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# How Do Children Control Rate, Amplitude, and Coordination Stability During Bimanual Circle Drawing?

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Coordination instability (e.g., weak coupling strength) in young children may cause them to control some aspects of coordination in a different manner than adults. This experiment investigated the influence of rate and amplitude on bimanual coordination stability across development (4-, 6-, and 8-year-olds, and adults). Participants traced circles of different amplitudes (5, 10, 15, and 20 cm) while increasing movement rate twice during the trial. The results revealed that 4- and 6-year-olds produced much larger amplitudes than required and increased the amplitude of their movements with increases in rate. Four- and 6-year-olds also produced higher standard deviation of relative phase at all rates than did adults. Discussion examines differences in movement control and the rate–amplitude relation as a consequence of weaker coupling strength in young children than in older children and adults.

From an information processing perspective, learning and development serves to reduce error (R. A. Schmidt, 1975). As ecological psychologists, we recast error as meaningful patterns of variability and stability that are indicative of learning and development. Dynamical systems is a theoretical approach with mathematical

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techniques that capture lawful changes in stability, particularly in the area of motor coordination (Smith & Thelen, 1993; Thelen & Smith, 1994; van Geert, 1994). This article examines movement stability to determine differences in control and coordination of a bimanual circle-drawing task among 4-, 6-, and 8-year-old children, and adults.

## DEVELOPMENT OF COUPLING STRENGTH

The dynamics of bimanual coordination are captured by the Haken, Kelso, and Bunz (1985) model (HKB model). Two patterns may be performed spontaneously, that is, without practice: in-phase and antiphase. Those are the attractors of the coordination dynamics. When the limbs that are used to produce in-phase and antiphase are physically identical (same size, weight, orientation), stability of the two patterns changes as a function of the strength of the coupling between the limbs. *Coupling strength* is an abstract term for the influence of one limb on another. As coupling strength increases, relative coordination is observed, where a pattern is identifiable but not performed precisely. This slight imperfection, or variability, characterizes most adult performance. Greater coupling strength is identified with more stable pattern production. In the limit, rigid coupling should produce absolute coordination, the maintenance of a single pattern with no variability observed. Bimanual coordination dynamics are general and persistent; they have been demonstrated for one-person and two-person coordination (e.g., P. G. Amazeen, Schmidt, & Turvey, 1995; R. C. Schmidt, Carello, & Turvey, 1990), for one-dimensional and two-dimensional movements (e.g., Semjen, Summers, & Cattaert, 1995), and for both adults and children (e.g., Fitzpatrick, Schmidt, & Lockman, 1996).

Coupling strength, however, can change as a function of task constraints, practice, and age. One example of a task constraint is movement rate, which is inversely related to coupling strength (Kelso, 1984, 1995; Sternad, Turvey, & Schmidt, 1992). At low movement rates, both in-phase and antiphase are produced quite stably. As rate is increased, variability of both patterns increases. Performance of antiphase is no longer possible at a critically high rate, and an abrupt transition is observed to in-phase. At extremely high rates, phase wandering is observed. In a bimanual drawing task, coupling is a measure of the strength of coordination between the hands, which is determined from variability and stability measures such that low variability of relative phase and high stability of coordination (e.g., little time in less stable coordination patterns) represent strong coupling.

Other research shows that, with practice, we can learn to produce patterns other than the spontaneously adopted in-phase and antiphase patterns (e.g., P. G. Amazeen, 2002; Kelso & Zanone, 2002; Zanone & Kelso, 1992, 1997). During practice, we progress from not being able to sustain the practiced pattern for any length of time to performing it stably. Analysis of the dimensionality of movements reveals that the dynamical attractors for learned movements decrease in size and become simpler over the course of learning (P. G. Amazeen, 2002; Mitra, Amazeen, & Turvey, 1998). The implication is that practice serves to minimize the control space for that particular pattern.

Although there has been minimal bimanual coordination research in childhood, a scenario similar to learning was observed. Research in childhood has shown high coordination variability, increased numbers of transitions, and less time spent in stable coordination patterns than adults. These results are behavioral indications of weak coupling strength, which is suggested to strengthen as age increases (Fitzpatrick et al., 1996; Robertson, 2001). One consequence of increased coupling strength during learning and development is the ability to select, from a varied repertoire of patterns, the one that we intend to perform (Scholz & Kelso, 1990). Thus, one goal of this study is to evaluate the development of coupling strength across development. Furthermore, a consequence of weak coupling strength in young children may correspond to an attempt to control movement stability in ways that children find controllable (e.g., increasing movement amplitude and using a positive rate–amplitude relation) when movements become challenging.

