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The production of bimanual percussion in 12- to 24-month-old children

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Abstract

Bimanual coordination represents a complex self-organizing system that is subject to both internal and contextual constraints. Although there has been interest in examining bimanual development throughout the lifespan, few data exist relative to the bimanual activity of children between 1 and 4 years of age. The study reported here represents an initial effort to address this gap. Twenty-seven children who were either 12, 18 or 24 months old were videotaped while drumming with sticks on a plastic drum. Two independent observers recorded bout length as well as number and phase relation of movement cycles within bouts. Kinematic analysis provided more detailed information about the timing and form of children's activity. Results indicate that bimanual drumming becomes preferred over unimanual drumming by 2 years of age, that the proportions of different phase relations exhibited by children change between 1 and 2 years of age, and that the behavior appears to go through periods of stability and variability within this age range. These results are discussed in the context of the child's physical development and interactions with the environment during this period.

Keywords: Bimanual; Motor coordination; Motor development; Percussion; Phase relationships

1. Introduction

Skilled interlimb coordination of the two arms in bimanual action involves the precise organization of motor, perceptual and cognitive processes within a given context, all of which must be in place in order for the behavior pattern to occur successfully. Bimanual coordination is clearly important to adaptive human functioning, yet our understanding of its development during early childhood is incomplete. Such understanding is important in its own right as well as for its potential to contribute to improvements in diagnosis and characterization of developmental disorders such as dyslexia (Gladstone, Best, & Davidson, 1989; Wolff, Michel, Ovrut, & Drake, 1990) and developmental coordination disorder (Mandich, Buckolz, & Polatajko, 2002; Volman & Geuze, 1998).

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1.1. Coordinated bimanual movements as coupled oscillators

The development of skilled bimanual activity provides a valuable platform for systems-based examination of motor development across both microgenetic and ontogenetic time scales. There is an extensive literature on the control of bimanual activity in adults, and the ways in which self-organizing motor systems responding to environmental, cognitive, and neuromotor constraints affect the form and timing of coordinated movement (e.g., Bingham, Schmidt, Turvey, & Rosenblum, 1991; Carson, Riek, Smethurst, Parraga, & Byblow, 2000; Haken, Kelso, & Bunz, 1985; Newell, Liu, & Mayer-Kress, 2001; Park, Collins, & Turvey, 2001; Semjen, Summers, & Cattaert, 1995; Temprado, Swinnen, Carson, Tourment, & Laurent, 2003). As pointed out by Guiard (1987) and others (Fagard, 1991; Obhi, 2004), different types of bimanual skills, requiring different levels of symmetry and complementarity, exist in an individual's repertoire. Investigators of adult bimanual coordination, however, have primarily focused on the patterns of coordination that appear in cyclic movements such as continuous finger-tapping, pendulum-swinging, or circle-drawing with both hands. These actions have been used because they are motorically relatively straightforward, but are sensitive to changes in cognitive (Temprado, Monno, Zanone, & Kelso, 2002; Temprado, Zanone, Manno, & Laurent, 1999) and kinematic demands (Temprado et al., 2003), and allow analysis of many dimensions of movement. As continuous rather than discrete actions, these behaviors also can be indefinitely extended in time to allow for perturbations to be experimentally manipulated both within and between bouts.

Within this context of cyclic action, many authors characterize the two limbs' movements as a pair of coupled oscillators that interact with each other and self-organize at certain phase relations of movement (Yamanishi, Kawato, & Suzuki, 1980). In particular, the dynamic systems model, which provides a useful framework for description and analysis of coordinated movement, asserts that human adults' bimanual movement systems are strongly attracted to mirror-image, or 'in-phase' movements in which homologous right and left muscle groups are producing identical acts simultaneously (relative phase lag $\Phi = 0$). To a lesser extent, 'anti-phase' movement patterns, in which homologous muscle groups are simultaneously performing opposing acts ($\Phi = 180$; e.g. the left forefinger hits the top of the tapping cycle when the right hits the bottom), serve as a second type of attractor state. That these states are stable and preferred has been documented empirically in several studies (e.g., Cohen, 1971; Haken et al., 1985; Yamanishi et al., 1980). People tend to produce these patterns spontaneously over others and will even drift into them—especially the in-phase pattern—after starting with another pattern, especially if perturbations such as a change in tempo or attentional demand are introduced (Haken et al., 1985; Pellecchia & Turvey, 2001; Temprado et al., 1999; Yamanishi et al., 1980).

