Protracted development of visuo-proprioceptive integration for uni- and bimanual motor coordination

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ABSTRACT

Human motor control relies on spatial integration of information from multiple sensory modalities. During movement, both vision and proprioception signal posture and location of body parts. Currently, understanding of the developmental trajectory of the interplay between sensory processing and motor control is limited. Most previous studies have either investigated selective age groups, or focused on isolated motor functions.

Here, we assessed, within-participant, three functional aspects of visual and proprioceptive integration for motor control across seven experimental tasks in a large cross-sectional sample of 4-12 year-old children: symmetric bimanual coordination, symmetric unimanual coordination with an externally produced signal, and the strategic, selective use of visual information for asymmetric bimanual coordination. All experiments used a hand circling task during which hand position could be available or hidden, allowing direct performance comparison across the entire study.

Performance for all investigated functional aspects exhibited protracted development, evident in gradual average improvement over several years of age, albeit with different developmental trajectories for each function. Symmetrical bimanual coordination was efficient already at age 4, both with and without visual hand feedback. Symmetrical unimanual coordination with either a visual or a passive-proprioceptive signal continually improved until age 9. Asymmetric bimanual coordination was ineffective until age 9, and improved until age 12. Critically, performance was related within individuals between symmetric bi- and unimanual coordination, as well as between symmetric unimanual and asymmetric bimanual coordination, suggesting that the development of these motor functions is interdependent and serial.

KEYWORDS

Proprioception; feedback; multisensory integration; sensorimotor processing; vision; Lissajous

1 | INTRODUCTION

Motor control, the ability to generate accurate movement, is a central developmental challenge during ontogeny. Motor milestones are tightly linked to cognitive development and social skills. Mastering a new motor skill often sets the stage for learning further novel skills and changes the way the child interacts with its environment (Adolph & Franchak, 2017; Adolph & Hoch, 2019; Hamilton, Southgate, & Hill, 2016). Development protracts over almost two decades before humans possess the full set of abilities for the exquisite and highly complex motor behavior of adults. Given this complexity, it is an ongoing effort to comprehensively characterize motor development (Adolph, Hoch, & Cole, 2018).

The long protraction of development in motor control is mirrored by similar developmental time lines in sensory processing. For instance, adult-like integration of multisensory input is usually not observable until at least 8-10 years of age (for review, see, Burr & Gori, 2012; Gori, 2015), and proprioceptive processing appears to undergo changes until at least the age of 15 (Assaiante, Barlaam, Cignetti, & Vaugoyeau, 2014). Current models of motor control posit that motor planning and execution indispensably rely on sensory information about body and environment. This tight interplay of sensory and motor function raises the question how tightly development in one area is linked with that in the other area. Most previous studies have focused on one or few sensorimotor functions, have used a diverse range of methods and paradigms, and have often studied only a narrow age range, so that our understanding of motor control development and its relationship to sensory development is fractured.

1.1 | Study aims and rationale

Here, we assessed uni- and bimanual motor control, and their dependence on sensory information within a common experimental framework in 4-12 year-old children. We addressed three related functional aspects of motor control: actively coordinating two body parts, synchronizing a single body part with an external sensory signal, and segregating sensory information when only one of several sensory channels provides appropriate information for coordination. We implemented all aspects in an established uni- and bimanual circling paradigm, in which participants had to coordinate one or both hands while visual and proprioceptive information was, or was not, available. This paradigm enabled us to directly compare different motor tasks and their reliance on sensory information within participants as well as cross-sectionally over age.

1.2 | Bimanual coordination

The first aspect of our study pertains to coordinating two body parts, namely the two hands. In this task, participants might achieve coordination simply by dispatching parallel movement commands to the two limbs, rather than relying on sensory feedback. Indeed, the motor system prefers symmetrical over other types of bimanual movements, which usually require concurrent activation of homologous muscles (e.g. Brandes, Rezvani, & Heed, 2017; Kelso, Scholz, & Schöner, 1986; Spencer, Ivry, Cattaert, & Semjen, 2005). Symmetry is usually defined with respect to the body midline; for the example of circling, one hand turns clockwise, the other anti-clockwise (Mechsner et al., 2001). By convention, symmetry is referred to as in-phase, or 0°, coordination. Many studies have contrasted symmetrical with parallel movements, referred to as anti-phase, or 180°, coordination. In circling, parallel coordination means that both hands circle in the same direction, for instance clockwise. Performance of in-phase movements is regularly better than that of anti-phase movements (for review, see Gooijers & Swinnen, 2014). These findings were initially interpreted to indicate that bimanual coordination relies purely on synchronized motor commands (Cohen, 1971; Kelso, 1984; Riek & Woolley, 2005).

However, later studies also demonstrated a role of perceptual factors (Brandes, Rezvani, & Heed, 2016; Heed & Röder, 2014; Oliveira & Ivry, 2008; Swinnen et al., 1998; Temprado, Swinnen, Carson, Tourment, & Laurent, 2003; for review, see Shea, Buchanan, & Kennedy, 2016). For instance, when the index fingers are wiggled with one hand turned up, and the other down, symmetrical movements are still performed more successfully than parallel ones, although they now require concurrent activation of non-homologous muscles (Brandes et al., 2017; Heed & Röder, 2014; Mechsner et al., 2001).

Here, we addressed the role of visual information in bimanual coordination across development, using the bimanual circling approach. Preference for in-phase coordination in bimanual circling tasks has been observed beginning at age 5 (Robertson, 2001), with performance improving up to adulthood (de Boer, Peper, & Beek, 2012). Continuing from these findings, we asked whether bimanual coordination is more successful when vision of the hand movement is available than when it is not.

1.3 | Unimanual coordination

Bimanual movement tasks require that participants coordinate two body parts. Thus, at least some information, such as muscle commands, is self-produced and can be internally coordinated. The second aspect of motor control of our study pertains to coordinating a single body part with an externally produced signal. In everyday life we coordinate, for instance, dance steps with a partner, or the bow of the violin with the stroke of the orchestra's conductor. These contexts do not afford

internally produced signals to achieve coordination. Still, humans coordinate unimanual movements very well with external signals of different modalities such as vision (e.g. Buekers, Bogaerts, Swinnen, & Helsen, 2000; Hove, Spivey, & Krumhansl, 2010), proprioception (e.g. Kelso, Fink, DeLaplain, & Carson, 2001; Wing, Doumas, & Welchman, 2010), and audition (e.g. Kelso et al., 2001; Repp & Steinman, 2010). This observation has led to the suggestion that movement coordination is perhaps entirely perceptually driven (Bingham, 2004); in this view, bimanual coordination is but a subcategory of a more general ability to coordinate motorically by means of perception. Under this assumption, one might expect that uni- and bimanual coordination show similar developmental trajectories. If, in contrast, bimanual coordination relied predominately on motor synchronization, then one might expect different developmental trajectories for the two tasks.

Many studies that have investigated the integration of sensory information across sensory modalities (for review, see, Burr & Gori, 2012; Gori, 2015) or the use of sensory information for motor control (e.g. Kagerer & Clark, 2014; P. H. Wilson & Hyde, 2013) have uncovered extended development up to the age of at least 10 years. These previous results let us expect that unimanual coordination, too, might develop until at least this age. To test whether these potential trajectories differ across sensory modalities, we assessed children's ability to coordinate their hand with an externally-produced visual or passive proprioceptive signal.

1.4 | Sensory selectivity in motor control

The first two aspects of our study both addressed motor control in which participants perform symmetrical coordination. The third aspect of our study pertains to situations in which movement is not symmetrical; such coordination is harder, and can even be impossible to perform (Kelso, 1984). Critically, transforming visual information to make it appear symmetrical can vastly improve asymmetrical coordination performance in adults. For instance, circling the hands with a 90° phase difference, that is, with a relative delay of a quarter circle, is much easier when the visual feedback of the lagging hand is rotated forward by 90°, making the two visual signals appear in-phase, than when hand position is presented with its true orientation (Tomatsu & Ohtsuki, 2005). Non-symmetric movement can also improve when the positions of the two hands are merged as x and y coordinates of a single cursor feedback, referred to as Lissajous display. For instance, a 90° phase difference of wrist flexion and extension movements with the two hands results in a perfect circle of the display cursor (Chiou & Chang, 2016; Kovacs, Buchanan, & Shea, 2009). These visualizations presumably support motor coordination by making the motor constraints perceptually identifiable or salient (Bingham, 2004).

Like unimanual coordination, these kind of tasks require coordination with a signal that does not, at least not directly, reflect limb position. However, differing from unimanual coordination, participants must ignore non-visual information. This is because only visual information contains the correct phase information, whereas proprioceptive information for the two hands differs from moment to moment by task design. Consequently, it is detrimental to the task if participants use multisensory integration strategies that would usually reduce sensory noise. Furthermore, equivalent motor signals for the two hands, too, must be produced non-symmetrically, in contrast to performing regular, symmetrical bimanual coordination.

Out-of-phase paradigms have been realized with the circling paradigm we employed in our study. For instance, adult participants had to turn two handles that were connected to cogwheels which translated one circle of the left hand into one-fourth revolution of a left visual marker, but transformed one circle of the right hand into one-third of a circle of a right visual marker (Mechsner et al., 2001). Thus, the two visual markers moved in synchrony when participants circled the left hand four times while circling the right hand three times. Such a 4:3 pattern is impossible for participants to perform without vision, or when visual markers are moved at the true speed of each respective hand. In contrast, adults performed the 4:3 coordination successfully with the transformed visual feedback after just a few minutes of practice. Notably, performance in such tasks breaks down when the transformed visual feedback is removed. This finding indicates that participants do not typically undergo motor learning in these contexts (Sigrist, Rauter, Riener, & Wolf, 2013). However, learning can take place when, during training, visual feedback is only partially removed, for instance by starting each trial with feedback available, and removing it towards the trial's end. With this paradigm, participants presumably focus more on proprioceptive signals, enabling them to acquire an internal representation of the coordination pattern (Buchanan & Wang, 2012; Kovacs & Shea, 2011).

It is currently unknown how the ability selective use of visual information develops. Children aged 8-10 successfully performed 2:1 wrist movements under visual guidance of a Lissajous display, even if less efficiently than adults (Leinen et al., 2016). However, a 2:1 rhythm is comparably easy to perform, as the two hands synchronize at the end of every two rounds of the faster hand. Here, we tested a more difficult 2:3 coordination task, as well as its retention, and we tested a larger age range.

In sum, the present study addressed, in a cross-sectional sample of 4-12 year-old children, visual and proprioceptive coordination of active bimanual control, unimanual coordination with an external visual or passive-proprioceptive guiding signal, and the ability to focus entirely on visual information while ignoring proprioception, to perform otherwise impossible movements. This extensive task set allows direct, within-participant comparison of the respective motor control functions involved in these functions.

2 | MATERIALS AND METHODS

2.1 | Participants and ethical approval

We enrolled children who signed up in diverse public science popularization events, school visits to our lab, or through flyers, until we had recruited at least 12 children of each age from 4-12 years that met our inclusion criteria. Of 138 tested children, 120 were included in the final sample (52 girls, 68 boys). Additionally, we enrolled a control group of 12 adults (6 female, mean age: 27.2 years; s.d.: 2.2 years). All included participants had normal or corrected-to-normal vision and were free of any known neurological, visual and tactile impairments and disorders. Furthermore, children had to have been born in regular term (> 37th gestational week), score between 70 and 130 on a short IQ test, and pass screening for attentional disorders, learning disabilities and delayed psychomotor acquisition (see supplementary information for details). Finally, four four-year-olds were unable to follow the task instructions or did not want to complete the experiment. We replaced one adult who exhibited unusual difficulty in handling the experimental setup and exhibited accuracy outside 2 s.d. of the adult sample in some experimental tasks.

We conducted an additional spatial memory span task, on which we report in the Supplementary Information.

The experiment was approved by the local ethics committee of Bielefeld University and was conducted in accordance with the Declaration of Helsinki. Adult participants and children's parents gave written informed consent prior to the experiment. Children gave oral consent after they had received all information prior to the experiment. Children received a small gift of about 10 € value for their participation. Participants of the adult control group received course credit.

2.2 | Experimental tasks

We devised seven tasks in which participants had to move one or both hands in circles. Together, they address the three aspects of motor control we laid out in the introduction. The task setup mimicked turning wheels, that is, participants could move two handles in circles. We tested how well they could coordinate phase and speed of these circular movements.

2.2.1 | Bimanual motor coordination

Task 1 – Bimanual 1:1 Coordination Without Vision (Biman-NoVis): Participants had to move the two unseen hands symmetrically in six trials of 10 s duration each.