## DEVELOPMENT OF INTENTIONAL CONTROL

As development progresses, children have an increased ability to intentionally control their movements. As a child's limbs change size, and as they gain muscular control over their activities, they are able to produce more complex and goal-directed coordinative patterns, such as reaching (Thelen et al., 1993), clapping (Fitzpatrick et al., 1996), tapping (Volman & Geuze, 2000), walking (Clark & Phillips, 1991; Whitall & Clark, 1994), drawing (Robertson, 2001), and writing (Birch & Lefford, 1967; Reimer, Eaves, Richards, & Chrichton, 1975). Because children's bodies are still changing, they may solve task constraints differently than adults. In this study, we instructed 4-, 6-, and 8-year-old children, and adults to trace circles of different sizes on different trials and measured amplitude, shape, and variability of movement to determine whether children at different ages can respond to instructions to perform circle drawing of different sizes.

## DEVELOPMENT OF THE RATE–AMPLITUDE RELATION

Previous bimanual circle- and line-drawing studies have shown a relation between rate and amplitude in children when amplitude was self-selected. The finding was that young children draw larger when they draw faster (Robertson, 2001; Robertson, Van Gemmert, & Maraj, 2002). This result is a reversal of an inverse rate–amplitude relation that is commonly seen in adults (e.g., Beek, Schmidt, Morris, Sim, & Turvey, 1995; Haken, et al., 1985; Kay, Kelso, Saltzman, & Schoner, 1987).

Despite the complexity of bimanual circle drawing, it exhibits nearly the same coordination dynamics as one-dimensional bimanual movements, such as tapping and clapping (Semjen et al., 1995). A major exception is the rate–amplitude relation. As predicted by the HKB model with a hybrid oscillator, the phase transition from antiphase to in-phase is mediated by a drop in amplitude that occurs as a person moves more quickly (Beek et al., 1995; Kay et al., 1987). This was shown across different types of movements in which a limb moved along a single dimension: wrist flexion–extension (Kay et al., 1987), elbow flexion–extension (Post, Peper, & Beek, 2000), and hand-held pendular movement (Beek et al., 1995). One study showed transitions for constant or slightly increasing amplitudes, but those amplitudes were manipulated explicitly (Peper & Beek, 1998).

The rate–amplitude relation also has been investigated in two-dimensional nonreversal unimanual movements (elliptical drawing) in adults (Viviani & Cenzato, 1985; Viviani & Flash, 1995) and children (Vinter & Mounoud, 1991; Viviani & Schneider, 1991), and bimanual circle drawing in adults (Ryu & Buchanan, 2004). Generally, the results of this research showed that when amplitude was manipulated and rate was left free to vary, amplitude increased as rate increased. When rate was manipulated and amplitude was left free to vary in bimanual circle drawing, adults held amplitude fairly constant across increases in movement rate and variability, whereas the rate–amplitude relation was reversed for children: Amplitudes increased rather than decreased with increases in movement rate (Robertson, 2001). This effect was replicated in a follow-up study in which rate was decreased during the course of a trial: Children decreased their circle size as movement rate decreased (Ringenbach, Ericsson, & Kao, 2003). In this study we vary amplitude explicitly to determine whether a positive rate–amplitude relation still exists in children.

We used a representative age range spanning early to middle childhood (i.e., 4-, 6-, and 8-year-olds) and an adult comparison group. These ages are appropriate for our task because children start drawing shapes around 3 years of age and stabilize their writing skills between the ages of 5 and 7 (Birch & Lefford, 1967; Reimer et al., 1975). Stability of coordination was probed by increasing movement rate during the trial while participants were instructed to trace similar-sized circle templates with both hands simultaneously in whatever coordination pattern was most comfortable. Circle templates of different sizes were used across trials. This is the first study, to our knowledge, that has examined multiple aspects of circle drawing (e.g., rate, amplitude, shape) in concert with coordination stability in children and adults.

This study was designed to examine three issues: First, we evaluated behavioral indications that coupling strength is weak in young children and increases developmentally. Decreases in coordination variability (standard deviation of relative phase) and increases in stability (more time in in-phase and less time in antiphase and intermediate phase) across increasing age groups will indicate that coupling strength increases as age increases. Second, we examined whether the ability to intentionally control movement changes throughout childhood. Movements that do not conform to the instructions will indicate a lack of intentional motor control. In general we predict that the variability of all measures will decrease as development of motor control progresses. Specifically, we predict that children can increase rate of bimanual circle drawing but will be slower than adults. Similarly, young children will draw less circular circles than older children and adults. More important, we predict that young children may have trouble drawing small circles stably. Last, we explicitly investigated the rate–amplitude relation in bimanual circle drawing across development. We expect that amplitude will change as a function of movement rate, with adults decreasing circle amplitude and children increasing circle amplitude with increases in movement rate.