1.2. Bimanual coordination in school-aged children and infants

Several investigators have examined the performance of children as young as 4 years of age on bimanual tasks similar to those assessed in adults (e.g., Fagard & Peze, 1992; Njiokiktjien et al., 1997; Robertson, 2001; Wolff, 1998). These studies indicate that there appears to be strong motor coupling between the two hands in children of all ages. However, as expected, there are several developmental changes that appear to occur between the ages of 4 and 11 years. In particular, children are more variable in timing many of their bimanual movements than are adults; their hand movements are coupled, but response times from one sequence or cycle of action to the next may not be stable (Njiokiktjien et al., 1997; Robertson, 2001; Wolff, 1998). Children also tend to move at a slower pace when performing repetitive actions, such as finger-tapping or circle-drawing, when compared with adults (Fagard, Hardy-Leger, Kervella, & Marks, 2001). It also appears more difficult for younger children to initiate release from the strongly coupled action patterns in order to practice or perform new patterns (Fagard, 1987). These changes all relate to improving control of bimanual coordination as children get older.

The changes experienced by young children in various aspects of bimanual control have been attributed by some to maturing systems, in particular those facilitating efficient interhemispheric communication (Fagard et al., 2001; Njiokiktjien et al., 1997; Wolff, 1998) and executive control such as sustained attention (Robertson, 2001) or response inhibition (Wolff, 1998). However, these maturational changes are accompanied not only by development of peripheral physical systems (e.g., changes in arm muscle strength) but also by experience-based changes such as increased practice with many action patterns (e.g., locomotion, drawing, and so on) as well as the encounter of new tasks and environments that require new behavioral responses to be developed. Some or all of these factors may contribute to developing bimanual skill; thus, this represents a complex system that appears to be amenable to ecologically-based analyses.

To date, few investigators have attempted to examine cyclic behavior patterns such as finger-tapping in children younger than 4 years of age. This may be in part because of the difficulties experienced by younger children both in producing the precise fine-motor acts examined in adults and in responding reliably to verbal instructions in an experimental setting. Instead, in response to the challenges of working with infants and young children, investigators have typically used structured play situations that take advantage of the infant's spontaneous exploratory or play actions when assessing bimanual activity. The behaviors elicited, such as reaching (Corbetta & Thelen, 1996; Fagard & Peze, 1997; Goldfield & Michel, 1986), have tended to be discrete rather than continuous, in contrast to the types of behaviors typically measured in older children and adults.

As with other, more extensively studied motor systems such as locomotion (e.g., Thelen & Ulrich, 1991), however, the development of bimanual coordination in young children is a continuous process marked by apparently discrete behavioral stages. From birth, there is evidence of motor coupling between the two arms and it is not until approximately 10 months of age that goal-directed role-differentiated activity—when the two hands perform different actions and thus fill different roles—is first observed (Bruner, 1970; Fagard & Jaquet, 1989; Goldfeld & Michel, 1986). Typically, early role differentiation occurs when one hand performs a support function, such as holding an object, while the other hand is used to explore or manipulate the object. This development represents a step forward in the infant's interlimb control in that it requires separate yet integrated/coordinated motor sequences for each limb. However, it still represents a relatively simple coordination mode in that one hand often serves only a support/stability role while the other performs the bulk of the manipulatory action. Development of different types and complexity of role differentiation continues through at least 2 years of age for some types of tasks (Fagard & Jacquet, 1989), but little else is known about bimanual coordination in this age range.