Task 2 – Bimanual 1:1 Coordination With Vision (Biman-Vis): Participants had to move the two hands symmetrically while receiving feedback about hand position in form of cursors on the screen above their hands. They performed six trials of 10 s duration each.

2.2.2 | Unimanual motor coordination

Task 3 – Match the Cursor: Unimanual Visual Coordination (Uniman-Vis)**:** Participants had to coordinate their unimanual movement with an externally controlled visual signal. They saw a visual cursor moving along the circular trajectory as the non-dominant hand in Biman-Vis. However, here the cursor was computer-controlled and the non-dominant hand rested on the lap. Participants had to symmetrically match the cursor position with their dominant hand. The position of their own hand, too, was visualized as a cursor. Thus, the task appeared visually identical to Biman-Vis. There were six trials of 20 s duration each.

Task 4: Match the Other Hand: Unimanual Proprioceptive Coordination (Uniman-Prop)**:** The robot passively moved the participant's non-dominant hand. Participants had to symmetrically match the passive movement of their non-dominant hand with their dominant hand. They were instructed to relax the passively guided arm and let the robot lead them without actively supporting the movement. No visual feedback of either hand's position was available. There were six trials of 20 s duration each.

2.2.3 | Sensory selectivity in bimanual motor coordination

Task 5 – 2:3 Coordination With Veridical Hand Position Feedback (2:3-NoTransform): Participants had to concurrently perform three circles with their dominant, and two with their non-dominant hand. Hand position was indicated by visual cursors, as in Biman-Vis and Uniman-Vis. Accordingly, if the task was performed correctly, the two cursors did not move symmetrically. This kind of task is very difficult even for adults and constituted the baseline 2:3 coordination task. Participants performed six trials of 20 s duration each.

Task 6 – 2:3 Coordination With Transformed Feedback (2:3-Transform): Participants had to perform 2:3 coordination as in 2:3-NoTransform. However, cursor position did not reflect the hands' veridical location, but was transformed to appear symmetrical: For the dominant hand, the cursor completed one full circle on the display while participants performed 3 circles with their hand. For the non-dominant hand, the cursor completed one circle while the hand circled twice. Accordingly, participants could correctly perform the task by maintaining a symmetrical visual feedback on the display. We explicitly explained this task feature to participants. They performed three practice trials and 3 x 6 experimental trials of 20 s duration each. The higher trial number was introduced to allow learning, which we tested in 2:3-Retention.

Task 7: 2:3 Coordination – Recall Without Feedback (2:3-Retention): Participants had to perform three circles with their dominant, and two with their non-dominant hand. Each trial began with transformed visual feedback just like 2:3-Transform. However, after 5 s, visual feedback was removed. Participants had to continue the 2:3 coordination, allowing us to assess their ability to perform the task feedback after having previously learned 2:3-Transform. Neither children nor adults exhibited any retention in this task, and we therefore report its results in the supplementary information.

2.3 | Task setup and procedure

All tasks were implemented on the KINARM End-Point-Lab (BKIN Technologies Ltd, Kingston, Ontario, Canada), a robot that serves as a hand manipulandum for movements in a 2D horizontal plane in front of the user. Participants grab two handles whose position is continually measured at a sampling rate of 1000 Hz. Mobility of the handles can be constrained by the robot. A monitor projects from above onto a mirror placed above the hands, so that visual information displayed on the mirror appears to be in the same plane as the hands.

Depending on their body height, participants were seated on a height-adjustable chair, or stood on an adjustable platform, so that their elbows were angled at 90°. Most children aged 7 and older were tall enough to be seated.

The overall setup was similar across all tasks. Hand movement was restricted via the Kinarm to movement along two circles of 10 cm diameter, one for each hand. The two circles were visualized in a common color and were separated by a straight vertical line that was styled as a fence. In its middle was a white fixation square. The circle centers were 10 cm away from the fixation point. On each trial, the hands started at the innermost circle positions, which were marked as blue, 1 cm diameter dots on the circles. We gave the tasks a child-friendly design and story line to support children's motivation to complete the experiment. Each child chose one of several stimulus themes that each featured four 2 cm diameter characters to represent hand position (see Fig. 1).

An opaque apron attached to the participant's neck prevented vision of the arms, and the display mirror was opaque, so that participants could not see their hands. This setup allowed us to fully control visual feedback about hand position via the screen.

In all tasks, a trial began with participants first moving their hand(s) to the starting position(s) (Fig. 1, blue dots). A beep of 150ms duration instructed them to begin circling in the inward direction until a beep of 300ms duration signaled the end of the trial. The eyes had to fixate the fixation square.

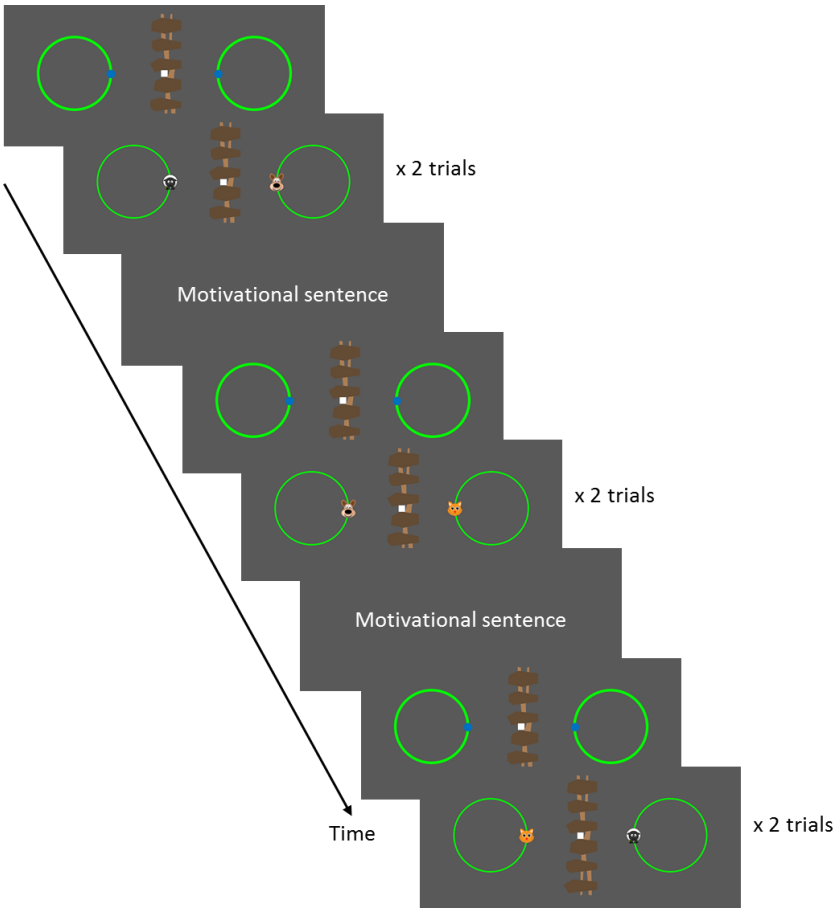

Fig. 1

General layout of the circling tasks. The display was mounted above the hands, and visual stimuli appeared as if they were at the level of the hands. During trials, movement was restricted to 10 cm diameter circles that were displayed on the screen. When the participant moved to the blue starting positions, a beep indicated the beginning of the trial. Participant then made continuous circling movements until a beep indicated the trial's end. Hand position was indicated by small characters, here a fox and a sheep. The task was framed using these characters; for instance, one animal was to try and catch the other. Every two trials, short motivational sentences were displayed, and the experimenter reminded the participant to fixate the white central square.

For all tasks, participants performed three practice trials during which we gave oral feedback on whether task performance complied with the instructions. If necessary, we added up to two additional practice trials. During experimental trials, we gave no feedback, unless if the direction of rotation was incorrect; in this case, the trial was repeated. The experimenter watched whether the child kept fixation; if not, the respective trial was repeated.

After every two trials, we displayed short sentences on the screen for 5 s to frame the experiment as a story and support children's motivation. These sentences playfully reflected the task instruction. For

instance, one sentence of Biman-Vis was *"While the dog is away, the cat steals its food. The dog runs after the cat"*; 2:3-NoTransform included *"The sheep and the dog are racing; but the dog is way faster"*, and 2:3-Transform and 2:3-Retention included *"Remember that the animals want to run together"*. We read the sentences aloud for children who could not yet read.

Participants were first acquainted with the Kinarm by playing a short game. They then performed the seven circling tasks and the memory span task in the order illustrated in Table 1. Participants always started with the bimanual coordination tasks, Biman-NoVis and Biman-Vis. We always devised these two tasks in this order because we wanted to avoid that performance without vision would benefit from experience of the visual task if it were done first. Then, UniMan-Vis, Uniman-Prop, 2:3-NoTransform and the memory span task were conducted in randomized order by participants drawing pieces of paper in an envelope. The session ended with 2:3-Transform and 2:3-Retention. 2:3-Transform had to be conducted after 2:3-NoTransform because it potentially involved learning. In turn, 2:3-Retention tested learning of 2:3-Transform and, thus, had to be done last. All tasks were 3 and 5min long, except for 2:3-Transform, which lasted 12 min. Participants rested between tasks, and after every 6 trials in 2:3 Transform.

Not all participants performed all tasks. Table 1 lists the number of individuals per year of age and task. We lost some data due to equipment failure; this was especially prevalent for Uniman-Prop; thus, the low number of young participants is not due to younger children being unable to perform the task. However, some children, especially at younger ages, found it difficult to maintain motivation and to stay focused; some young children did not understand all tasks, especially the 2:3 tasks; thus, for those tasks, low participant numbers are due to task difficulty, not technical problems.

Table 1. Participant numbers for all tasks. Low participant numbers in Task 4 were due to temporary equipment failure that selectively affected this task. Low participant numbers in Tasks 5-7 were due to task difficulty for the younger children. The spatial span test is a standard task available with the Kinarm device; it is designed for adults, and many younger children could not reach all positions involved in the task. We therefore did not test children who were too small for this task.

Age Group **Number of included participants**	**4 yo** **n = 14**	**5 yo** **n = 12**	**6 yo** **n = 12**	**7 yo** **n = 12**	**8 yo** **n = 12**	**9 yo** **n = 16**	**10 yo** **n = 18**	**11 yo** **n = 12**	**12 yo** **n = 12**	**Adults** **n = 12**
Control task: **Spatial Span**	1	7	11	11	12	15	18	12	12	12
Task 1 – Bimanual 1:1 Coordination Without Vision – Biman-NoVis	14	12	12	12	12	16	18	12	12	12
Task 2 – Bimanual 1:1 Coordination With Vision – Biman-Vis	14	12	12	12	12	16	18	12	12	12
Task 3 – Match the Cursor: Unimanual Visual Coordination – Uniman-Vis	14	12	12	12	11	16	18	12	12	12
Task 4 – Match the Other Hand: Unimanual Proprioceptive Coordination – Uniman-Prop	1	2	3	5	4	7	6	12	12	12
Task 5 – 2:3 Coordination With Veridical Hand Position Feedback – 2:3-NoTransform	6	3	11	12	11	16	18	12	12	12
Task 6 – 2:3 Coordination With Transformed Feedback – 2:3-Transform	5	3	11	12	12	16	18	12	12	12
Task 7 – 2:3 Coordination – Recall Without Feedback – 2:3-Retention	3	1	7	11	11	16	17	12	12	12

2.4 | Data processing and analysis

We analyzed data in Matlab (version: R2015aSP1). Each hand's position time series was filtered using a low pass Butterworth filter with a cut-off frequency of 10 Hz. We extracted three measures: signed and unsigned phase difference, and percentage of adequate coordination.

Signed and unsigned phase difference. We coded individual positions as the angle between the circles' innermost position (which was also the starting position) and location on the circle along movement direction. Thus, when the hands were at the lowest position, their phase angle was 90°, at the outermost position it was 180° etc. Because participants performed continuously for an extended duration, they performed several circles. In the bimanual tasks, we computed the phase angle of the dominant minus the non-dominant hand. In the unimanual tasks, we computed the phase angle difference between the moving hand and the position of the leading signal, that is, the cursor or the passively moved hand. In the 2:3 tasks we transformed each hand's position to the transformed cursor position. This involved dividing the dominant hand's phase angle by 3, and the non-dominant hand's phase angle by 2. These two transformed locations would be in perfect phase if participants performed the 2:3 task correctly. We, thus, report the difference between transformed phase angles for these tasks.

