{ort} increase, V_{ucm} may need to be increased to counter the variability in joint angles that destabilizes the index-finger position (which has also been suggested in the literature; Black et al., 2007; Greve et al., 2015). As children grow older, both V_{ort} and V_{ucm} decrease, resulting in more consistent endpoint movements as well as a decreased flexibility in movement execution.

Although the condition-age interaction for V_{ucm} appears to reflect an enhanced control strategy, we should also consider alternative explanations given that the plateau for V_{ucm} recorded for the 7-8 and 9-10-year-olds in both conditions seems to question this interpretation. The absence of a V_{ucm} difference for these two age groups in the challenging condition may point to stagnation in motor development. To explore this alternative explanation, future studies could conduct a learning experiment similar to that used by Contreras-Vidal (2006) and King, Kagerer, Contreras-Vidal, Clark, 2009, and J. E. (2009) in which children are exposed to a visuomotor distortion, by which a conflict is created between the visual feedback of the hand position and the actual hand position. Mastering the task then implies having to learn a new mapping between what is seen and how to move. If 9-10-year-olds show more flexibility than younger peers, as reflected by an increase in V_{ucm} when learning this new mapping (c.f., Yang & Scholz, 2005), this may imply that the V_{ucm} increase in the older-aged children exhibited in the current study reflects an enhanced control strategy.

As to limitations, it needs mentioning that our study may have been confounded by using a single pointing distance for all age groups, which means that the target distance was not related to the lengths of the

participants' arms. With their arms being shorter, the task may accordingly have been more difficult for the younger children, which may have affected the results. However, in our earlier study (Golenia et al., 2018) we had scaled the target distance to the mean arm length of each age group and found similar age-specific effects. Also, consistency was rather high (VE not exceeding 3.5 mm and CE not exceeding 6 mm), which indicates that all children met the task demands and reached the target in most trials.

In summary, investigating the development of consistency and flexibility in pointing movements during middle childhood, we found that, in line with an earlier study of ours and other studies, in a group of 5 to 10-year-old children end-effector consistency increased and flexibility in movement execution (i.e., the variability in joint angle configurations) decreased with age. We confirmed that, if required by the situation, adults exploit their system's flexibility. Importantly, our results suggest that children are able to do so from the age of 9 years and not before.

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REFERENCES

- Adolph, K. E., Cole, W. G., & Vereijken, B. (2015). Intraindividual variability in the development of motor skills in childhood. In M. Diehl, K. Hooker, & M. Sliwinski (Eds.), *Handbook of Intra-individual variability across the lifespan* (pp. 59–83). New York: Routledge/Taylor & Francis Group.
- Adolph, K., & Robinson, S. R. (2015). Motor development. In R. M. Lerner, L. Liben, & U. Muller (Eds.), *Handbook of child psychology and developmental science: Vol. 2: Cognitive processes* (7th ed., pp. 114–157). New York: Wiley.
- Bakeman, R. (2005). Recommended effect size statistics for repeated measures designs. *Behavior Research Methods*, 37(3), 379–384. <https://doi.org/10.3758/BF03192707>
- Bard, C., Hay, L., & Fleury, M. (1990). Timing and accuracy of visually directed movements in children: Control of direction and amplitude components. *Journal of Experimental Child Psychology*, 50, 102–118. [https://doi.org/10.1016/0022-0965\(90\)90034-6](https://doi.org/10.1016/0022-0965(90)90034-6)
- Bernstein, N. (1967). *The coordination and regulation of movements*. Oxford: Pergamon Press.

Black, D. P., Smith, B. A., Wu, J., & Ulrich, B. D. (2007). Uncontrolled manifold analysis of segmental angle variability during walking: Preadolescents with and without Down syndrome. *Experimental Brain Research*, 183(4), 511–521. <https://doi.org/10.1007/s00221-007-1066-1>

Cohen, J. (1988). *Statistical power analyses for the behavioral sciences*, 2nd ed. Hillsdale: Erlbaum.