1.3. Addressing a gap in the literature

Because of the different theoretical and empirical traditions in the adult and infant research on bimanual activity, there tend to be few points of contact between the two literatures (however, see Corbetta and Thelen, 1996 for a dynamic systems approach to infant reaching). For example, the discrete actions studied in infants do not allow one to examine within-bout stability and variability in the same way as extended cyclic behavior patterns—such as rhythmic percussion—do. This gap is compounded by the scarcity of empirical literature of any approach reporting the bimanual activity of children between the ages of 1 and 3 years. This age range is replete with contextual, behavioral and neurological changes, and yet with few exceptions (e.g., Fagard & Marks, 2000), children between infancy and school age have not been included in the literature. Changes in attentional control (e.g., Case, 1985; Ruff & Rothbart, 1996), motor control (e.g., Kochanska, Murray, & Harlan, 2000), representational complexity (Langer, 1986), response inhibition (Diamond & Gilbert, 1989), and other skills during this period are supported by neural reorganization and development of areas such as the prefrontal cortex and corpus callosum (Case, 1992; Thatcher, 1997). At the same time, children are changing physically and gaining experience with a wide variety of different environmental contexts. All of these elements have the potential to facilitate increasing complexity and flexibility of interlimb coordination in young children. Nonetheless, little attention has been given to the development of bimanual skill in older infants and preschool children, who are developing executive control competencies at the same time as they are exposed to a wide range of new tasks that require sophisticated coordination patterns.

This study represents a first step in addressing the empirical and theoretical gap that exists in the study of the development of bimanual coordination. In order to provide a complete picture of dynamic systems development, of course, it is necessary to address the four objectives of such research as outlined by Thelen and Smith (1994). These are (1) identifying an observable and informative collective variable; (2) characterizing the attractor states of the system; (3) describing the developmental trajectory of the collective variable through longitudinal study; and (4) identifying points of transition from one preferred state to another. The current research has focused on addressing only the first two of these issues; the final two steps await longitudinal study.

Here, children at 12, 18 and 24 months of age perform a cyclic, rhythmic percussion activity that is commonly recognized as drumming. We selected this activity because we believed it would provide a gross-motor analog to bimanual finger-tapping, and because children in this age range frequently and spontaneously engage in it in a variety of play contexts. It also produces a useful collective variable, relative phase, along with potential in-phase and anti-phase attractor states, that can be used to describe the activity of the system. Here, we report observational data scored from videotapes supplemented by kinematic analysis of drumstick displacement in a subset of the activity bouts.

Following evidence from existing studies (Fagard & Jacquet, 1989; Ledebt, 2000) suggesting increasing bimanual flexibility in different contexts during the second year of life, we hypothesized that older children would more frequently engage in bimanual percussion than younger children, and that children's bimanual activity would be characterized by different predominant coordination patterns at different ages. Specifically, because in-phase motion exploits the symmetrical coupling that appears to be strongly expressed in much of infants' early two-handed activity (Corbetta & Thelen, 1996; Ramsey, 1985) and stable adult finger-tapping (e.g., Haken et al., 1985), we expected in-phase patterns to appear at a younger age than anti-phase patterns, which require some degree of release from coupling.

Also, given that one of the tenets of developmental systems analysis is that behavioral change incurs a period of variability as individuals make the transition from one stable behavioral pattern to another, whether it be along microgenetic or ontogenetic time scales (Thelen & Smith, 1994), we believed that we would see this pattern reflected across children, with some children demonstrating a high degree of variability within and between bouts in this domain, and others currently in a stable period of behavior expressed either unimanually or bimanually. To the extent that these periods were associated with the different age groups being examined, these cross-sectional data would potentially "map the boundaries of change" (Thelen & Smith, 1994. p. 97) that occur in this domain during this period of life and lay the groundwork for future longitudinal and experimental studies of early bimanual coordination.

2. Method

2.1. Participants

Participants included 27 typically-developing children within 2 weeks of 12 ($n = 8$), 18 ($n = 9$), or 24 months ($n = 11$) of age recruited through daycares and personal contacts in a small university town in the southeastern US. Eighteen of the children were male. Three children were of Hispanic descent, one of Asian descent, one of African descent, and the remaining children of European descent. One 24-month-old refused to engage in any of the target tasks and was omitted from the analyses, leaving a final n of 10 in the oldest age group. At least one parent accompanied each child to the test session and gave informed consent for the child's participation in the study as well as for restricted use of the videotaped images produced during the sessions.

2.2. Apparatus and materials

Children were videotaped with a Panasonic camcorder placed on a tripod directly in front of the test platform, and the videotape from this camera was used as the basis for the observational analyses reported here. In addition, four high-speed video cameras were placed to the left, left-front, right-front, and right of the child in order to facilitate kinematic analysis. A spotlight was placed next to each of these four cameras. Cameras were placed approximately 3–4 m away from the child. Fig. 1 provides a schematic representation of the test area.