We analyzed unsigned and signed error. Signed error is the absolute phase angle difference between the two entities that had to be coordinated – the two hands in bimanual tasks; the visual cursor or the passively guided hand and the active hand in unimanual tasks, and the two transformed locations in the 2:3 tasks. For any given sampling point, a positive (negative) error indicates that the dominant/active hand leads (lags) the other hand or cursor. Because the phase difference is unsigned, both leading and lagging increase variable error in the same manner. In addition, we report the average signed error which signifies how much the dominant hand leads or lags on average; here, positive and negative error average out.

Percentage of adequate coordination. For comparison with some previous studies, we report adequate performance as a maximal deviation of +/-30° from the correct phase difference as an additional measure in the supplementary information (Mechsner et al., 2001; Mechsner, Stenneken, Cole, Aschersleben, & Prinz, 2007). This measure is similar to the proportion of time-on-task used by some authors (e.g. Bingham, Snapp-Childs, & Zhu, 2018), and renders comparable conclusions to those obtained with raw angle measures (Brandes et al., 2017).

Analysis strategy. We separately analyzed Tasks 1-4 (symmetrical tasks) and 5-7 (2:3 tasks). To assess changes in performance across development, we computed two models for each of the two sets of

tasks: one in which age in months was used as a continuous predictor, and one in which we contrasted age groups, pooled in years. In a second type of analysis we aimed to assess whether there were developmental dependencies across tasks. We compared performance between each pair of tasks while partialing out age to eliminate trivial correlation due to general improvement over age. Adults were only included in the analysis contrasting age groups, but not in the analysis with continuous age in months, nor in the correlations.

Models of unsigned difference with a continuous age variable. We statistically analyzed data in R (R Core Team, 2018; R: 3.5.1; R Studio: 1.1.456). We implemented multilevel Bayesian modeling with the R package *brms* (Bürkner, 2017). The dependent variable was the averaged phase angle difference in degrees per full circle of the dominant hand, rendering multiple observations per subject in the different experimental tasks, that is, completed circles within trial and multiple trials per subject. This analysis strategy captured performance variability within trials, rather than averaging together entire 10 or 20 s chunks into a single measurement value, while keeping model fitting computationally tractable. The independent predictors comprised the within-subject, categorical variable Task (Task 1-4: Biman-NoVis, Biman-Vis, Uniman-Vis and Uniman-Prop; Task 5-7: 2:3-NoTransform, 2:3-Transform and 2:3-Retention), the between-subject, continuous variable Age (in months), and the interaction between Task and Age. The model was defined as: Phase_Difference ~ Task * Age + (1|subject) + (1|trial), thus allowing random effects per subject and trial. To evaluate all contrasts of interests, the model was run with different experimental tasks as reference, and defining, for each model, treatment-coded contrasts of the respective baseline task with each other task. Because Bayesian model fitting relies on random sampling, parameter estimates will vary slightly between models; however, all results were numerically consistent, with minimal deviation, across equivalent models.

Models of unsigned difference with age groups. In these models, one for Tasks 1-4 and one for Tasks 5-7, the predictor Age was grouped by year as a categorical variable. The model was defined similarly to the previous models as: Phase_Difference ~ Task * Group + (1|subject) + (1|trial). We used these models to test at which age (in years) children performed similarly as adults, and to contrast performance between Tasks within a given age group.

Models of signed difference with age coded as continuous and categorical variable. We also fitted the four models described so far with signed phase angle difference between the two hands as dependent variable.

All described models were fitted using a Gaussian likelihood and the *brms* package default weakly-informative, improper, flat priors for population-level ("fixed") effects. The estimation of parameters' posterior distribution were obtained by Hamiltonian Monte-Carlo sampling with 4 chains, 1,000

sample warmup, and 11,000 iterations, and checked visually for convergence (high ESS and Rhat ≈ 1). For each main effect and interaction, we report the estimate of the mean and its 95% high-density interval (HDI), that is, the interval that covers 95% of the posterior distribution. We used the R package sjstats (Lüdecke, 2018) for inference on the presence of statistical effects, testing for each factor whether the HDI excluded a region of practical equivalence (ROPE) of effect sizes of 0.1 around 0 (Kruschke, 2011, 2018). This approach is conservative, because it requires not only that the HDI exclude 0, but in addition that no overlap exist with the ROPE interval (Kruschke, 2011). For models with a continuous predictor Age, we standardized the posterior distribution of this covariate (and respective interactions) by multiplying the covariate and respective interaction estimates (and their respective HDIs) by the standard deviation of subjects' age.

Relationship between tasks beyond age. We correlated unsigned phase angle between pairs of tasks, but removed the effect of age using Bayesian partial correlations as implemented in the R package BayesMed (Wetzels & Wagenmakers, 2012) using a default Jeffrey's-Zellner-Siow prior set-up (Nuijten, Wetzels, Matzke, Dolan, & Wagenmakers, 2015). This analysis strategy ensured that any relationships revealed by correlation analysis cannot simply be due to unspecific improvement across all tasks with age.

3 | RESULTS

3.1 | Bimanual motor coordination

3.1.1 | Unsigned phase difference

3.1.1.1 | Unsigned phase difference between the hands across all ages

We assessed the variability of children's coordination performance in a model that predicted the unsigned phase difference between the two hands with respect to the four bimanual and unimanual coordination tasks, and with respect to participants' age. We first describe the effects of age in the two bimanual tasks here, and return to the unimanual tasks in section 3.2.1.1. Figure 2 shows that the performance in both Biman-NoVis and Biman-Vis improved with Age (left panel, dark and light red symbols). In the model, both slope coefficients were negative and different from 0 (Biman-NoVis: β_{Age} = -8.8, $HDI_{95\%}$ = [-10.9; -6.7]; Biman-Vis: β_{Age} = -7.6, $HDI_{95\%}$ = [-9.7; -5.8]). These negative slope values indicate that variability between the hands decreased by the respective amount of degrees with each standardized age unit of 30.3 months. The contrast between the two bimanual tasks intercept and the Task*Age interaction, reflecting differences of the slopes across tasks, were not credibly different from 0 (see Table 2 for a summary of all model estimates), thus indicating that the performance in the two bimanual tasks did not differ.

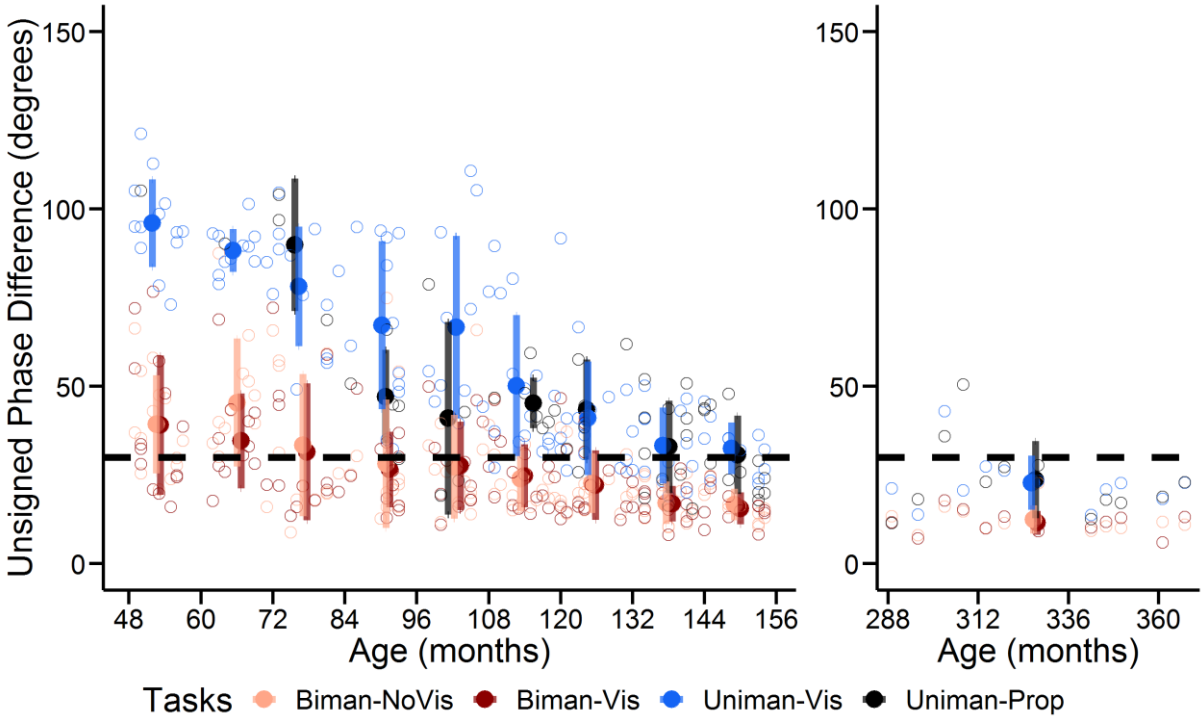

Fig. 2.

Unsigned phase difference between the two hands in bimanual Tasks 1 and 2 (dark and light red) and in unimanual Tasks 3 and 4 (blue and black) for children (left panel) and adults (right panel). The dashed lines represent the 30° threshold under which we considered subjects to perform well. Coloured circles represent the mean for each age group; bars show the s.d. Fewer than half of the 4-8 year-old participants performed Task 4 (Uniman-Prop; black), the means are thus likely to be non-representative (means in Uniman-Prop are not shown for 4- to 5-year-old children, because n ≤ 2).

Table 2. Beta Estimates reflecting the comparison between Tasks 1 to 4. Negative β Estimates indicate that performance was better with age (smaller variability for each standardized unit of Age of 30.3 months). For Task, negative β Estimates indicate that Intercept was higher in the reference task (first one in each line). Credible differences are indicated in bold and italic (HDI outside [-4.1; 4.1]). ESS stands for the Effective Sample Size as calculated during Bayesian model fitting. The Lower and Upper Confidence Interval (CI) values constitute the 95% High Density Interval (HDI).

Effect	Contrasts	β Estimate	Lower CI	Upper CI	ESS
Age	***Biman-NoVis***	***-8.8***	***-10.9***	***-6.7***	***4297***
	Biman-Vis	***-7.6***	***-9.7***	***-5.8***	***4016***
	Uniman-Vis	***-21.8***	***-23.6***	***-19.7***	***3399***
	Uniman-Prop	***-19.4***	***-21.8***	***-17.0***	***3589***
Task	Biman-NoVis vs. Biman-Vis	-5.0	-9.3	-0.7	19121
	Uniman-Vis vs. Biman-NoVis	***-75.3***	***-79.2***	***-71.4***	***22854***
	Uniman-Vis vs. Biman-Vis	***-80.3***	***-84.0***	***-76.6***	***23103***
	Uniman-Vis vs. Uniman-Prop	***-12.1***	***-18.2***	***-6.1***	***22181***

	Uniman-Prop vs. Biman-NoVis	***-63.2***	***-69.5***	***-56.9***	***12026***
	Uniman-Prop vs. Biman-Vis	***-68.2***	***-74.4***	***-61.8***	***11805***
Interaction Task * Age	Biman-NoVis vs. Biman-Vis	1.2	0.00	2.4	*19157*
	Uniman-Vis vs. Biman-NoVis	***12.7***	***11.8***	***13.9***	***23131***
	Uniman-Vis vs. Biman-Vis	***13.9***	***13.0***	***15.2***	***23268***
	Uniman-Vis vs. Uniman-Prop	2.4	0.9	3.9	21531
	Uniman-Prop vs. Biman-NoVis	***10.6***	***9.1***	***12.1***	***12672***
	Uniman-Prop vs. Biman-Vis	***11.8***	***10.0***	***13.3***	***12365***

3.1.1.2 | Unsigned phase difference between the hands per age group

In a second analysis, we grouped children into yearly cohorts and contrasted, for each cohort as well as for an adult group, performance between tasks. Again, we first focus on the bimanual tasks and will return to the unimanual tasks in section 3.2.1.1; Table 3 presents estimates for all four tasks. In brief, performance between the two bimanual tasks did not credibly differ at any age, including adults. There was an exception for the cohort of age 5 (Biman-Vis – Biman-NoVis: β_{Age} = -11, $HDI_{95\%}$ = [-14.9; -7.1]), for which coordination was worse when no visual feedback was available (compare light and dark red large dots in Figure 2).

Table 3. Beta Estimates of the within comparison between Tasks 1 to 4 for each age group. Comparison with Task 4 (Uniman-Prop) was not processed for children aged 4-5 years as only few children per group performed the task (≤ 2). Negative β Estimates indicate that performance was worse in the reference Task (first one of each line). Comparisons in which the difference between tasks is credible are in indicated in bold italic (HDI outside [-3.9; 3.9]). ESS stands for the Effective Sample Size as calculated during Bayesian model fitting. The Lower and Upper Confidence Interval (CI) values constitute the 95% High Density Interval (HDI).