Contreras-Vidal, J. L. (2006). Development of forward models for hand localization and movement control in 6 to 10-year-old children. *Human Movement Science*, 25, 634–645. <https://doi.org/10.1016/j.humov.2006.07.006>

de Freitas, S. M. S. F., & Scholz, J. P. (2010). A comparison of methods for identifying the Jacobian for uncontrolled manifold variance analysis. *Journal of Biomechanics*, 43(4), 775–777. <https://doi.org/10.1016/j.jbiomech.2009.10.033>

de Freitas, S. M. S. F., Scholz, J. P., & Stehman, A. J. (2007). Effect of motor planning on use of motor abundance. *Neuroscience Letters*, 417(1), 66–71. <https://doi.org/10.1016/j.neulet.2007.02.037>

Domkin, D., Laczko, J., Djupsjöbacka, M., Jaric, S., & Latash, M. L. (2005). Joint angle variability in 3D bimanual pointing: Uncontrolled manifold analysis. *Experimental Brain Research*, 163, 44–57. <https://doi.org/10.1007/s00221-004-2137-1>

Dutta, G. G., Freitas, S. M. S. F., & Scholz, J. P. (2013). Diminished joint coordination with aging leads to more variable hand paths. *Human Movement Science*, 32(4), 768–784. <https://doi.org/10.1016/j.humov.2013.04.002>

Ekberg, T. L., Rosander, K., Von Hofsten, C., Olsson, U., Soska, K. C., & Adolph, K. E. (2013). Dynamic reaching in infants during binocular and monocular viewing. *Experimental Brain Research*, 229(1), 1–12. <https://doi.org/10.1007/s00221-013-3588-z>

Favilla, M. (2006). Reaching movements in children: Accuracy and reaction time development. *Experimental Brain Research*, 169, 122–125. <https://doi.org/10.1007/s00221-005-0291-8>

Ferrel, C., Bard, C., & Fleury, M. (2001). Coordination in childhood: Modifications of visuomotor representations in 6 to 11-year-old children. *Experimental Brain Research*, 138, 313–321. <https://doi.org/10.1007/s002210100697>

Gelfand, I. M., & Latash, M. L. (1998). On the problem of adequate language in motor control. *Motor Control*, 2, 306–313. <https://doi.org/10.1123/mcj.2.4.306>

Golenia, L., Schoemaker, M. M., Otten, E., Mouton, L. J., & Bongers, R. M. (2018). Development of reaching during mid-childhood from a developmental systems perspective. *PLoS ONE*, *13*(2), e0193463. <https://doi.org/10.1371/journal.pone.0193463>

Greve, C., Hortobágyi, T., & Bongers, R. M. (2015). Physical demand but not dexterity is associated with motor flexibility during rapid reaching in healthy young adults. *PloS One*, *10*(5), e0127017. <https://doi.org/10.1371/journal.pone.0127017>

Hay, L. (1979). Spatial-temporal Analysis of movements in children: Motor programs versus feedback in the development of reaching. *Journal of Motor Behavior*, *11*(3), 189–200. <https://doi.org/10.1093/pch/17.2.81>

Henderson, S., Sugden, D., & Barnett, A. (2007). *Movement assessment battery for children*, 2nd ed. Oxford: Pearson.

Kandice Mah, V., & Lee Ford-Jones, E. (2012). Spotlight on middle childhood: Rejuvenating the “forgotten years”. *Paediatrics and Child Health*, *17*(2), 81–83. <https://doi.org/10.1093/pch/17.2.81>

King, B. R., Kagerer, F. A., Contreras-Vidal, J. L., & Clark, J. E. (2009). Evidence for multisensory spatial-to-motor transformations in aiming movements of children. *Journal of Neurophysiology*, *101*(1), 315–322. <https://doi.org/10.1152/jn.90781.2008>

Krishnamoorthy, V., Scholz, J. P., & Latash, M. L. (2007). The use of flexible arm muscle synergies to perform an isometric stabilization task. *Clinical Neurophysiology*, *118*(3), 525–537. <https://doi.org/10.1016/j.pestbp.2011.02.012>

Latash, M. (2000). There is no motor redundancy in human movements. *There is Motor Abundance. Motor Control*, *4*, 259–260. <https://doi.org/10.1123/mcj.4.3.259>

Latash, M. L. (2012). The bliss (not the problem) of motor abundance (not redundancy). *Experimental Brain Research*, *217*(1), 1–5. <https://doi.org/10.1007/s00221-012-3000-4>

Latash, M. L., Scholz, J. P., & Schöner, G. (2007). Toward a new theory of motor synergies. *Motor Control*, *11*, 276–308. <https://doi.org/10.1123/mcj.11.3.276>

Lee, M., Farshchiansadegh, A., & Ranganathan, R. (2017). Children show limited movement repertoire when learning a novel motor skill. *Developmental Science*, e12614. [10.1111/desc.12614](https://doi.org/10.1111/desc.12614)

Malina, R. M., Bouchard, C., & Bar-Or, O. (2004). *Growth, maturation, and physical activity*, 2nd ed. Champaign, Ill: Human Kinetics. (Chapter 3).