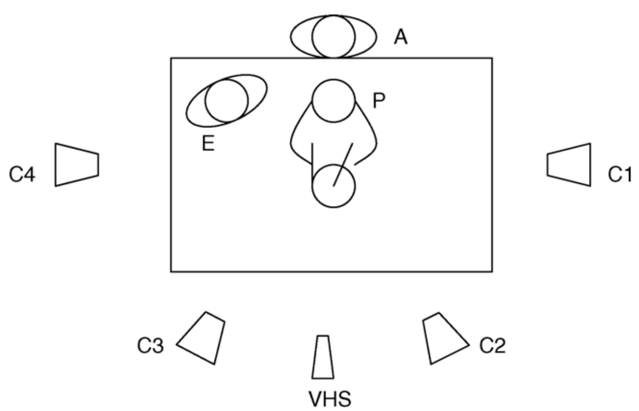

Fig. 1. Schematic aerial view of testing. Child participant P sits on a slightly raised platform in front of adult parent A. Experimenter E sits to the side. Four high-speed cameras C1–C4 and one VHS camera record the child's activity.

Materials used for task production included a 17 cm diameter × 8.5 cm high plastic container with a lid that was covered with black contact paper, which served as a drum. Two red plastic drumsticks 15 cm long with 2.5 cm spherical heads were connected to each other and to the drum by a nylon cord, with each stick extending from the drum with about 40 cm of cord. The back ends of the sticks were connected to the drum in order to allow freedom of motion while keeping the apparatus together and preventing non-target actions such as throwing of the sticks.

Each child sat on a .9 m × 1.2 m wooden platform covered in black contact paper. The platform rested 4 cm above the floor, to bring the child's activity within range of the calibrated space identified for kinematic analysis.

In order to enhance the visibility of action, children either wore their own dark long-sleeved shirt on which 1 cm^2 pieces of reflective tape were placed at each shoulder, elbow, and wrist, or a special long-sleeved black polyester shirt with a Velcro closure down the back and strips of Velcro on the sleeves. Small spherical reflective markers (1/2 to 1 cm) were attached to the Velcro strips at each shoulder, elbow, and wrist. These were placed on clothing to avoid contact with the children's potentially sensitive skin. Reflective tape was also placed on the drumstick tips, the center of the drum's top surface, and at three reference points at the edge of the calibrated test area. These positions of the markers served as the basis for the digitized model of action that was produced using a Peak Motus™ (v. 6.1) motion measurement system.

2.3. Procedure

All sessions took place in the university's biomechanics laboratory. Upon arrival at the laboratory, parents were given an overview of the upcoming session and asked to sign permission forms while the child became accustomed to the setting and personnel through play and exploration. When the parent indicated that she or he and the child were ready to continue, each was asked to don a long-sleeved black shirt if they were not already wearing something dark. This clothing facilitated analysis of the child's actions by making the light-reflective markers on the child's arms easier to identify and track, and also allowed experimenters to attach markers to the child's clothing rather than skin. Because we did not specify legwear, however, some children wore shorts and the reflection from the skin on their legs sometimes interfered with digitizing the position of the drumsticks. We included these bouts in the observational analyses, but in many cases were unable to do so with the kinematic analyses.

The parent was asked to sit cross-legged on the floor immediately behind the slightly raised test platform. The child was seated directly in front of, with his or her back to, the parent. In this way, the parent could both physically support the child in a seated position if necessary as well as encourage him or her to attend to the tasks at hand. The experimenter sat to the side and slightly behind the child so that she could reach forward and demonstrate tasks without blocking any camera views.

Each child was asked to engage in seven percussive tasks. Four of these tasks involved unimanually hammering pegs into a pegboard with different types of hammers; data from these tasks will be reported in a separate manuscript. Alternating with these tasks were three bimanual tasks. The first engaged the child in banging two small wooden cymbals together, the second was the drumming task reported here, and the third was to slide two metal knobs along tracks that ran laterally in front of the child. Of these tasks, the drumming activity yielded the greatest amount of data and the greatest range of behavioral patterns across children, so this task has been analyzed first.

The task reported herein involved drumming with two plastic drumsticks after a brief demonstration. Children were allowed to engage in the activity for as long as they were interested; this period of time lasted from only a few seconds up to $4\frac{1}{2}$ min. Also, the children were allowed to produce the percussive actions with the objects in any orientation; for example, the drumsticks could be moved along a vertical or angled axis. Nearly all activity bouts were vertical or nearly so, so this is the dimension that served as the basis for the motion analysis.