Group	Contrasts	β Estimate	Lower CI	Upper CI	ESS
Adults	Task 1 vs. 2 – Biman-NoVis vs. Biman-Vis	-1.8	-5.2	1.6	11726
	Task 3 vs. 1 - Uniman-Vis vs. Biman-NoVis	***-10.1***	***-13.2***	***-7.0***	***14589***
	Task 3 vs. 2 - Uniman-Vis vs. Biman-Vis	***-11.9***	***-15.0***	***-8.9***	***15336***
	Task 3 vs. 4 - Uniman-Vis vs. Uniman-Prop	0.8	-2.0	3.6	16840
	Task 4 vs. 1 - Uniman-Prop vs. Biman-NoVis	***-10.9***	***-14.0***	***-7.7***	***11968***
	Task 4 vs. 2 - Uniman-Prop vs. Biman-Vis	***-12.7***	***-15.8***	***-9.6***	***11671***
12yo	Task 1 vs. 2 – Biman-NoVis vs. Biman-Vis	-0.6	-4.1	2.8	3781
	Task 3 vs. 1 - Uniman-Vis vs. Biman-NoVis	***-15.6***	***-18.9***	***-12.5***	***5104***
	Task 3 vs. 2 - Uniman-Vis vs. Biman-Vis	***-16.3***	***-19.4***	***-13.1***	***4863***
	Task 3 vs. 4 - Uniman-Vis vs. Uniman-Prop	-1.8	-4.6	1.1	5479
	Task 4 vs. 1 - Uniman-Prop vs. Biman-NoVis	***-13.9***	***-17.1***	***-10.6***	***6548***
	Task 4 vs. 2 - Uniman-Prop vs. Biman-Vis	***-14.5***	***-17.7***	***-11.3***	***6374***
11yo	Task 1 vs. 2 – Biman-NoVis vs. Biman-Vis	0.3	-2.9	3.5	4462
	Task 3 vs. 1 - Uniman-Vis vs. Biman-NoVis	***-16.6***	***-19.6***	***-13.7***	***2918***
	Task 3 vs. 2 - Uniman-Vis vs. Biman-Vis	***-16.3***	***-19.3***	***-13.2***	***2763***
	Task 3 vs. 4 - Uniman-Vis vs. Uniman-Prop	-0.4	-3.2	2.4	3280
	Task 4 vs. 1 - Uniman-Prop vs. Biman-NoVis	***-16.2***	***-19.2***	***-13.1***	***9153***

	Task 4 vs. 2 - Uniman-Prop vs. Biman-Vis	***-15.9***	***-18.9***	***-12.8***	***9896***
10yo	Task 1 vs. 2 – Biman-NoVis vs. Biman-Vis	0.4	-2.3	3.1	8908
	Task 3 vs. 1 - Uniman-Vis vs. Biman-NoVis	***-18.4***	***-20.9***	***-15.9***	***10802***
	Task 3 vs. 2 - Uniman-Vis vs. Biman-Vis	***-18.0***	***-20.5***	***-15.4***	***10750***
	Task 3 vs. 4 - Uniman-Vis vs. Uniman-Prop	-0.7	-4.2	2.9	10999
	Task 4 vs. 1 - Uniman-Prop vs. Biman-NoVis	***-17.7***	***-21.4***	***-14.1***	***4158***
	Task 4 vs. 2 - Uniman-Prop vs. Biman-Vis	***-17.3***	***-21.0***	***-13.7***	***4186***
9yo	Task 1 vs. 2 – Biman-NoVis vs. Biman-Vis	0.7	-2.3	3.7	11590
	Task 3 vs. 1 - Uniman-Vis vs. Biman-NoVis	***-25.7***	***-28.5***	***-23.0***	***5152***
	Task 3 vs. 2 - Uniman-Vis vs. Biman-Vis	***-25.1***	***-27.7***	***-22.3***	***4896***
	Task 3 vs. 4 - Uniman-Vis vs. Uniman-Prop	-0.2	-3.6	3.1	4763
	Task 4 vs. 1 - Uniman-Prop vs. Biman-NoVis	***-25.5***	***-29.1***	***-21.9***	***4739***
	Task 4 vs. 2 - Uniman-Prop vs. Biman-Vis	***-24.8***	***-28.3***	***-21.3***	***4708***
8yo	Task 1 vs. 2 – Biman-NoVis vs. Biman-Vis	1.3	-2.10	4.67	5827
	Task 3 vs. 1 - Uniman-Vis vs. Biman-NoVis	***-36.8***	***-40.0***	***-33.5***	***6173***
	Task 3 vs. 2 - Uniman-Vis vs. Biman-Vis	***-35.5***	***-38.7***	***-32.3***	***5642***
	Task 3 vs. 4 - Uniman-Vis vs. Uniman-Prop	***-14.8***	***-19.2***	***-10.4***	***6423***
	Task 4 vs. 1 - Uniman-Prop vs. Biman-NoVis	***-21.9***	***-26.5***	***-17.4***	***3042***
	Task 4 vs. 2 - Uniman-Prop vs. Biman-Vis	***-20.6***	***-25.1***	***-16.1***	***2905***
7yo	Task 1 vs. 2 – Biman-NoVis vs. Biman-Vis	-2.6	-6.0	0.7	3535
	Task 3 vs. 1 - Uniman-Vis vs. Biman-NoVis	***-37.9***	***-41.2***	***-34.7***	***4454***
	Task 3 vs. 2 - Uniman-Vis vs. Biman-Vis	***-40.5***	***-43.6***	***-37.4***	***4660***
	Task 3 vs. 4 - Uniman-Vis vs. Uniman-Prop	***-17.0***	***-21.1***	***-13.1***	***5823***
	Task 4 vs. 1 - Uniman-Prop vs. Biman-NoVis	***-20.8***	***-25.1***	***-16.6***	***5725***
	Task 4 vs. 2 - Uniman-Prop vs. Biman-Vis	***-23.4***	***-27.6***	***-19.2***	***5868***
6yo	Task 1 vs. 2 – Biman-NoVis vs. Biman-Vis	-2.4	-5.9	1.1	4370
	Task 3 vs. 1 - Uniman-Vis vs. Biman-NoVis	***-41.8***	***-45.0***	***-38.6***	***4782***
	Task 3 vs. 2 - Uniman-Vis vs. Biman-Vis	***-44.2***	***-47.4***	***-40.9***	***4821***
	Task 3 vs. 4 - Uniman-Vis vs. Uniman-Prop	-1.8	-6.7	3.2	4734
	Task 4 vs. 1 - Uniman-Prop vs. Biman-NoVis	***-39.9***	***-44.7***	***-35.1***	***2410***
	Task 4 vs. 2 - Uniman-Prop vs. Biman-Vis	***-42.3***	***-47.2***	***-37.4***	***2358***
5yo	***Task 1 vs. 2 – Biman-NoVis vs. Biman-Vis***	***-11.0***	***-14.9***	***-7.1***	***3570***
	Task 3 vs. 1 - Uniman-Vis vs. Biman-NoVis	***-41.8***	***-45.2***	***-38.4***	***3952***
	Task 3 vs. 2 - Uniman-Vis vs. Biman-Vis	***-52.9***	***-56.2***	***-49.5***	***4557***
4yo	Task 1 vs. 2 – Biman-NoVis vs. Biman-Vis	1.6	-1.9	5.2	7206
	Task 3 vs. 1 - Uniman-Vis vs. Biman-NoVis	***-57.0***	***-60.2***	***-53.7***	***4274***
	Task 3 vs. 2 - Uniman-Vis vs. Biman-Vis	***-55.4***	***-58.3***	***-52.4***	***4472***

Next, we compared, for each task, performance of each age cohort with that of adults to assess at which age children show adult-like variability in each task. Figure 3 show the estimates for each task and age group (see supplementary Table S1 for detailed statistics).

For Biman-NoVis, there was overlap of the HDI and the ROPE for the comparisons of the 9-12 year cohorts with adults, indicating that these age groups did not perform credibly different than adults. The younger cohorts showed higher variability than adults.

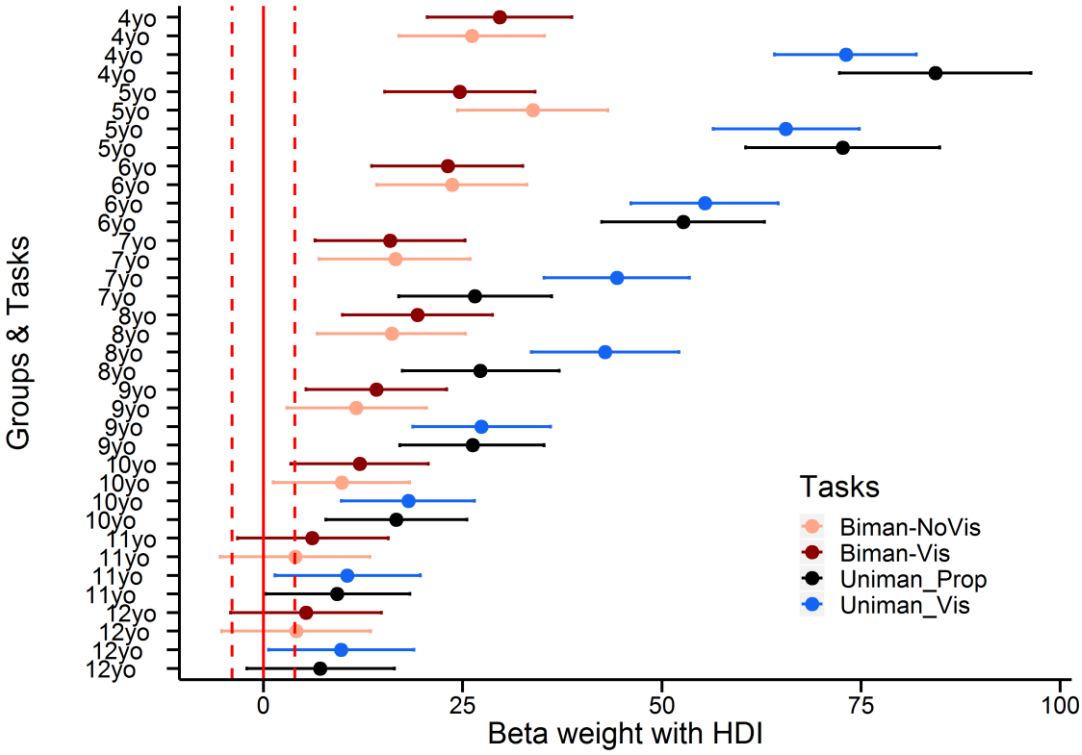

Fig. 3.

Illustration of age effects in Tasks 1-4. The area between whiskers represents the highest density interval (HDI) of a β weight's posterior distribution in the model with Age Group as a categorical variable and the Age group adult as reference. Vertical dashed red lines represent the ROPE to establish that an age group differed from adults (ROPE: [-3.9; 3.9]).

For Biman-Vis, the HDI overlapped with the ROPE for the comparison of 10 to 12 year cohorts with adults, but variability was higher for children in the 4-9 year cohorts. In summary, performance in the bimanual task was comparable across almost all age groups, and was indistinguishable from adult performance around age 9-10.

3.1.2 | Signed phase difference between the two hands

Analysis up to now has focused on variability in coordinating the two hands. Next, we asked whether one hand had a constant offset relative to the other, that is, whether one hand regularly leads the other by a few degrees. We ran the same Bayesian model as the one used for variability, but with the signed error as dependent measure. Figure 4 shows that the signed error was generally negative for both unimodal tasks, without a clear change across ages. In the model, the intercept differed from zero for both tasks (Biman-NoVis: $\beta_{Intercept}$ = -15.6, $HDI_{95\%}$ = -24.7 – -6.3; Biman-Vis: $\beta_{Intercept}$ = -17.3, $HDI_{95\%}$ = -26.5 – -8.2), but neither the continuous Age predictor (Biman-NoVis: β_{Age} = 2.7, $HDI_{95\%}$ = [0.0; 5.2]; Biman-Vis: β_{Age} = 3.0, $HDI_{95\%}$ = [0.6; 5.8]), nor the Task (β = -1.7, $HDI_{95\%}$ = [-8.1; 4.7]) or the Task*Age interaction (β = 0.6, $HDI_{95\%}$ = [-1.2; 2.4]) contrasts between the two bimanual tasks were credibly different from 0. Together, these results indicate that the dominant hand lagged behind the non-dominant hand for all ages.