## METHOD

### Participants

There were 10 participants in each age group: 4-year-olds ($M_4 = 4.4$, $s_4 = 0.48$), 6-year-olds ($M_6 = 6.3$, $s_6 = 0.71$), 8-year-olds ($M_8 = 8.3$, $s_8 = 0.83$), and adults ($M_{adult} = 24.1$, $s_{adult} = 2.7$). All participants were screened for handedness using a shortened six-item handedness inventory[1] (Oldfield, 1971), and only right-handed participants were included in the study. All participants had normal or corrected-to-normal vision. The Human Subjects Institutional Review Board of Arizona State University approved all protocols.

### Task and Apparatus

The task was to trace identical circles with each hand at the same time while rate increased throughout a trial. It has been shown that young children have difficulty following a metronome (Fitzpatrick et al., 1996; Volman & Geuze, 2000). Thus, the increase in movement rate was achieved by asking the participant to "begin slowly"; after 10 sec the experimenter said, "draw faster," and after 10 more sec the experimenter said, "draw as fast as you can!" The experimenter continued to encourage the participant verbally until the end of the trial. Circle size was manipulated between trials by instructing participants to trace circle templates that varied in diameter (5, 10, 15, and 20 cm). Circle templates were printed in black ink on

[1]The Oldfield (1971) handedness questionnaire was physically performed by child groups and verbally answered by adults. All children wrote their name with a pen, drew a circle with a pen, used scissors to cut paper, threw a tennis ball, pretended to eat with a spoon, and pretended to brush their teeth. If four of the six items were performed with the right hand, the participant was included in the experiment. Thus, all participants were dominantly right-handed.

white poster boards (50 cm deep and 86 cm wide) and placed on a tabletop. The centers of the circles were held constant (approximately 30 cm apart and 20 cm from the front of the table) across all circle sizes and participants. Participants wore rubber thimbles on the index fingers of both hands. A sensor was mounted on each thimble, from which data were collected at a sampling rate of 120 Hz (samples per sec) using a three-dimensional data collection system (Polhemus Ultratrak™ [Polhemus, Colchester, Vermont] and Skill Technologies™ software [Phoenix, Arizona]; see Figures 1 and 2).

## Procedure

Participants were seated at a table in a wooden chair that could be positioned at a comfortable height for each participant. On arrival, participants read (or were read) and signed the informed consent forms. A parent or guardian also signed a consent form when appropriate. Next, we administered and scored the handedness inventory. We attached a sensor to each rubber thimble, which we then placed over the index finger of each hand. We secured the sensor wires to the arms using Velcro straps. We instructed the participants to draw circles in whatever manner of coordination between the hands was most comfortable. Four trials were performed

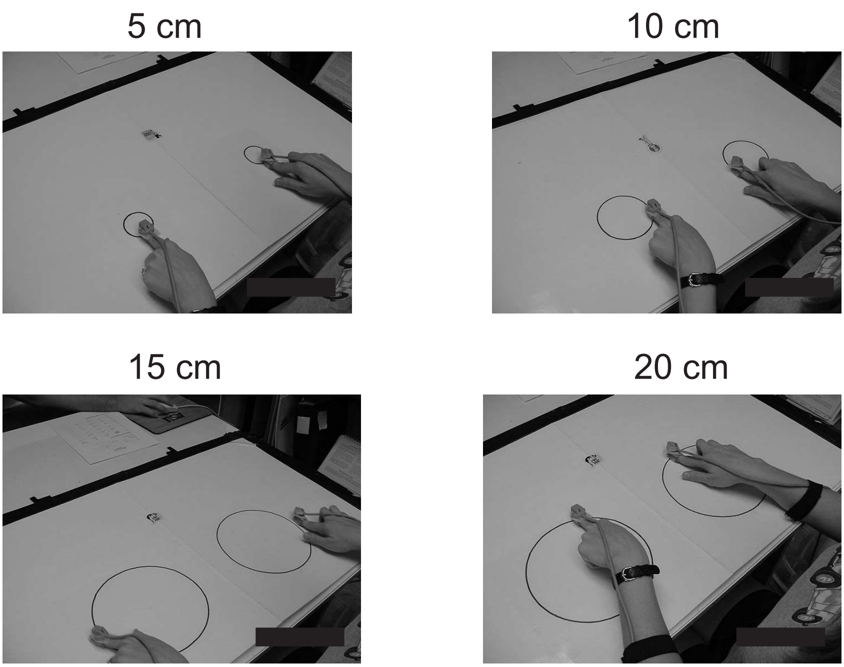


FIGURE 1 Experimental setup of the four different sizes of circle templates used for bimanual circle drawing in all groups.