Rachwani, J., Soska, K. C., & Adolph, K. E. (2017). Behavioral flexibility in learning to sit. *Developmental Psychobiology*, *59*(8), 1–12. <https://doi.org/10.1002/dev.21571>

Reisman, D. S., Scholz, J. P., & Schöner, G. (2002). Coordination underlying the control of whole body momentum during sit-to-stand. *Gait and Posture*, *15*(1), 45–55. [https://doi.org/10.1016/S0966-6362\(01\)00158-8](https://doi.org/10.1016/S0966-6362(01)00158-8)

Scholz, J. P., Reisman, D., & Schöner, G. (2001). Effects of varying task constraints on solutions to joint coordination in a sit-to-stand task. *Experimental Brain Research*, *141*(4), 485–500. <https://doi.org/10.1007/s002210100878>

Scholz, J. P., & Schöner, G. (1999). The uncontrolled manifold concept: Identifying control variables for a functional task. *Experimental Brain Research*, *126*, 289–306. <https://doi.org/10.1007/s002210050738>

Tuitert, I., Bootsma, R. J., Schoemaker, M. M., Otten, E., Mouton, L. J., & Bongers, R. M. (2017). Does practicing a wide range of joint angle configurations lead to higher flexibility in a manual obstacle-avoidance target-pointing task? *PLoS ONE*. <https://doi.org/10.1371/journal.pone.0181041>

Tuitert, I., Valk, T. A., Otten, E., Golenia, L., & Bongers, R. M. (2018). Comparing different methods to create a linear model for the uncontrolled manifold method analysis. *Motor Control*.

Valk, T. A., Mouton, L. J., & Bongers, R. M. (2016). Joint-angle coordination patterns ensure stabilization of a body-plus-tool system in point-to-point movements with a rod. *Frontiers in Psychology*, *7*, 826. <https://doi.org/10.3389/fpsyg.2016.00826>

van Andel, C. J., Wolterbeek, N., Doorenbosch, C. A. M., Veeger, D. H. E. J., & Harlaar, J. (2008). Complete 3D kinematics of upper extremity functional tasks. *Gait & Posture*, *27*(1), 120–127. <https://doi.org/10.1016/j.gaitpost.2007.03.002>

Van Der Steen, M. C., & Bongers, R. M. (2011). Joint angle variability and co-variation in a reaching with a rod task. *Experimental Brain Research*, *208*, 411–422. <https://doi.org/10.1007/s00221-010-2493-y>

van der Heide, J. C., Otten, B., van Eykern, L. A., & Hadders-Algra, M. (2003). Development of postural adjustments during reaching in sitting children. *Experimental Brain Research*, *151*, 32–45. <https://doi.org/10.1007/s00221-003-1451-3>

Vereijken, B. (2010). The complexity of childhood development: Variability in perspective. *Physical Therapy, 90*, 1850–1859. <https://doi.org/10.2522/ptj.20100019>

Verrel, J. (2010). Distributional properties and variance-stabilizing transformations for measures of uncontrolled manifold effects. *Journal of Neuroscience Methods, 191*(2), 166–170. <https://doi.org/10.1016/j.jneumeth.2010.06.016>

Verrel, J. (2011). A formal and data-based comparison of measures of motor-equivalent covariation. *Journal of Neuroscience Methods, 200*(2), 199–206. <https://doi.org/10.1016/j.jneumeth.2011.04.006>

Wilson, P. H., & Hyde, C. (2013). The development of rapid online control in children aged 6–12years: Reaching performance. *Human Movement Science, 32*(5), 1138–1150. <https://doi.org/10.1016/j.humov.2013.02.008>

Wu, G., Van Der Helm, F. C. T., Veeger, H. E. J., Makhsous, M., Van Roy, P., Anglin, C., & Buchholz, B. (2005). ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion Part II: Shoulder, elbow, wrist and hand. *Journal of Biomechanics, 38*(5), 981–992. <https://doi.org/10.1016/j.jbiomech.2004.05.042>

Yang, J. F., & Scholz, J. P. (2005). Learning a throwing task is associated with differential changes in the use of motor abundance. *Experimental Brain Research, 163*, 137–158.

Yang, J. F., Scholz, J. P., & Latash, M. L. (2007). The role of kinematic redundancy in adaptation of reaching. *Experimental Brain Research, 176*, 54–69. <https://doi.org/10.1007/s00221-006-0602-8>