2.4. Observational data analysis

The first round of analysis included manual observational coding of percussion behavior visible on the VHS videotape. For the purposes of this scoring and analysis, bouts were defined as sequences of continuous activity that were separated by pauses of 2 s or more, by abrupt change in the direction of movement, or by change between unimanual and bimanual action. The primary axis of movement for each bout could be vertical or angled, with drumsticks striking the top or side of the drum respectively. Each scored bout of action served as a trial that potentially could be identified on the high-speed videotapes and later isolated, synchronized, and digitized for motion analysis purposes. Because many of the analyses focused on the phase relationships and timing within each bout, a bout was only scored if at least one drumstick contacted the drum top three or more times, resulting in at least two movement cycles. Variables produced by this initial analysis include number of activity cycles within each bout, unimanual versus bimanual engagement, and phase relations between the two hands in bimanual bouts.

The predominant phase relationship for each bout was assigned one of four codes. ‘In-phase’ bouts were those for which the two hands were perceived by the observer to be moving symmetrically, with drum strikes occurring simultaneously. If one hand appeared to be leading and striking the drum slightly ahead of the other, with approximately a 90° phase lag, it was called an ‘off-phase’ bout. ‘Anti-phase’ bouts were those perceived as including predominant motion of the two drumsticks in opposite directions with approximately 180° lag, so that one stick reached its highest point as the other struck the drum. Finally, those bouts for which no clearly prevalent pattern could be perceived were assigned to a category called ‘inconsistent’. This category included bouts in which one hand might be moving erratically so that a one-to-one ratio of right to left beats was not established, and bouts in which the child held one stick to the drum top without clear oscillatory movement. These bouts were included in analysis because the intent to include both hands in the activity appeared to be extant and this type of action represented a potential transitory stage in the mastery of the task.

2.5. Interobserver reliability of observational coding

Three trained observers participated in coding behaviors from the videotaped records. Two of the observers independently coded each participant’s complete drumming test session; each pair of observers’ codes were compared for one-third of the participants (e.g., observers A and B coded eight participants). This allowed interobserver reliability to be measured for the entire data set across the three pairs of observers. Percent agreement between each pair was calculated for bout occurrence, unimanual versus bimanual activity, phase relationship, and number of cycles in the bout. Interobserver agreement for bout occurrence was 92–100% between the pairs of observers; for unimanual versus bimanual, 98–100%; for phase relationship, 86–100%; and for number of cycles, 92–100%. In all cases, data from the person designated as primary coder for each child were used in analyses.

2.6. Analysis of kinematic data

Using the Peak Motus™ (v. 6.1) motion measurement system, for all bouts that met the criterion of an acceptable bout, the reflective markers were digitized from the video, transformed into 3D coordinates (modified, direct linear transformation), and filtered using a quintic spline (with smoothing factor selected using an optimized, least squares routine). Criteria for usable bouts included aspects of the activity itself, such as including a minimum of three movement cycles, and characteristics related to the videotaping of the bout, such as markers being visible at all times from at least two of the cameras. Although a number of quantities were produced, only the vertical displacement data for the drumsticks were used for the kinematic analyses reported herein. Additionally, because the data set included a limited number of bouts, analysis was restricted to descriptive characterization of individual participants, a common technique used in studies of biomechanics.

3. Results

Observational analysis of the videotapes suggested that this context is a useful one to study the emergence of bimanual percussion in young children, and that such activity emerges between 12 and 24 months of age in many children. Most of the children in the study produced unimanual bouts of drumming, suggesting that the activity was one that interested these children, even in a laboratory setting surrounded by cameras and bright lights (Fig. 2).

The mean number of unimanual bouts remained relatively constant at 2–3 bouts per child (S.D.s 2.14, 1.76 and 4.03, medians 1.5–2.0, respectively) across all ages (Fig. 3). Despite their interest in the drum, only one 12-month-old, five 18-month-olds, and seven 24-month-olds produced bimanual bouts. The mean number of bimanual bouts produced was 1.0 (S.D. 2.83, median 0; range 0–8) at 12 months, 3.0 (S.D. 3.61, median 4.0; range 0–9) at 18 months, and 6.7 (S.D. 11.48, median 3.0; range 0–38) at 24 months. This is consistent with the hypothesis that bimanual drumming is a skill that is just starting to develop during the second year of life.