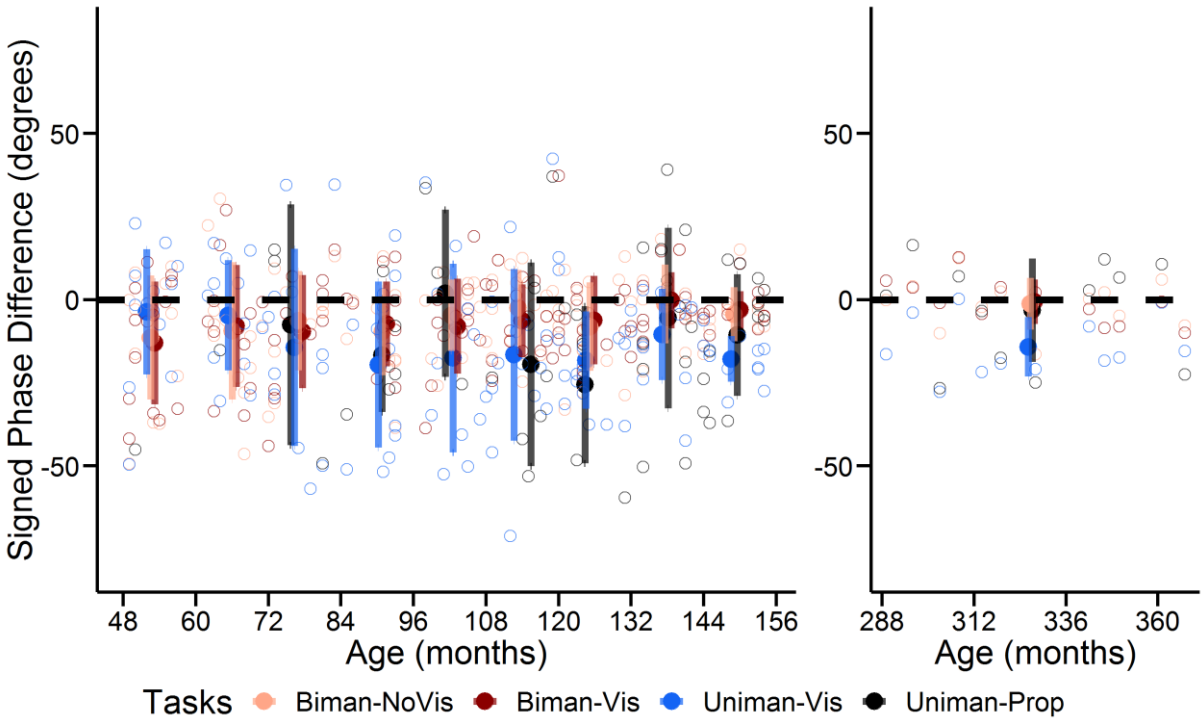

Fig. 4.

Signed phase difference between the two hands in bimanual Tasks 1 and 2 (dark and light red) and in unimanual Tasks 3 and 4 (blue and black) for children (left panel) and adults (right panel). Coloured circles represent the mean for each age group; bars show the s.d. Fewer than half of the 4-8 year-old participants performed Task 4 (Uniman-Prop; black), the means are thus likely to be non-representative (means in Uniman-Prop are not shown because n ≤ 2)

3.2 | Unimanual motor coordination

3.2.1 | Unsigned phase difference between hand and external signal

3.2.1.1 | Unsigned phase difference between hand and external signal across all ages

We now turn to the analysis of the unimanual coordination tasks. In these tasks participants had to synchronize the movement of their dominant hand with a circling dot (Uniman-Vis) or with the passively moved, non-dominant hand (Uniman-Prop). Figure 2 shows that, as in the bimanual tasks, in unimanual tasks coordination improved with age (blue and black dots). The respective slope coefficients were negative and different from 0 (Uniman-Vis: β_{Age} = -21.8, $HDI_{95\%}$ = [-23.6; -19.7]; Uniman-Prop: β_{Age} = -19.4, $HDI_{95\%}$ = [-21.8; -17]), statistically confirming the effect of age. There was a credible difference for the contrast between the two tasks, indicating that the Intercept coefficient was higher for Uniman-Vis than Uniman-Prop (β = -12.12, $HDI_{95\%}$ = [-18.2; -6.1]). However, there was no credible Task*Age interaction contrast (see Table 2), indicating that the rate of performance improvement did not differ between unimanual tasks. However, both unimanual tasks exhibited large effects of Task and Task*Age interactions when contrasted with the bimanual tasks (see Table 2 for all model estimates). Unimanual intercepts were higher, and the negative slopes were steeper, indicating that the performance was worst at younger ages, and the improvement with age larger, in the unimanual than in the bimanual tasks.

3.2.1.1 | Unsigned phase difference between hand and external signal per age group

Analysis by yearly cohorts confirmed this overall result pattern across all experimental groups, including adults (see Table 3). Thus, coordination was better for bimanual than for unimanual tasks, although this difference was more pronounced for younger than for older children.

Finally, we assessed at what age unimanual performance of children likened that of adults (see Table S1 in the supplementary information). There was no credible difference in performance in Uniman-Vis and Uniman-Prop for 11 and 12 year-old children as compared to adults, whereas all other age groups performed worse than adults. As for Biman-NoVis and Biman-Vis, performance in Uniman-Vis and Uniman-Prop gradually improved over age (see Fig. 3), and we did not observe a step at any point in the developmental trajectory.

3.2.2 | Signed phase difference between hand and external signal

3.2.2.1 | Signed phase difference between hand and external signal across all ages

If a participant moves the hand following an external guiding signal, there should be a constant offset between the guiding signal and the hand, given that processing of sensory information takes time. If,

in contrast, the hand maintained a zero phase lag, this would imply that the hand is moved predictively. Figure 4 shows that the signed error for unimanual tasks resembled that for bimanual tasks in that it was generally negative and without a clear change across ages. However, model analysis indicated that the Task intercept for Uniman-Prop was different from zero and also credibly more negative than Uniman-Vis (Uniman-Vis: $\beta = -2.1$, $HDI_{95\%} = [-10.8; 6.6]$; Uniman-Prop: $\beta = -19.6$, $HDI_{95\%} = [-31.1; -7.9]$; Task contrast: $\beta = -17.5$, $HDI_{95\%} = [-26.5; -8.3]$). Neither Age (Uniman-Vis: $\beta_{Age} = -3.3$, $HDI_{95\%} = [-5.8; -0.9]$; Uniman-Prop: $\beta_{Age} = 1.8$, $HDI_{95\%} = [-1.2; 4.9]$) nor the Task*Age interaction ($\beta_{Interaction} = 5.2$, $HDI_{95\%} = [3.3; 7.6]$) contrasts between the two unimanual tasks were credibly different from 0, implying similar performance across ages. Together, these results indicate that at all ages the hand moved predictively in the visual task but followed the external guiding signal in the proprioceptive task.

3.2.2.2 | Signed phase difference between hand and external signal per age group

Although the intercept of Uniman-Vis did not differ from 0 overall in the previous analysis, visual inspection suggested that this conclusion may be overly conservative. Therefore, we tested the difference of the intercept against zero separately for each age group. Beta estimates are listed in Table S3 in the supplementary information. Adults lagged in Uniman-Vis ($\beta = -14.2$, $HDI_{95\%} = [-22.02; -6.55]$, but not in Uniman-Prop ($\beta = -3.2$, $HDI_{95\%} = [-10.8; 4.6]$). Most children cohorts exhibited lag in Uniman-Vis. For Uniman-Prop. However, participant numbers were low up to age 8, so we refrain from reporting their statistics. Lag was evident for children at ages 9-10, but it decreased thereafter. Performance was indistinguishable between the 12-year-olds and adults. Thus, the cohort-wise analysis rendered qualitatively different results than the overall analysis; given these differences between analyses, their interpretation should be tentative.

3.3 | Sensory dominance in bimanual motor coordination

3.3.1 | Unsigned phase difference between transformed hand positions

3.3.1.1 | Unsigned phase difference between transformed hand positions across all ages

As a third aspect of motor control we investigated the ability of children to perform asymmetric coordination. We analyzed Tasks 5 to 7 separately from Tasks 1-4, because they required different speeds of the two hands, and, thus, the dependent measures were not identical between symmetrical and asymmetrical tasks. We report on the 2:3-Retention (Task 7) in the Supplementary Information, because none of our participants, including adults, performed better than chance in this task. The model was equivalent to that for Tasks 1-4. Because most of the youngest participants did not perform the 2:3 tasks, the standardized unit of age differed from the previous analyses and was 24.6 months.

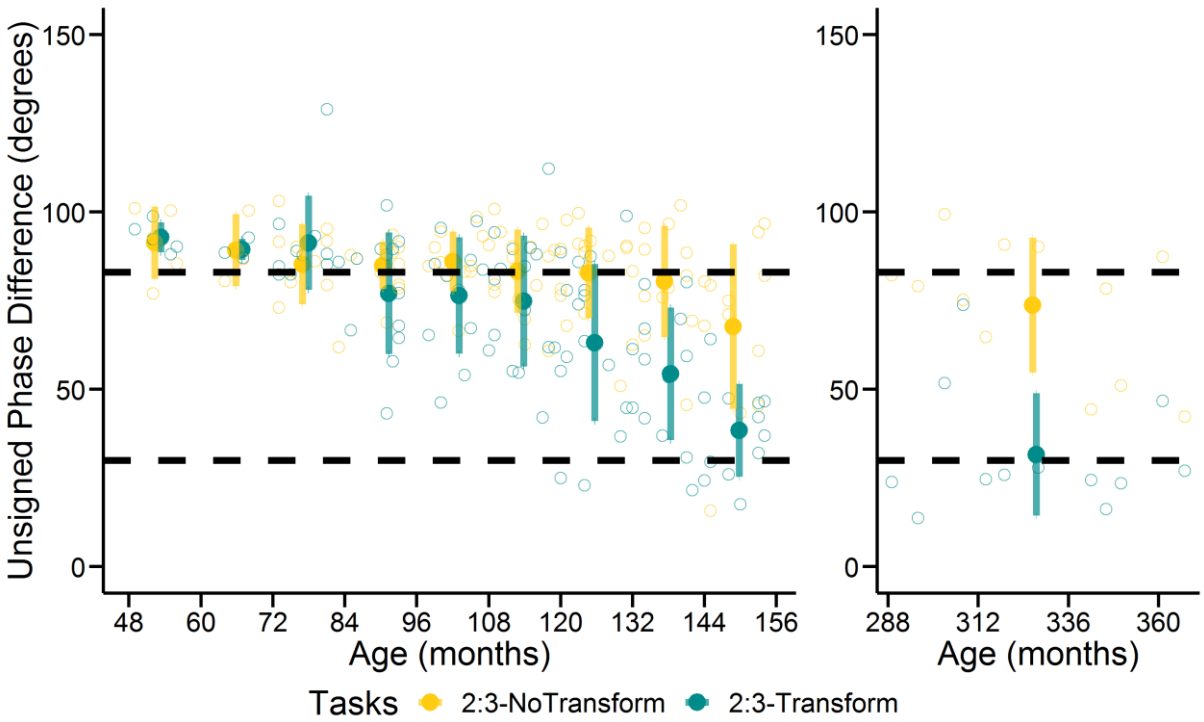

Fig. 5.

Unsigned phase difference between the two hands in the 2:3 coordination tasks for children (left panel) and adults (right panel). The lowest dashed lines represent the 30° threshold under which we considered subjects to perform well. The higher dashed line (83°) represents the phase angle when participants (incorrectly) perform 1:1 coordination. Coloured circles are the mean for each age group; error bars denote s.d. Fewer than half of the 4-5 year-old participants performed Task 5 (yellow), the means are thus likely to be non-representative**.**

Figure 5 shows that performance in 2:3-Transform improved with age (green dots), as shown by the negative, non-zero slope coefficient (β_{Age} = -13.5, $HDI_{95\%}$ = [-15.7; -11.3]). The negative slope value indicates that the variability of the phase difference between hands decreased by the respective amount of degrees with each standardized age unit of 24.6 months. In contrast, performance in the 2:3-NoTransform did not credibly vary with age (Fig. 5, yellow dots; β_{Age} = -4.18, $HDI_{95\%}$ = [-6.40; -1.97]). There was a credible difference between tasks for both Task and Task*Age interaction contrasts, indicating that the intercept and rate of improvement was larger for 2:3-Transform than 2:3-NoTransform (β_{Task} = -28.5, $HDI_{95\%}$ = [-27.5; -14.0]; $\beta_{Interaction}$ = 9.3, $HDI_{95\%}$ = [8.1; 10.6]). During a 2:3 coordination, the correct phase difference between the two hands changes from moment to moment. If a participant incorrectly performed symmetrical (i.e., 1:1) coordination, a pattern that often emerges automatically, then the resulting variable error will be about 83°. In Fig. 5, we plot this error as reference, together with participants' performance. Note, that performance in 2:3-NoTransform (Fig. 5, yellow color) mostly scatters around the 83° line across all ages, including adults. Thus, participants were unsuccessful with veridical feedback across all age groups. In contrast, performance improved in the older groups (Fig. 4, green color).