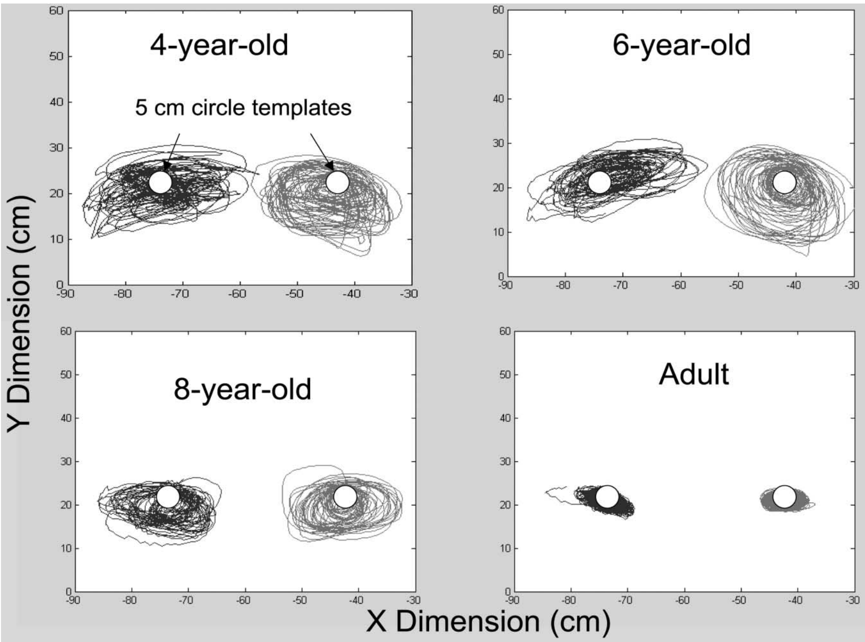


FIGURE 2 Representative tracings of entire trial (e.g., slow, fast, and fastest) for the 5 cm bimanual circle drawing condition for each group.

for each of the circle sizes (5, 10, 15, and 20 cm). Trial order was randomized in blocks for different amplitude conditions to minimize the exchange of circle templates. Participants were permitted to rest after each trial until they were ready for the next trial. The testing session lasted approximately 30 min.

## Data Collection and Reduction

The position-movement data were collected in the *x* dimension, which corresponded to medial–lateral (side-to-side) movements and in the *y* dimension, which corresponded to anterior–posterior (front-to-back) movements. All data were filtered using a fifth-order 6-Hz Butterworth filter in both the forward and backward directions. For differentiation of the filtered data, a three-point central difference technique was used. All graphical and numerical techniques were completed using MATLAB™ (MathWorks, Natick, Massachusetts).

## Dependent Measures and Design

Movement rate was calculated as the number of movement cycles per sec (Hz). A *movement cycle* was defined as the time for one front-to-back motion (i.e., minimum displacement) in the *y* dimension. The mean and coefficient of variation (CV) of movement rate provided estimates of the central tendency and the variability within a single trial. The CV of movement rate was calculated by dividing the standard deviation of movement rate in the *y* dimension by the mean of movement rate in the *y* dimension. In keeping with previous developmental research using similar tasks (Ringenbach, Chua, Maraj, Kao, & Weeks, 2002; Robertson et al., 2002), this measure was used for variability of movement rate to eliminate any differences in variability due to differences in movement rate across the age groups.

Movement amplitude was calculated as the diameter (maximum value – minimum value) of the drawn circle in both the *x* and *y* dimensions. Like rate, amplitude was calculated cycle by cycle and then averaged over a trial. The standard deviation of amplitude provided an estimate of amplitude variability. An aspect ratio of the *x* and *y* amplitudes was used to estimate the shape of the circle (1.0 indicates a perfect circle; Franz, Zelaznik, & McCabe, 1991), which also was calculated cycle by cycle and then averaged over a trial. The standard deviation of the aspect ratio was used as an index of the variability of spatial performance.

Relative phase was measured in the *x* dimension. To obtain a continuous measure of relative phase, the displacement and velocity records for each movement cycle were normalized. The absolute difference between the phase angles of the left and right hands was calculated for each sample. The mean and standard deviation of relative phase were calculated across samples within a trial. In keeping with the standards set by previous studies (e.g., Carson, Thomas, Summers, Walters, & Semjen, 1997; Robertson, 2001; Scholz & Kelso, 1990), relative-phase values between 0° and 45° described in-phase; values between 135° and 180° described antiphase; and the range of 46° to 134° described intermediate phase. The standard deviation of relative phase served as the first index of coordination stability. The percentage of time during a trial spent in each of these coordination patterns served as a second index of coordination stability.

Analyses of variance (ANOVAs) were performed on the mean and CV of movement rate, the mean and standard deviation of amplitude, and aspect ratio. Six mixed-factorial ANOVAs were conducted with a between-group variable of group (4, 6, 8, and adult) and three repeated measures variables of circle size (5-, 10-, 15-, and 20-cm bimanual circles), hand (right, left), and instructed rate (slow, faster, fastest). A familywise Bonferroni adjustment was used to adjust the alpha level to 0.0083 for the evaluation of these unimanual analyses. Coordination analyses were conducted on the mean and standard deviation of relative phase and on percentage of time in each coordination pattern (in-phase, antiphase, intermediate phase). Five mixed-factorial ANOVAs were conducted with a between-group variable of group (4, 6, 8, and adult) and two repeated measures variables of circle size (5-, 10-, 15-, and 20-cm bimanual circles) and instructed rate (slow, faster, fastest). A familywise Bonferroni adjustment was used to adjust the alpha level to 0.002 for the evaluation of these bimanual coordination analyses. All significant and relevant results are reported.