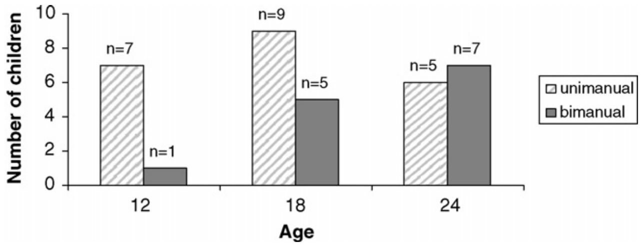

Fig. 2. Number of children producing unimanual and bimanual percussion bouts in each age group.

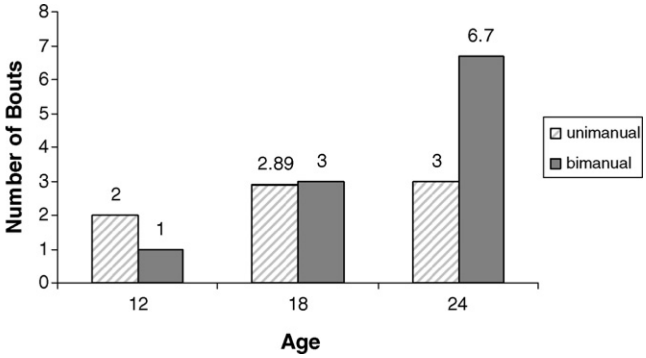

Fig. 3. Mean number of unimanual and bimanual bouts produced by each child. Numbers include children who produced zero bouts within one condition.

3.1. Production of unimanual and bimanual percussion bouts

In order to further characterize the bimanual activity of children within this context, the number of percussion cycles within each bout ("bout length") was recorded. A percussion cycle was defined as the vertical or angled movement of a drumstick from the point at which it strikes the drumhead one time until it strikes the drumhead the next time, i.e. the cycle of movement from drum-strike to drum-strike. Bout length was determined by the first drumstick to strike the drum head and was counted for that limb only. Because the number of bouts produced by different children varied widely, the mean bout length for each child was computed, and then each child's average was used to calculate an average for the age group, so that each child's behavior contributed equally to the group figures. As shown in Fig. 4, unimanual bout length decreased slightly as age increased, while bimanual bout length remained relatively constant among those who engaged in such activity. The mean number of unimanual action cycles per bout produced was 7.34 (S.D. 4.24) at 12 months, 6.80 (S.D. 3.23) at 18 months, and 5.17 (S.D. 1.31) at 24 months. For bimanual bouts, the means were 8.38 (S.D. 2.07) at 12 months, 8.60 (S.D. 5.46) at 18 months, and 7.41 (S.D. 2.68) at 24 months.

Independent samples *t*-tests comparing average bout length of 18- and 24-month olds revealed no significant difference among children in the two age groups who engaged in unimanual activity [$t(11.35) = 1.35$, ns] or bimanual

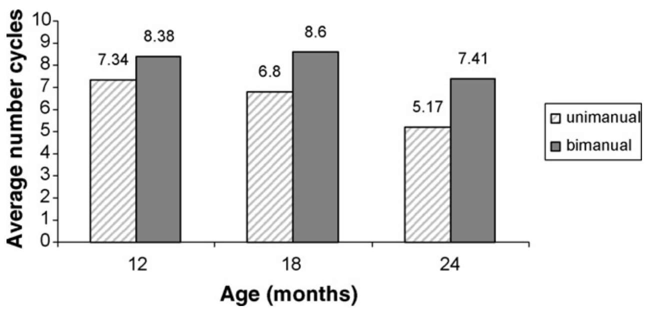

Fig. 4. Mean number of action cycles per bout in unimanual and bimanual activity in each age group.