3.3.1.2 | Unsigned phase difference between transformed hand positions per age group

Next, we contrasted performance between 2:3-NoTransform and 2:3-Transform within each age group. Beta estimates for these comparisons are shown in Table 4. In brief, performance between the two tasks credibly differed in all age groups older than 9, suggesting a consistent use of transformed visual feedback to perform the coordination for these participants. A credible difference was also present at age 7, but it was absent at 8 years. Children younger than 7 were unable to use transformed feedback (Table 4).

Table 4. Beta Estimates of the within comparison between Tasks 5 and 6 for each age group. Negative β Estimates indicate that performance was better in Task 6 (2:3-Transform) than Task 5 (2:3-NoTransform). Credible difference between the tasks in indicated in bold italic (HDI outside [-5.4; 5.4]). ESS stands for the Effective Sample Size as calculated by the Bayesian model. The Lower and Upper Confidence Interval values constitute the 95% High Density Interval (HDI).

Groups	β Estimate	Lower CI	Upper CI	ESS
Adults	***-44.9***	***-48.7***	***-41.2***	***5349***
12 yo	***-29.6***	***-33.7***	***-25.5***	***4415***
11 yo	***-28.3***	***-31.8***	***-24.8***	***7283***
10 yo	***-18.4***	***-21.3***	***-15.4***	***6866***
9 yo	***-8.6***	***-11.5***	***-5.6***	***6152***
8 yo	-8.7	-12.5	-4.8	5455
7 yo	***-10.4***	***-14.2***	***-6.4***	***4627***
6 yo	1.6	-2.4	5.5	7705
5 yo	-0.8	-9.1	7.4	3073
4 yo	1.68	-5.0	8.37	5384

Comparison of each age group's performance in 2:3-NoTransform with that of adults did not reveal a credible difference for any age cohort, in line with the above result that 2:3-NoTransform did not improve with age (see Fig. 6; statistics reported in Table S2 of the supplementary information). In the 2:3-Transform, the adult group performed better than all age cohorts except the 12 year-olds (see Fig. 6; $\beta = 10.1$, $HDI_{95\%} = [0.3; 19.8]$).

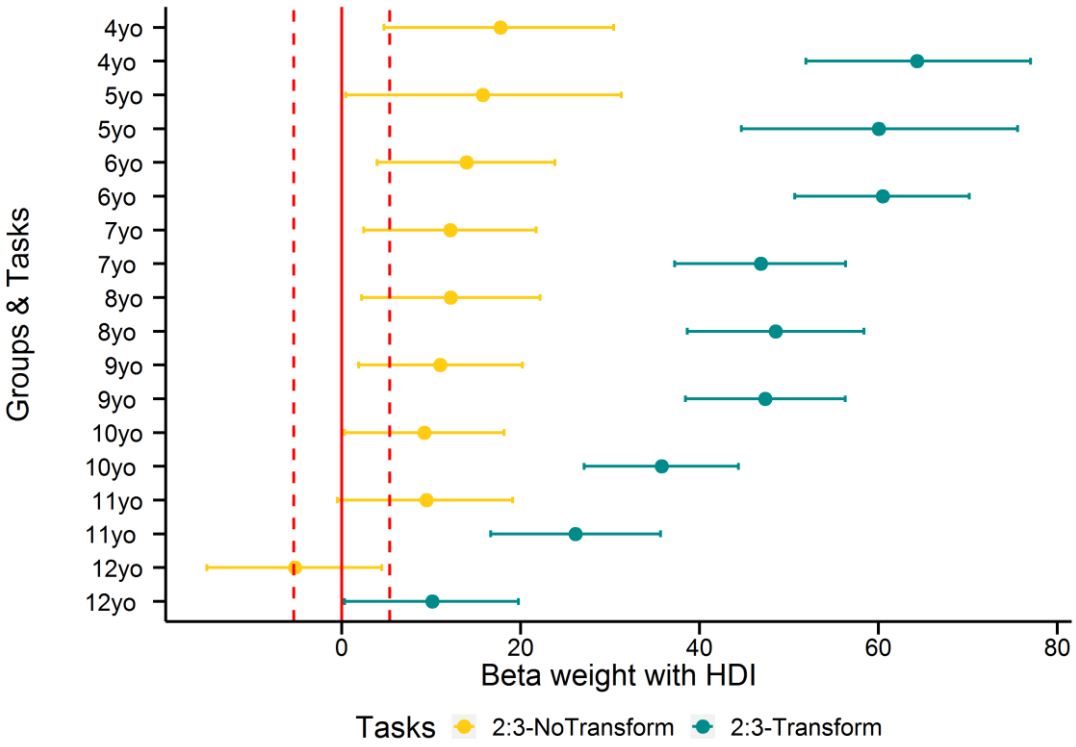

Fig. 6.

Illustration of age effects in Tasks 5 (2:3-NoTransform) and 6 (2:3-Transform). The area between whiskers represents the highest density interval (HDI) of a β weight's posterior distribution obtained with Age Group as a categorical variable and the Age group adult as reference. Vertical dashed red lines represent the ROPE to establish that an age group differed from adults (ROPE: [-5.4; 5.4]).

Note, that we did not assess the signed difference for the 2:3 coordination, because the instructions were to be faster with one hand, and whether one or the other transformed cursor leads the other would not be informative about general aspects of coordination.

3.4 | Relationship between tasks beyond improvement with age

3.4.1 | Relationship between bimanual tasks

Our analysis has so far shown that both Biman-NoVis and Biman-Vis improve with age, and that, overall, this development is similar for the two tasks. However, this conclusion pertains to the average performance of all children. In other words, it is possible that performance globally improves with age, implying that the seemingly similar average development is trivially explained by unspecific factors. To assess whether performance in the two tasks is related beyond a global age improvement, we computed their correlation with age partialed out. The partial correlation was 0.70 ($HDI_{95\%}$ = [0.57; 0.84]; n =120; two-sided test; BF = 2.60e15; BF expresses the odds of an H1 of true correlation compared to an H0 of zero correlation). This high correlation implies that a child that was good in one

task was also good in the other, and, thus, suggests that the two tasks are driven by common underlying development.

3.4.2 | Relationship between bimanual and unimanual tasks

Next, we compared within-participant performance across tasks through correlations between all pairs of tasks, with age partialed out (see Table 5). Like the two bimanual tasks, the two unimanual tasks exhibited high correlation ($\rho = 0.6$; $HDI_{95\%}$= [0.3; 0.85]), though the confidence interval was wide due to the low N available for Uniman-Prop. In contrast, correlations between uni- and bimanual tasks were smaller, ranging from .28 to .42, with only the higher correlations exhibiting BFs that suggest reliable relationships. Counterintuitively, higher correlations were obtained for Biman-NoVis with Uniman-Vis and for Biman-Vis with Uniman-Prop. For the two visual uni- and bimanual tasks (Biman-Vis and Uniman-Vis) and the two proprioceptive tasks (Biman-NoVis and Uniman-Prop), correlations were estimated to be lower; however, the wide HDIs again indicate that N is too low to draw firm conclusions about comparisons including Uniman-Prop.

Table 5. Two-sided correlations between Tasks 1 to 6, with Age partialed out. Credible correlations are in italic bold. Lower and Upper Confidence Interval values constitute the 95% HDI.

Tasks	Coefficient	Lower CI	Upper CI	BF	Sample (N)
Biman-NoVis / Biman-Vis	***0.70***	***0.57***	***0.84***	***2.60e15***	***120***
Biman-NoVis / Uniman-Vis	***0.42***	***0.18***	***0.67***	***16.5***	***119***
Biman-NoVis / Uniman-Prop	0.29	-0.06	0.64	0.44	51
Biman-Vis / Uniman-Vis	0.28	0.02	0.54	0.60	119
Biman-Vis / Uniman-Prop	***0.40***	***0.10***	***0.69***	***3.4***	***51***
Uniman-Vis / Uniman-Prop	***0.58***	***0.30***	***0.85***	***264***	***51***
2:3-NoTransform / 2:3-Transform	***0.40***	***0.17***	***0.64***	***23.2***	***100***
Biman-NoVis / 2:3-Transform	0.08	-0.09	0.26	0.17	101
Biman-Vis / 2:3-Transform	0.10	0.07	0.27	0.22	101
Uniman-Vis / 2:3-Transform	***0.30***	***0.08***	***0.52***	***3.0***	***100***
Uniman-Prop / 2:3-Transform	0.33	0.04	0.62	1.49	50

Note, for Uniman-Prop, participants had to let their non-dominant hand be passively guided. It is theoretically possible that children did not conform with this instruction. If children had, instead, actively moved their non-dominant hand, then they would effectively have performed a bimanual coordination task without vision, i.e., Biman-NoVis. Both the much worse performance of the unimanual tasks, and the lower correlations between unimanual and bimanual tasks than those between the bimanual tasks, indicate that children did not perform bimanual coordination and, thus, did not actively synchronize their hands, during Uniman-Prop.

3.4.3 | Relationship between asymmetric coordination tasks

Finally, we asked how performance in the 2:3 tasks was related amongst each other and with the 4 symmetrical tasks within participants (see Table 5). Partial correlation between the two 2:3 tasks, partialing out age, revealed a credible correlation of 0.40 ($HDI_{95\%}$ = [0.17; 0.64]; two-sided test; n = 100, BF = 23.2). Thus, a child who performed well with veridical feedback performed well also with transformed feedback, and a child who performed badly in the veridical feedback task gained less from transformed feedback. Correlations with the symmetrical tasks were overall low. They were lowest with the bimanual tasks, and higher, though with moderate reliability, for the uni-manual tasks.

4 | DISCUSSION

This study investigated three aspects of motor control in children aged 4-12. First, symmetrical bimanual tasks assessed the ability of children to use vision and proprioception for symmetrical bimanual coordination. Children performed these tasks well already at age 4. However, performance improved with age in a similar manner for both sensory contexts. Second, symmetrical unimanual tasks assessed coordination with an externally rather than a self-created signal. Young children performed much worse in these tasks, and performance improved dramatically with age. Third, 2:3 tasks assessed the development of the ability to separate different sensory modalities and focus on symmetrical visual feedback to perform asymmetrical movements. While all participants, including adults, were unable to perform asymmetric coordination with veridical visual feedback, providing transformed visual feedback improved the coordination in some individuals already at age 7, though more regularly starting at age 9.

4.1 | Bimanual motor coordination

Our study highlighted good performance for bimanual coordination already at age 4. Variability, operationalized as the unsigned phase difference, was moderate at this age, with a mean phase difference of 39° in each task for the 4-year-old children, quite close to the 30° threshold that has been previously suggested to indicate adequate coordination (Mechsner et al., 2001, 2007). Yet, variability decreased from ages 4 to 12, indicating refinement of the performance and increased accuracy. There was no evidence of improvement with age in the constant error, that is, the constant offset between the two hands measured as signed phase difference. Adding visual feedback during symmetric bimanual coordination did not improve coordination, underlining the high correlation between the two tasks: good performance in one meant good performance in the other, whatever the type of sensory information received. This suggests two possible interpretations: either bimanual coordination relies exclusively on somatosensory (proprioceptive) information to perform circling movements, or it

relies predominately on coordinated motor signals sent through the corpus callosum. This latter interpretation is supported by studies on neurological patients: bimanual performance was preserved in absence of proprioception, whether vision was available or not (Spencer et al., 2005); in contrast, callosotomy patients were unable to maintain symmetric coordination (Kennerley, Diedrichsen, Hazeltine, Semjen, & Ivry, 2002). Thus, symmetrical bimanual coordination may generally depend on motor connectivity more than on sensory information.

Accordingly, most previous developmental studies on bimanual coordination have focused on the role of the corpus callosum (e.g. Fagard, Hardy-Léger, Kervella, & Marks, 2001; Jeeves, Silver, & Milne, 1988), The corpus callosum starts to grow very fast at age 3 (Tanaka-Arakawa et al., 2015; Uda et al., 2015), which may explain why our youngest children were able to perform our tasks. Yet, myelination of the corpus callosum leads to increased interhemispheric connectivity until late adolescence (Giedd et al., 1996), linked to improvement in motor performance (Muetzel et al., 2008). This continual development may, thus, explain the gradual improvement over age observed in our present study.