## RESULTS

### Movement Rate

Three main effects were significant on the measure of mean movement rate: group, $F(3, 36) = 5.6, p < .004$; circle size, $F(3, 108) = 14.58, p < .0001$; and rate instruction, $F(2, 72) = 78.20, p < .0001$. Although the last effect confirmed the intentional manipulation of increasing rate as instructed, movement rates were slower in children than in adults ($M_4 = 1.1$ Hz, $M_6 = 1.4$ Hz, $M_8 = 1.1$ Hz, $M_{adult} = 1.8$ Hz). The similarity of movement rates in 4- and 8-year-olds is likely due to different factors. Four-year-olds' slow movement rate has been suggested to be associated with limited or distracted attention (Ringenbach et al., 2003; Robertson, 2001), whereas 8-year-olds' slow movement rate may be due to the overuse of feedback (Hay, 1984; Ringenbach et al, 2003). This experiment, however, cannot determine the cause of movement rate at different ages. The circle size and rate instruction main effects were clarified by the Circle Size × Rate Instruction interaction, $F(6, 216) = 4.63, p < .0003$. At the slow movement rate, the smaller circles were drawn faster than the larger circles, but this difference decreased at the fast, and disappeared at the fastest, instructed rate. On the measure of CV of movement rate, there were two main effects of group, $F(3, 36) = 5.26, p < .005$, and circle size, $F(3, 108) = 6.80, p < .0004$. Overall, movement rate was less variable for adults than for children ($M_4 = 20.1\%$, $M_6 = 18.6\%$, $M_8 = 14.7\%$, $M_{adult} = 9.5\%$) and less variable in the larger circles than in the smaller circles ($M_5 = 17.1\%$, $M_{10} = 16.7\%$, $M_{15} = 14.8\%$, $M_{20} = 14.3\%$).

### Movement Amplitude

On the variable of mean amplitude (in the *x* dimension), there were main effects of group, $F(3, 36) = 9.89, p < .0001$; circle size, $F(1, 108) = 220.93, p < .0001$; hand, $F(1, 36) = 9.61, p < .004$; and instructed rate, $F(2, 72) = 41.11, p < .0001$. These main effects were superseded by four two-way interactions: Group × Circle Size, $F(9, 108) = 2.77, p < .006$; Group × Instructed Rate, $F(6, 72) = 4.36, p < .001$; Circle Size × Instructed Rate, $F(6, 216) = 9.64, p < .0001$; and Hand × Instructed Rate, $F(2, 72) = 14.10, p < .0001$. The Group × Circle Size interaction is depicted in Figure 3. Overall, children (darker bars) produced larger movements than adults, and amplitude increased when instructed for all participants. However, younger children had difficulties matching the required amplitude of the templates, preferring to draw much larger circles than were required. They also did not differentiate among the circles to the same extent as the older children and adults: The size difference between the smallest and largest circles increased as age increased ($M_4 = 7.2$ cm, $M_6 = 9.6$ cm, $M_8 = 11.5$ cm, $M_{adult} = 12.6$ cm).

Figure 4 depicts the mean amplitude across instructed rate for all ages. In support of previous findings with children (Robertson, 2001; Robertson et al., 2002),

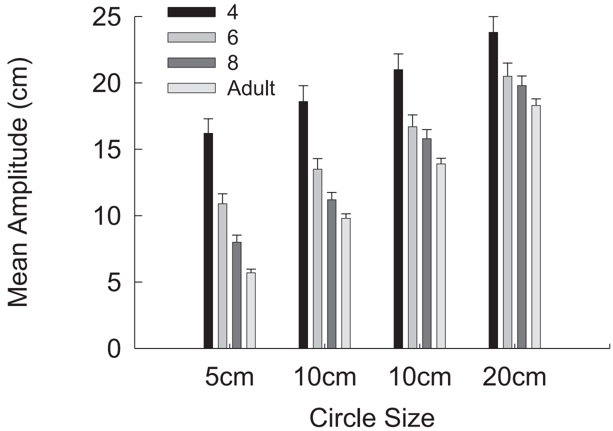


FIGURE 3 Mean amplitude as a function of group and task with standard error bars.