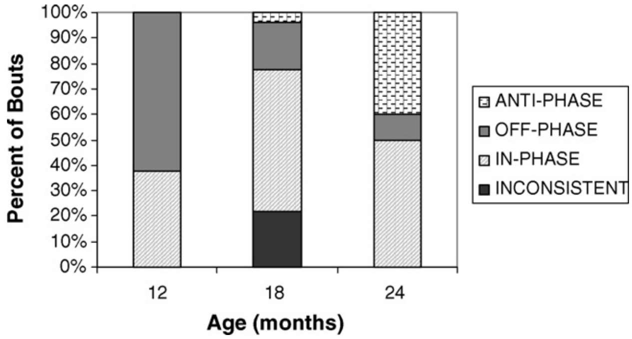

Fig. 5. Phase relationships of drumming bouts exhibited by children at 12, 18 and 24 months of age. Bimanual drumming increases with age, and in-phase and anti-phase activity dominate by 24 months.

activity [$t(10) = .502$, ns]. These tests should be regarded as inconclusive because of the low N and resultant weak level of statistical power yielded; however, they suggest that children at both 18 and 24 months of age are producing bouts of roughly equivalent length.

3.2. Phase relations of bimanual activity

When examining the coordination patterns of the entire corpus of children's bouts at 12, 18 and 24 months, some interesting findings emerge. These patterns are depicted in Fig. 5. As mentioned, at 12 months, only one of eight children produced bimanual drumming activity. This child engaged in eight bouts of such activity. The majority of these, 62%, were coded as "off-phase" with one hand leading the other at approximately a 90° lag between hands. At 18 months, there is considerable variability in phase relations as more children produce bimanual drumming behavior, but in-phase (approximately 0° lag) activity is dominant. At 24 months, the oldest age studied to date using this method, anti-phase activity (approximately 180° lag) has emerged and in fact is produced nearly as much as in-phase coordination patterns; three of the children in this age group preferred in-phase activity and three anti-phase. "Inconsistent" activity, or that which is highly variable in phase relation within the bout, has disappeared at this age.

3.3. Coordination of limbs within bimanual bouts: kinematic analysis

A subset of 28 bimanual bouts, representing six children, were suitable for digitizing and thus available for kinematic analysis. Although the available sample was not extensive, these analyses yielded information at a level of detail not possible with 'naked-eye' observation alone. For example, from plots such as the ones in Fig. 6, it is apparent that, typically, one hand (usually the right) moved with a high degree of regularity. The other hand (usually the left) was more variable in its frequency and often engaged at a lesser amplitude in some children. Timing and regulation of activity varied considerably, supporting the observational data reported above and providing evidence that this was a task that many children were still learning. However, some children at 24 months produced highly stable, spatially and temporally symmetrical bimanual activity in both in-phase and anti-phase relationships.

With such data, it is possible to derive a cross-correlation value between the vertical position of the left and right hands as recorded during each videotaped frame of the bout, and then report a single coefficient value for the entire bout. This is an appropriate technique if one is comparing bouts that have internally stable relationships and are similar to one another in characteristics other than phase relationship, such as the bouts depicted in Fig. 6a and b. However, because microgenetic changes in activity patterns were observed both within and between many of the bouts, analyses using whole-bout summary statistics were not considered appropriate for this data set. For example, cross-correlation values for Fig. 6c and d are very similar ($r = .772$ and .854, respectively), as are the values for Fig. 6e and f (r values of .054 and .074), but the actions represented are clearly very different.

Such aggregate analyses, whether linear or circular, obscure the differences in coordination patterns between children and within the bouts themselves. Thus, different means of characterizing the activity had to be developed with these data. Inspection of the displacement plots suggested that the activity of one hand was more stable than the other in some bouts but not in others. Therefore, for each bout the length, in number of frames included in the period for each activity