4.2 | Unimanual motor coordination

In our study, we observed no evidence for a difference between the visual and proprioceptive unimanual tasks in the unsigned phase difference. This suggests some common development for the use of external sensory inputs in coordination, in line with the high correlation between the two tasks. Yet, there was a credible difference between the two tasks in the signed phase difference, which expresses a constant phase error between the guiding signal and active hand. Different strategies for performing the two tasks emerged only for the oldest children, who, just like adults, produced feedback-based, lagging movement when following a visual cursor, but moved predictively when following their own, passively moved hand. Furthermore, accuracy, indexed by variable error, was severely impaired in the younger groups, suggesting difficulty in coordinating their movement with external feedback.

These difficulties of the younger children are surprising, given that children can integrate visual and proprioceptive feedback to correct their movement online already at age 4 (e.g. Contreras-Vidal, Bo, Boudreau, & Clark, 2005; Konczak, Jansen-Osmann, & Kalveram, 2003). This divergence in skill may depend on task differences: motor adaptation studies apply forces or visuo-motor rotations directly to (feedback of) the moving hand during short, discrete movements. In our study, children had to use, in addition, information about an external, moving cue, which may require different cognitive resources than responding to limb perturbation. Furthermore, motor correction during continuous coordination, as used here, does not afford a previous motor command to which current performance can be

compared. Instead, it requires integrating the external cue to derive the necessary correction of the ongoing movement. These task features appear to rely on mechanisms that develop later than those responsible for online corrections of discrete movements.

The fact that development of unimanual coordination clearly lags that of bimanual coordination calls into question the idea that bimanual coordination is merely a special case of coordination in general, based on the idea that coordination always requires salient signals that pertain to the feature that must be coordinated (Bingham, 2004). Although other paradigms have revealed that bimanual coordination can rely on visual information (Brandes et al., 2017; Mechsner et al., 2001), here in the case of a standard symmetrical task, it appeared to be independent of visual guidance. Whether children would use visual information in situations in which symmetry is evident in the visual signal, but not in the required motor command, such as when wiggling the index fingers with one hand turned over (Mechsner et al., 2001) currently remains open.

A previous study concluded from end-point error variability in center-out movements that proprioceptive and kinesthetic hand feedback of 6-8 year-olds, but not of 11-12 year-olds, is noisier than that of adults (Contreras-Vidal, 2006). Indeed, motor performance at ages 11 and 12 has often been reported to be adult-like (Forssberg, Eliasson, Kinoshita, Johansson, & Westling, 1991; Roy et al., 2013). Our findings corroborate these previous results, with our young children exhibiting large phase difference between their hand and the external source, whereas our 11 and 12 year-olds did not statistically differ from adults.

4.3 | Asymmetric coordination

Adding visual transformed feedback in the 2:3 coordination task consistently improved coordination in children from 9 to 12 years of age. Performance in this task moderately correlated with the ability of each child to integrate visual feedback independently of age. This finding suggests that the ability to integrate visual feedback was an important factor for task success, fitting with the need to monitor visual symmetry during the task. The ability to perform the task was evident around age 9, in line with a previous study on the use of Lissajous displays by children (Leinen et al., 2016). This is also the age at which children first exhibit adult-like optimal multisensory integration (Burr & Gori, 2012; Gori, 2015). Thus, possibly the ability to strategically ignore, or down-weight, proprioception based on task demands appears to require mature multisensory integration abilities.

It is noteworthy that some children were able to use visual feedback to improve coordination as early as age 7, but 8-year-old children did not show this ability. Although this conclusion is based on a

statistical group comparison and should not be overinterpreted given the N of our age groups, this result fits with the many previous reports of performance decrements around the age of 8 years (Badan, Hauert, & Mounoud, 2000; Hay, 1978; Pellizzer & Hauert, 1996; Smyth, Katamba, & Peacock, 2004), such as haptic feedforward control (Martel et al., submitted). For instance, in many tasks, children weigh visual information more strongly than proprioceptive information before age 8, but reverse this preference thereafter (Contreras-Vidal et al., 2005; King, Pangelinan, Kagerer, & Clark, 2010). In other tasks, sensory preference changes in the opposite direction, but again around age 8 (Hay, Fleury, Bard, & Teasdale, 1994; Lantero & Ringenbach, 2007). Under this notion, adult-like motor control strategies are being set up at age 8 leading to transient disorganization of the motor processes that were at work until this point.

4.4 | Conclusion and open questions

Our results suggest interdependent, serial development of different motor control functions. Mastering of simple, symmetrical bimanual coordination may rely predominately on motor-related interhemispheric transfer. This basic coordination ability develops early, just like online movement control in unimanual reaching (e.g. Contreras-Vidal et al., 2005; Konczak et al., 2003). Yet, even this seemingly basic ability matures until about age 9. Unimanual synchronization with externally produced signals develops later until about age 11, but likely depends, in part, on bimanual ability, as suggested by the correlations between the two types of tasks in the present study. Finally, selecting rather than integrating multisensory information matured even later, first being adult-like at age 12. Again, moderate correlation with unimanual task performance suggests dependence of this function on those motor functions that develop earlier. Notably, the lack of a correlation of 2:3 coordination with bimanual performance implies that the correlations of these two tasks with the unimanual tasks are based on different variance portions of the unimanual task. This finding makes intuitive sense given that the 2:3 coordination requires the exact opposite of symmetrical bimanual coordination, namely to dissociate, rather than synchronize, movement of the two hands. Moreover, 2:3 coordination requires coordinating each of the two hands with its own “external” signal, given that the transformed cursor location is dissociated from true hand location by task design.

What our study cannot address is how these functions develop longitudinally within individuals. The correlations between tasks suggest that presence of one function promotes development of subsequent functions. However, one cannot conclude that the overall monotonous improvement over age evident cross-sectionally adequately describes individual development. It is well possible that more abrupt performance improvements would be evident if individuals were tested over protracted

time intervals. Longitudinal studies will, furthermore, be instrumental in further clarifying the developmental dependencies between bimanual, unimanual, and sensory-selectional coordination.

Finally, caution is advisable when concluding that a function has reached its final developmental stage. First, although our statistical comparisons often did not provide evidence for differences between children aged about 10-12 and adults, one cannot firmly conclude equivalent ability. Indeed, the HDIs in our statistical models would be expected to shrink significantly if higher participant numbers were available, and it is likely that some of the now non-credible results would then turn out credible. Furthermore, although it seems to be a common assumption that performance will remain adult-like once it has reached adult level at some age, impairment of some motor control functions have been reported during adolescence (Viel, Vaugoyeau, & Assaiante, 2009). Similarly, the transient impairment of 7 and 8-year-olds in many motor control paradigms (Hay, 1978; Hay, Bard, Ferrel, Olivier, & Fleury, 2005; Pellizzer & Hauert, 1996; Smyth, Peacock, & Katamba, 2004), which was evident also in our study, cautions against assuming that development must reflect monotonous improvement over time.

REFERENCES

Adolph, K. E., & Franchak, J. M. (2017). The development of motor behavior. *Wiley Interdisciplinary Reviews: Cognitive Science*, *8*(1–2), n/a-n/a. https://doi.org/10.1002/wcs.1430

Adolph, K. E., & Hoch, J. E. (2019). Motor Development: Embodied, Embedded, Enculturated, and Enabling. *Annual Review of Psychology*, *70*(1), null. https://doi.org/10.1146/annurev-psych-010418-102836

Adolph, K. E., Hoch, J. E., & Cole, W. G. (2018). Development (of Walking): 15 Suggestions. *Trends in Cognitive Sciences*, *22*(8), 699–711. https://doi.org/10.1016/j.tics.2018.05.010

Assaiante, C., Barlaam, F., Cignetti, F., & Vaugoyeau, M. (2014). Body schema building during childhood and adolescence: a neurosensory approach. *Neurophysiologie Clinique = Clinical Neurophysiology*, *44*(1), 3–12. https://doi.org/10.1016/j.neucli.2013.10.125

Badan, M., Hauert, C. A., & Mounoud, P. (2000). Sequential pointing in children and adults. *Journal of Experimental Child Psychology*, *75*(1), 43–69. https://doi.org/10.1006/jecp.1999.2522

Bingham, G. P. (2004). A Perceptually Driven Dynamical Model of Bimanual Rhythmic Movement (and Phase Perception). *Ecological Psychology*, *16*(1), 45–53. https://doi.org/10.1207/s15326969eco1601_6

Bingham, G. P., Snapp-Childs, W., & Zhu, Q. (2018). Information about relative phase in bimanual coordination is modality specific (not amodal), but kinesthesis and vision can teach one another. *Human Movement Science*, *60*, 98–106. https://doi.org/10.1016/j.humov.2018.05.010

Brandes, J., Rezvani, F., & Heed, T. (2016). *Visual guidance of bimanual coordination relies on movement direction* (No. biorxiv;063404v1). Retrieved from http://biorxiv.org/lookup/doi/10.1101/063404

Brandes, J., Rezvani, F., & Heed, T. (2017). Abstract spatial, but not body-related, visual information guides bimanual coordination. *Scientific Reports*, *7*(1), 16732. https://doi.org/10.1038/s41598-017-16860-x

Buchanan, J. J., & Wang, C. (2012). Overcoming the guidance effect in motor skill learning: feedback all the time can be beneficial. *Experimental Brain Research*, *219*(2), 305–320. https://doi.org/10.1007/s00221-012-3092-x

Buekers, M. J., Bogaerts, H. P., Swinnen, S. P., & Helsen, W. F. (2000). The synchronization of human arm movements to external events. *Neuroscience Letters*, *290*(3), 181–184. https://doi.org/10.1016/S0304-3940(00)01350-1

Bürkner, P.-C. (2017). brms: An R Package for Bayesian Multilevel Models Using Stan. *Journal of Statistical Software*, *80*(1), 1–28. https://doi.org/10.18637/jss.v080.i01

Burr, D., & Gori, M. (2012). Multisensory Integration Develops Late in Humans. In M. M. Murray & M. T. Wallace (Eds.), *The Neural Bases of Multisensory Processes*. Retrieved from http://www.ncbi.nlm.nih.gov/books/NBK92864/

Chiou, S.-C., & Chang, E. C. (2016). Bimanual Coordination Learning with Different Augmented Feedback Modalities and Information Types. *PLOS ONE*, *11*(2), e0149221. https://doi.org/10.1371/journal.pone.0149221

Cohen, L. (1971). Synchronous Bimanual Movements Performed by Homologous and Non-Homologous Muscles. *Perceptual and Motor Skills*, *32*(2), 639–644. https://doi.org/10.2466/pms.1971.32.2.639

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*(4–5), 634–645. https://doi.org/10.1016/j.humov.2006.07.006

Contreras-Vidal, J. L., Bo, J., Boudreau, J. P., & Clark, J. E. (2005). Development of visuomotor representations for hand movement in young children. *Experimental Brain Research*, *162*(2), 155–164. https://doi.org/10.1007/s00221-004-2123-7

Daseking, M., & Petermann, F. (2013). *Verhaltensinventar zur Beurteilung exekutiver Funktionen für das Kindergartenalter, BRIEF-P. Deutschsprachige Adaptation des Behavior Rating Inventory of Executive Function for Preschoolers*.

de Boer, B. J., Peper, C. E., & Beek, P. J. (2012). Development of temporal and spatial bimanual coordination during childhood. *Motor Control*, *16*(4), 537–559.

Drechsler, R., & Steinhausen, H.-C. (2013). *Verhaltensinventar zur Beurteilung exekutiver Funktionen, BRIEF. Deutschsprachige Adaptation des Behavior Rating Inventory of Executive Function*.

Fagard, J., Hardy-Léger, I., Kervella, C., & Marks, A. (2001). Changes in interhemispheric transfer rate and the development of bimanual coordination during childhood. *Journal of Experimental Child Psychology*, *80*(1), 1–22. https://doi.org/10.1006/jecp.2000.2623

Forssberg, H., Eliasson, A. C., Kinoshita, H., Johansson, R. S., & Westling, G. (1991). Development of human precision grip. I: Basic coordination of force. *Experimental Brain Research*, *85*(2), 451–457.

Giedd, J. N., Rumsey, J. M., Castellanos, F. X., Rajapakse, J. C., Kaysen, D., Vaituzis, A. C., … Rapoport, J. L. (1996). A quantitative MRI study of the corpus callosum in children and adolescents. *Brain Research. Developmental Brain Research*, *91*(2), 274–280.