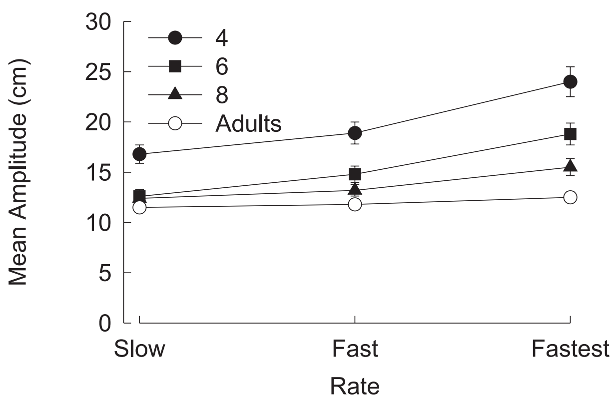


FIGURE 4 Mean amplitude as a function of group and instructed rate with standard error bars.

amplitude increased with increasing rate for the children, especially the 4-year-olds, but amplitude remained constant for adults. The Hand × Instructed Rate interaction revealed larger differences between the left and right hands at the fastest instructed rate, with the left hand producing larger amplitudes than the right hand. This manual asymmetry was present in all age groups, and thus is not a factor in group differences in coordination stability. The Circle Size × Instructed Rate interaction revealed that in general, the smaller circles increased in amplitude as rate increased, but the larger circles maintained their size at all rates.

The following main effects were significant on the measure of standard deviation of amplitude: group, $F(3, 36) = 26.92$, $p < .0001$; circle size, $F(3, 108) =$

18.48, $p < .0001$; and instructed rate, $F(2, 72) = 70.33$, $p < .0001$. Overall, children were more variable in amplitude than adults ($M_4 = 3.7$ cm, $M_6 = 2.7$ cm, $M_8 = 2.0$ cm, $M_{adult} = 1.2$ cm). This is what we expected because fine motor control improves as development progresses. Variability of amplitude increased as circle size increased ($M_5 = 2.1$ cm, $M_{10} = 2.3$ cm, $M_{15} = 2.5$ cm, $M_{20} = 2.7$ cm), and variability of amplitude increased with increasing rate ($M_{slow} = 1.8$ cm, $M_{fast} = 2.2$ cm, $M_{fastest} = 3.1$ cm). The former result is common as larger variability is associated with larger movements, and the latter is consistent with the HKB model predictions that as rate increases, stability decreases (i.e., variability increases).

## Aspect Ratio

Aspect ratio implies that higher values (e.g., closer to 1.0) represent more circular circles. For aspect ratio, there were main effects of circle size, $F(3, 108) = 11.74$, $p < .0001$, and instructed rate, $F(2, 72) = 25.76$, $p < .0001$. Circularity increased as circle size increased ($M_{5cm} = 0.83$, $M_{10cm} = 0.85$, $M_{15cm} = 0.86$, $M_{20} = 0.87$), and circularity decreased at the fastest rate ($M_{slow} = 0.88$, $M_{fast} = 0.87$, $M_{fastest} = 0.81$). On the measure of standard deviation of aspect ratio, there were main effects of group, $F(3, 36) = 4.81$, $p < .007$, and circle size, $F(3, 108) = 6.26$, $p < .0007$. These main effects were mediated by a Group × Circle Size × Hand interaction, $F(9, 108) = 2.91$, $p < .005$. Circle shape became more consistent as age group increased and as the circle being drawn increased in size. The interaction with hand was due to differences between the 4-year-olds and 6-year-olds when drawing 10-cm circles: 4-year-olds were more variable in drawing circles with their left hand and 6-year-olds were more variable in drawing circles with their right hand.

## Coordination Analysis: Relative Phase

For the measure of mean relative phase, there was only a main effect of instructed rate, $F(3, 72) = 5.98$, $p < .004$. Relative-phase values decreased as rate increased ($M_{slow} = 9.7°$, $M_{fast} = 7.6°$, $M_{fastest} = 6.7°$). Three significant main effects were found for standard deviation of relative phase: group, $F(3, 36) = 8.75$, $p < .0003$; circle size, $F(3, 108) = 22.55$, $p < .0001$; and instructed rate, $F(2, 72) = 52.86$, $p < .0001$. There were two significant two-way interactions, both of which clarified the instructed rate main effect. As can be seen in Figure 5, the Group × Instructed Rate interaction, $F(6, 72) = 3.74$, $p < .003$, showed that although variability increased during the trial for both 8-year-olds and adults, younger children displayed consistently high variability throughout the trial. The Circle Size × Instructed Rate interaction, $F(6, 216) = 4.04$, $p < .001$, showed that variability increased as rate increased, except for the 5-cm circle, in which variability increased only slightly as rate increased.

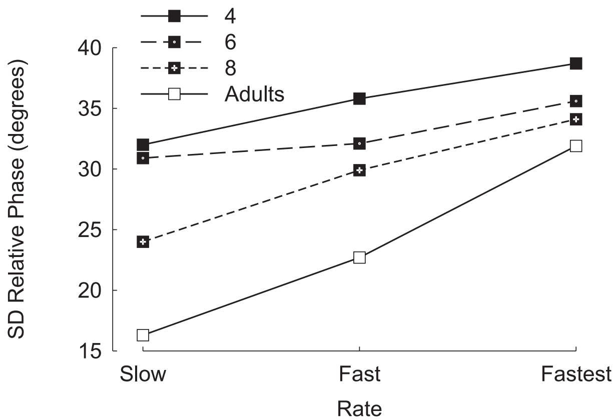


FIGURE 5 Standard deviation of relative phase as a function of group and instructed rate.

## Percentage of Time in Each Coordination Pattern

Another measure of coordination was the percentage of time spent in each of the three coordination patterns: in-phase, antiphase, and intermediate phase. There were two significant main effects on the measure of the percentage of time spent in in-phase: group, $F(3, 36) = 6.27$, $p < .002$, and circle size, $F(3, 108) = 6.20$, $p < .001$. Despite the lack of explicit instructions to maintain a particular coordination pattern, participants preferred to move in-phase. More time was spent in in-phase as age groups increased ($M_4 = 81\%$, $M_6 = 85\%$, $M_8 = 85\%$, $M_{adult} = 91\%$) and as circle size increased ($M_5 = 84\%$, $M_{10} = 84\%$, $M_{15} = 87\%$, $M_{20} = 87\%$). There were main effects of circle size, $F(3, 108) = 9.45$, $p < .0001$, and instructed rate, $F(2, 72) = 14.8$, $p < .0001$, on antiphase coordination. Complementing the circle-size effect for in-phase, less time was spent in antiphase as the circle size increased ($M_5 = 6.0\%$, $M_{10} = 6.2\%$, $M_{15} = 3.5\%$, $M_{20} = 3.4\%$). Surprisingly, and not predicted by the HKB model (Haken et al., 1985), the time spent in antiphase increased as rate increased ($M_{slow} = 3.6\%$, $M_{fast} = 4.3\%$, $M_{fastest} = 6.4\%$).

The amount of time spent in intermediate phase is inversely related to performance stability and is indicative of the shift from absolute coordination, in which the hands are tightly coupled and phase locked, to relative coordination, in which there is weak coupling between the hands and phase locking is intermittent or absent. On this measure, there were main effects of group, $F(3, 36) = 12.68$, $p < .0001$, and instructed rate, $F(2, 72) = 11.73$, $p < .0001$. Overall, all of the children spent more time than adults in intermediate-phase coordination ($M_4 = 12.8\%$, $M_6 = 10.1\%$, $M_8 = 10.2\%$, $M_{adult} = 5.5\%$), and the amount of time spent in intermediate-phase decreased at the fastest rate ($M_{slow} = 10.4\%$, $M_{fast} = 10.1\%$, $M_{fastest} = 8.4\%$).

## DISCUSSION

This study focused on the ability of children (4-, 6-, and 8-year-olds) and adults to draw circles of different sizes with increases in movement rate. We expected that weaker coupling strength for young children would lead to an increase in performance variability across several measures (e.g., rate, amplitude, shape, relative phase) and that children would compensate for decreased performance stability by increasing the size of their movements, particularly when movement rate was increased.

### Development of Coupling Strength

A number of developmental studies have equated coordination instabilities in young children to weaker coupling strength between the limbs (Clark, Whitall, & Phillips, 1988; Fitzpatrick et al., 1996; Robertson, 2001; Volman & Geuze, 2000). We know that movement rate is inversely related to coupling strength (Kelso, 1984, 1995; Sternad et al., 1992), so the effect of weaker coupling strength should be particularly evident at higher movement rates. In this study, stability decreased with increases in movement rate for adults and 8-year-old children, but not for the 4- and 6-year-olds, who demonstrated consistently low stability (high variability). Thus, our behavioral measures can be interpreted to suggest that younger children demonstrate weaker coupling strength than do older children and adults during bimanual circle drawing. Follow-up research to strengthen this argument should directly manipulate and measure coupling strength using the HKB model (Fitzpatrick et al., 1996; Haken et al., 1985). However, our results showed that younger children do not increase coordination variability as rate increases, as predicted by the HKB model (Haken et al., 1985). Perhaps young children are demonstrating a floor effect for coordination stability.