Gooijers, J., & Swinnen, S. P. (2014). Interactions between brain structure and behavior: The corpus callosum and bimanual coordination. *Neuroscience & Biobehavioral Reviews*, *43*, 1–19. https://doi.org/10.1016/j.neubiorev.2014.03.008

Gori, M. (2015). Multisensory Integration and Calibration in Children and Adults with and without Sensory and Motor Disabilities. *Multisensory Research*, *28*(1–2), 71–99.

Hamilton, A. F. de C., Southgate, V., & Hill, E. L. (2016). The development of action cognition. In A. K. Engel, K. J. Friston, & D. Kragic (Eds.), *The Pragmatic Turn: Toward Action-Oriented Views in Cognitive Science* (pp. 35–47). Retrieved from https://mitpress.mit.edu/books/pragmatic-turn

Hay, L. (1978). Accuracy of children on an open-loop pointing task. *Perceptual and Motor Skills*, *47*(3 Pt 2), 1079–1082. https://doi.org/10.2466/pms.1978.47.3f.1079

Hay, L., Bard, C., Ferrel, C., Olivier, I., & Fleury, M. (2005). Role of proprioceptive information in movement programming and control in 5 to 11-year old children. *Human Movement Science*, *24*(2), 139–154. https://doi.org/10.1016/j.humov.2005.05.002

Hay, L., Fleury, M., Bard, C., & Teasdale, N. (1994). Resolving power of the perceptual- and sensorimotor systems in 6- to 10-year-old children. *Journal of Motor Behavior*, *26*(1), 36–42. https://doi.org/10.1080/00222895.1994.9941659

Heed, T., & Röder, B. (2014). Motor coordination uses external spatial coordinates independent of developmental vision. *Cognition*, *132*(1), 1–15. https://doi.org/10.1016/j.cognition.2014.03.005

Hove, M. J., Spivey, M. J., & Krumhansl, C. L. (2010). Compatibility of motion facilitates visuomotor synchronization. *Journal of Experimental Psychology. Human Perception and Performance*, *36*(6), 1525–1534. https://doi.org/10.1037/a0019059

Jeeves, M. A., Silver, P. H., & Milne, A. B. (1988). Role of the corpus callosum in the development of a bimanual motor skill. *Developmental Neuropsychology*, *4*(4), 305–323. https://doi.org/10.1080/87565648809540415

Kagerer, F. A., & Clark, J. E. (2014). Development of interactions between sensorimotor representations in school-aged children. *Human Movement Science*, *34*, 164–177. https://doi.org/10.1016/j.humov.2014.02.001

Kelso, J. A. S. (1984). Phase transitions and critical behavior in human bimanual coordination. *The American Journal of Physiology*, *246*(6 Pt 2), R1000-1004. https://doi.org/10.1152/ajpregu.1984.246.6.R1000

Kelso, J. A. S., Fink, P. W., DeLaplain, C. R., & Carson, R. G. (2001). Haptic information stabilizes and destabilizes coordination dynamics. *Proceedings of the Royal Society of London. Series B: Biological Sciences*, *268*(1472), 1207–1213. https://doi.org/10.1098/rspb.2001.1620

Kelso, J. A. S., Scholz, J. P., & Schöner, G. (1986). Nonequilibrium phase transitions in coordinated biological motion: critical fluctuations. *Physics Letters A*, *118*(6), 279–284. https://doi.org/10.1016/0375-9601(86)90359-2

Kennerley, S. W., Diedrichsen, J., Hazeltine, E., Semjen, A., & Ivry, R. B. (2002). Callosotomy patients exhibit temporal uncoupling during continuous bimanual movements. *Nature Neuroscience*, *5*(4), 376–381. https://doi.org/10.1038/nn822

King, B. R., Pangelinan, M. M., Kagerer, F. A., & Clark, J. E. (2010). Improvements in proprioceptive functioning influence multisensory-motor integration in 7- to 13-year-old children. *Neuroscience Letters*, *483*(1), 36–40. https://doi.org/10.1016/j.neulet.2010.07.056

Konczak, J., Jansen-Osmann, P., & Kalveram, K.-T. (2003). Development of force adaptation during childhood. *Journal of Motor Behavior*, *35*(1), 41–52. https://doi.org/10.1080/00222890309602120

Kovacs, A. J., Buchanan, J. J., & Shea, C. H. (2009). Bimanual 1:1 with 90 degrees continuous relative phase: difficult or easy! *Experimental Brain Research*, *193*(1), 129–136. https://doi.org/10.1007/s00221-008-1676-2

Kovacs, A. J., & Shea, C. H. (2011). The learning of 90° continuous relative phase with and without Lissajous feedback: external and internally generated bimanual coordination. *Acta Psychologica*, *136*(3), 311–320. https://doi.org/10.1016/j.actpsy.2010.12.004

Kruschke, J. K. (2011). Bayesian Assessment of Null Values Via Parameter Estimation and Model Comparison. *Perspectives on Psychological Science*, *6*(3), 299–312. https://doi.org/10.1177/1745691611406925

Kruschke, J. K. (2018). Rejecting or Accepting Parameter Values in Bayesian Estimation. *Advances in Methods and Practices in Psychological Science*, *1*(2), 270–280. https://doi.org/10.1177/2515245918771304

Lantero, D. A., & Ringenbach, S. D. R. (2007). Developmental differences in the use of visual information during a continuous bimanual coordination task. *Journal of Motor Behavior*, *39*(2), 139–155. https://doi.org/10.3200/JMBR.39.2.139-157

Leinen, P., Vieluf, S., Kennedy, D., Aschersleben, G., Shea, C. H., & Panzer, S. (2016). Life span changes: Performing a continuous 1:2 bimanual coordination task. *Human Movement Science*, *46*, 209–220. https://doi.org/10.1016/j.humov.2016.01.004

Lüdecke, D. (2018). *sjstats: Statistical Functions for Regression Models.* https://doi.org/10.5281/zenodo.1489175

Mechsner, F., Kerzel, D., Knoblich, G., & Prinz, W. (2001). Perceptual basis of bimanual coordination. *Nature*, *414*(6859), 69–73. https://doi.org/10.1038/35102060

Mechsner, F., Stenneken, P., Cole, J., Aschersleben, G., & Prinz, W. (2007). Bimanual circling in deafferented patients: evidence for a role of visual forward models. *Journal of Neuropsychology*, *1*(Pt 2), 259–282.

Muetzel, R. L., Collins, P. F., Mueller, B. A., M Schissel, A., Lim, K. O., & Luciana, M. (2008). The development of corpus callosum microstructure and associations with bimanual task performance in healthy adolescents. *NeuroImage*, *39*(4), 1918–1925. https://doi.org/10.1016/j.neuroimage.2007.10.018

Nuijten, M. B., Wetzels, R., Matzke, D., Dolan, C. V., & Wagenmakers, E.-J. (2015). A default Bayesian hypothesis test for mediation. *Behavior Research Methods*, *47*(1), 85–97. https://doi.org/10.3758/s13428-014-0470-2

Oliveira, F. T. P., & Ivry, R. B. (2008). The Representation of Action: Insights From Bimanual Coordination. *Current Directions in Psychological Science*, *17*(2), 130–135. https://doi.org/10.1111/j.1467-8721.2008.00562.x

Oswald, W. D., & Roth, E. (1978). Der Zahlen-Verbindungs-Test (ZVT). *Göttingen, Germany: Hogrefe*.

Pellizzer, G., & Hauert, C.-A. (1996). Visuo-manual aiming movements in 6-to 10-year-old children: evidence for an asymmetric and asynchronous development of information processes. *Brain and Cognition*, *30*(2), 175–193.

R Core Team. (2018). *R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.*

Repp, B. H., & Steinman, S. R. (2010). Simultaneous Event-Based and Emergent Timing: Synchronization, Continuation, and Phase Correction. *Journal of Motor Behavior*, *42*(2), 111–126. https://doi.org/10.1080/00222890903566418

Riek, S., & Woolley, D. (2005). Hierarchical organisation of neuro-anatomical constraints in interlimb coordination. *Human Movement Science*, *24*(5), 798–814. https://doi.org/10.1016/j.humov.2005.10.002

Robertson, S. D. (2001). Development of bimanual skill: the search for stable patterns of coordination. *Journal of Motor Behavior*, *33*(2), 114–126. https://doi.org/10.1080/00222890109603144

Roy, A. C., Curie, A., Nazir, T., Paulignan, Y., des Portes, V., Fourneret, P., & Deprez, V. (2013). Syntax at hand: common syntactic structures for actions and language. *PloS One*, *8*(8), e72677. https://doi.org/10.1371/journal.pone.0072677

Shea, C. H., Buchanan, J. J., & Kennedy, D. M. (2016). Perception and action influences on discrete and reciprocal bimanual coordination. *Psychonomic Bulletin & Review*, *23*(2), 361–386. https://doi.org/10.3758/s13423-015-0915-3

Sigrist, R., Rauter, G., Riener, R., & Wolf, P. (2013). Augmented visual, auditory, haptic, and multimodal feedback in motor learning: a review. *Psychonomic Bulletin & Review*, *20*(1), 21–53. https://doi.org/10.3758/s13423-012-0333-8

Smyth, M. M., Katamba, J., & Peacock, K. A. (2004). Development of prehension between 5 and 10 years of age: distance scaling, grip aperture, and sight of the hand. *Journal of Motor Behavior*, *36*(1), 91–103. https://doi.org/10.3200/JMBR.36.1.91-103

Smyth, M. M., Peacock, K. A., & Katamba, J. (2004). The role of sight of the hand in the development of prehension in childhood. *The Quarterly Journal of Experimental Psychology. A, Human Experimental Psychology*, *57*(2), 269–296. https://doi.org/10.1080/02724980343000215

Spencer, R. M. C., & Ivry, R. B. (2007). The temporal representation of in-phase and anti-phase movements. *Human Movement Science*, *26*(2), 226–234. https://doi.org/10.1016/j.humov.2007.01.002

Spencer, R. M. C., Ivry, R. B., Cattaert, D., & Semjen, A. (2005). Bimanual coordination during rhythmic movements in the absence of somatosensory feedback. *Journal of Neurophysiology*, *94*(4), 2901–2910. https://doi.org/10.1152/jn.00363.2005

Spencer, R. M. C., Semjen, A., Yang, S., & Ivry, R. B. (2006). An event-based account of coordination stability. *Psychonomic Bulletin & Review*, *13*(4), 702–710.

Swinnen, S. P., Jardin, K., Verschueren, S., Meulenbroek, R., Franz, L., Dounskaia, N., & Walter, C. B. (1998). Exploring interlimb constraints during bimanual graphic performance: effects of muscle grouping and direction. *Behavioural Brain Research*, *90*(1), 79–87.

Tanaka-Arakawa, M. M., Matsui, M., Tanaka, C., Uematsu, A., Uda, S., Miura, K., … Noguchi, K. (2015). Developmental changes in the corpus callosum from infancy to early adulthood: a structural magnetic resonance imaging study. *PloS One*, *10*(3), e0118760. https://doi.org/10.1371/journal.pone.0118760

Temprado, J. J., Swinnen, S. P., Carson, R. G., Tourment, A., & Laurent, M. (2003). Interaction of directional, neuromuscular and egocentric constraints on the stability of preferred bimanual coordination patterns. *Human Movement Science*, *22*(3), 339–363.

Tomatsu, S., & Ohtsuki, T. (2005). The effect of visual transformation on bimanual circling movement. *Experimental Brain Research*, *166*(2), 277–286. https://doi.org/10.1007/s00221-005-2363-1

Uda, S., Matsui, M., Tanaka, C., Uematsu, A., Miura, K., Kawana, I., & Noguchi, K. (2015). Normal development of human brain white matter from infancy to early adulthood: a diffusion tensor imaging study. *Developmental Neuroscience*, *37*(2), 182–194. https://doi.org/10.1159/000373885

Viel, S., Vaugoyeau, M., & Assaiante, C. (2009). Adolescence: a transient period of proprioceptive neglect in sensory integration of postural control. *Motor Control*, *13*(1), 25–42.

Wetzels, R., & Wagenmakers, E.-J. (2012). A default Bayesian hypothesis test for correlations and partial correlations. *Psychonomic Bulletin & Review*, *19*(6), 1057–1064. https://doi.org/10.3758/s13423-012-0295-x

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

Wing, A. M., Doumas, M., & Welchman, A. E. (2010). Combining multisensory temporal information for movement synchronisation. *Experimental Brain Research*, *200*(3), 277–282. https://doi.org/10.1007/s00221-009-2134-5