It is interesting to note that in 4- and 6-year-olds' lowered stability was observed despite the fact that children moved more slowly than adults across all circle sizes. It seems that in this type of continuous coordination task, young children do not trade speed for accuracy in accordance with Fitts's law (Fitts, 1954). Slower movement could be indicative of attentional limitations in children. It has been documented that young children are poorer than adults at maintaining attention (Anslin & Ciuffreda, 1982), and Fitzpatrick et al. (1996) suggested that poor coordination in bimanual coordination between 3 and 7 years of age was related to weaker coupling and decreased intentional resources needed to maintain coordination. The consequence of a shift in attention is well known for adult motor coordination but has not been manipulated in experiments with children. In adults, attractors are destabilized when they are asked to engage in a dual, coordination-cognitive task (Pellecchia & Turvey, 2001; Temprado, Zanone, Monno, & Laurent, 1999), and they are shifted when attention is directed to one hand or the other (E. L. Amazeen, Amazeen, Treffner, & Turvey, 1997). We expect that attractors for young children, which are already relatively weak, are very susceptible to destabilization with difficult task constraints.

## Development of Intentional Control

Robertson (2001) found that young children drew larger circles and had higher variability and lower coordination stability than older children and adults. One explanation is that young children increased the size of their circles as a function of increases in movement rate to compensate for a decrease in stability. Indeed, we found that performance stability increased significantly with the increase in circle size across all groups. However, the intentional control of circle size varied according to age. Although children changed circle size as instructed, the size difference between the smallest and largest circles increased as age increased. In this study, children tended to draw large circles: The size of the smallest circle that 4-year-olds drew for the 5-cm circle condition was 16.2 cm, almost as large as the largest circle size (for the 20-cm circle condition) drawn by adults and considerably larger than the 5.7-cm circles drawn by adults for the same condition. Thus, children were able to change the size of their circles according to instruction, but they did not differentiate circle size as much as the adults did. They were also able to change the rate of circle drawing, which, together with the size manipulation, indicates that they were able to attend to both sets of instructions simultaneously. The extent to which one set of instructions (amplitude or rate) was primarily attended to cannot be determined from this data but can be explored in future studies.

Bimanual circle drawing is a task that is readily understood by children; however, from a biomechanical level of analysis, the production of the requisite two-dimensional curvilinear trajectories is complex because it involves the control of multiple joints. In Robertson (2001), circle size was notably larger for young children than it was for older children or adults. This mimics an early finding that young children (4-year-olds) print larger than older children (Birch & Lefford, 1967; Reimer et al., 1975) and supports the proximodistal developmental maturation hypothesis that early in development children use larger, more proximal muscle groups to perform even fine motor control movements (e.g., drawing).

In support of this explanation, previous research on the motor control of the arm during circular drawing has reported a change from proximal (e.g., shoulders) to distal (e.g., fingers) muscular involvement as age increased (between 3 and 6 years; Ozaki, 2000). Observation of videotapes of the experimental sessions revealed that children, especially the 4-year-olds, tended to use their arms rather than their fingers to draw all sizes and rates of circle drawing, whereas adults used their distal limbs to perform all movements. Whether the use of the arms was intentional or not, the effect of using larger limb segments (with greater inertia) was to stabilize movements that tended to be rather variable. Our future research plans are to examine the muscular involvement using electromyography sensors as well as the kinematics of the multiple degrees of freedom used in this task by children.

### Development of the Rate–Amplitude Relation

The rate–amplitude relation changes as a function of both task and age. Previous research on one-dimensional reversal movements in adults showed that amplitude decreases as rate increases (e.g., Beek et al., 1995; Kay et al., 1987; Post et al., 2000). The results for two-dimensional movements have been mixed. For example, a positive rate–amplitude relation has been found in elliptical drawing and circle drawing in adults, in which amplitude was manipulated and rate was constant (Ryu & Buchanan, 2004; Viviani & Schneider, 1991), but when rate was manipulated and amplitude held constant, adults maintained amplitude with increases in rate (Robertson, 2001). In this study, a comparison of children and adults revealed the rate–amplitude relation to be dependent on age: Despite instructions to maintain a given amplitude, children increased circle size with increases in rate. This relation was greatest for 4-year-old children and decreased as a function of age. Adults were able to maintain a constant amplitude as instructed. These results are not predicted in an HKB model with a hybrid oscillator term (see Beek et al., 1995), thus further research is warranted. It is possible that young children did not understand the instruction to maintain circle size. However, given that larger circle sizes were more stable for both children and adults, it is equally plausible that children increased circle size to compensate for the decrease in stability that occurred for all participants with increasing movement rate. We believe that due to weak coupling strength, young children solve task constraints in different ways than adults (e.g., positive rate–amplitude relation).

## CONCLUSION

This study was designed to examine consequences of weak coupling strength (e.g., coordination instability) in children. Young children demonstrate weaker coupling strength than older children and adults, which is manifested in amplified performance variability and an inability to select some, but not all, aspects of performance. Young children were able to differentiate among circle sizes in the drawing task of this study but drew notably larger circles than did adults and increased their circle size as their movement rate increased. The consequence was a positive rate–amplitude relation that is opposite to the relation that is observed in adults across a range of one-dimensional and two-dimensional tasks. Thus, young children use rate and amplitude to compensate for weak coupling or coordination instability during bimanual circle drawing.

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