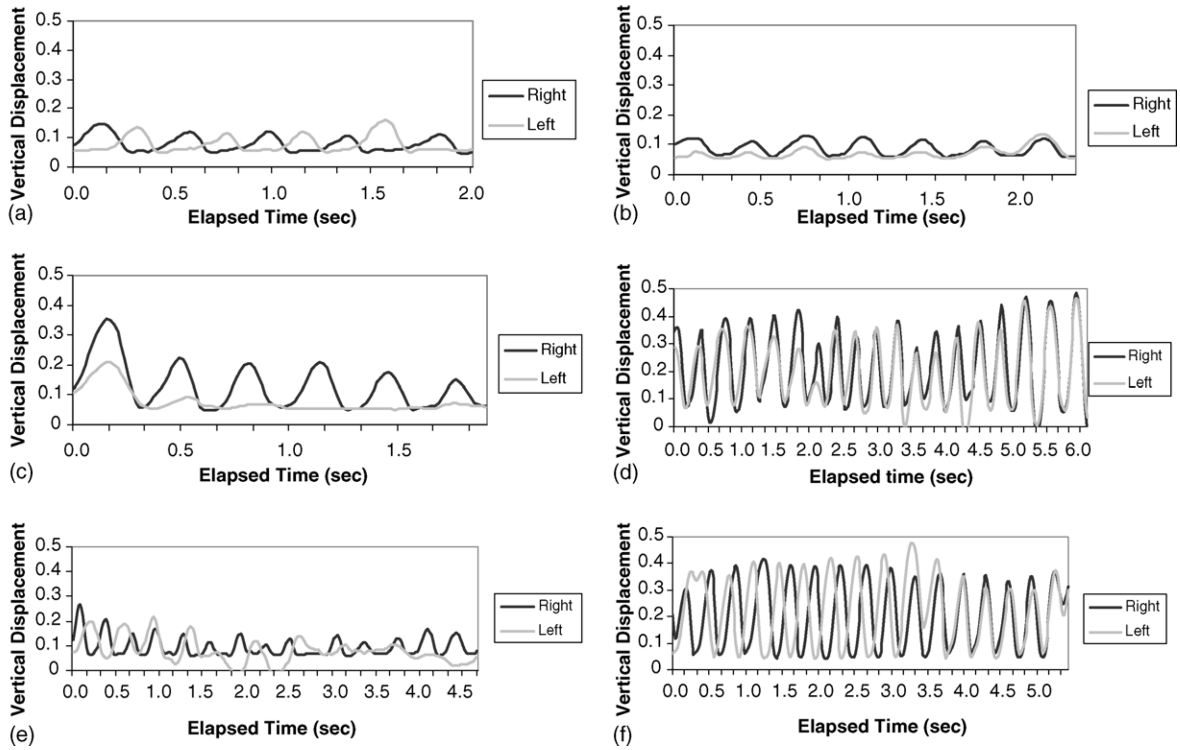

Fig. 6. (a–f) Examples of bimanual percussion bouts. Lines indicate vertical displacement (meters above the platform surface; the drum top is slightly raised) of each drumstick tip over the course of the bout. Plots in the left column represent bouts produced by 18-month-olds; those on the right were produced by 24-month-olds. Each bout was produced by a different child.

cycle (between successive maxima) was calculated separately for the right and left hands. The mean and standard deviation for these period lengths were then calculated for each bout, and compared for the right and left hands. As illustrated in Fig. 7, the ratio of the right mean period to left mean period is very close to 1.0 in all three 24-month-olds, indicating that the two hands were oscillating at virtually identical rates. Furthermore, the ratio of the period standard deviations is very close to 1.0 in the older children as well, suggesting that the action of the two hands was equally variable, and thus well-regulated. By contrast, the right-to-left ratios for the 18-month olds are more variable between children, and in most cases not equal to 1.0. This indicates that the left hand moved with different average period and with more variability than the right hand in these children.

A final analysis utilized cross-correlation values between the two hands; however, rather than calculating *r* values for entire bouts, each bout was segmented into windows that equaled the average period length for that bout.

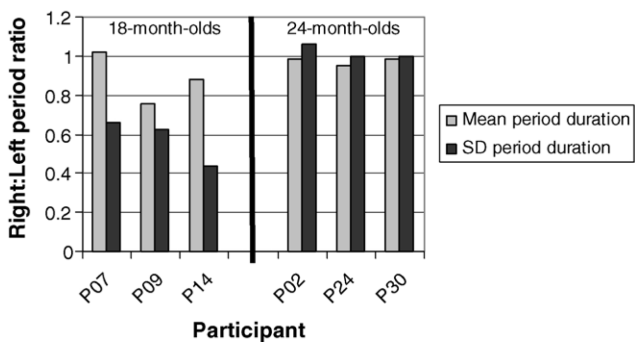

Fig. 7. Ratio of right hand to left hand period mean and standard deviation. A ratio of 1.0 for both mean and standard deviation indicates that the two hands are moving with the same frequency and degree of stability. This is more characteristic of the 24-month-olds than the 18-month-olds.

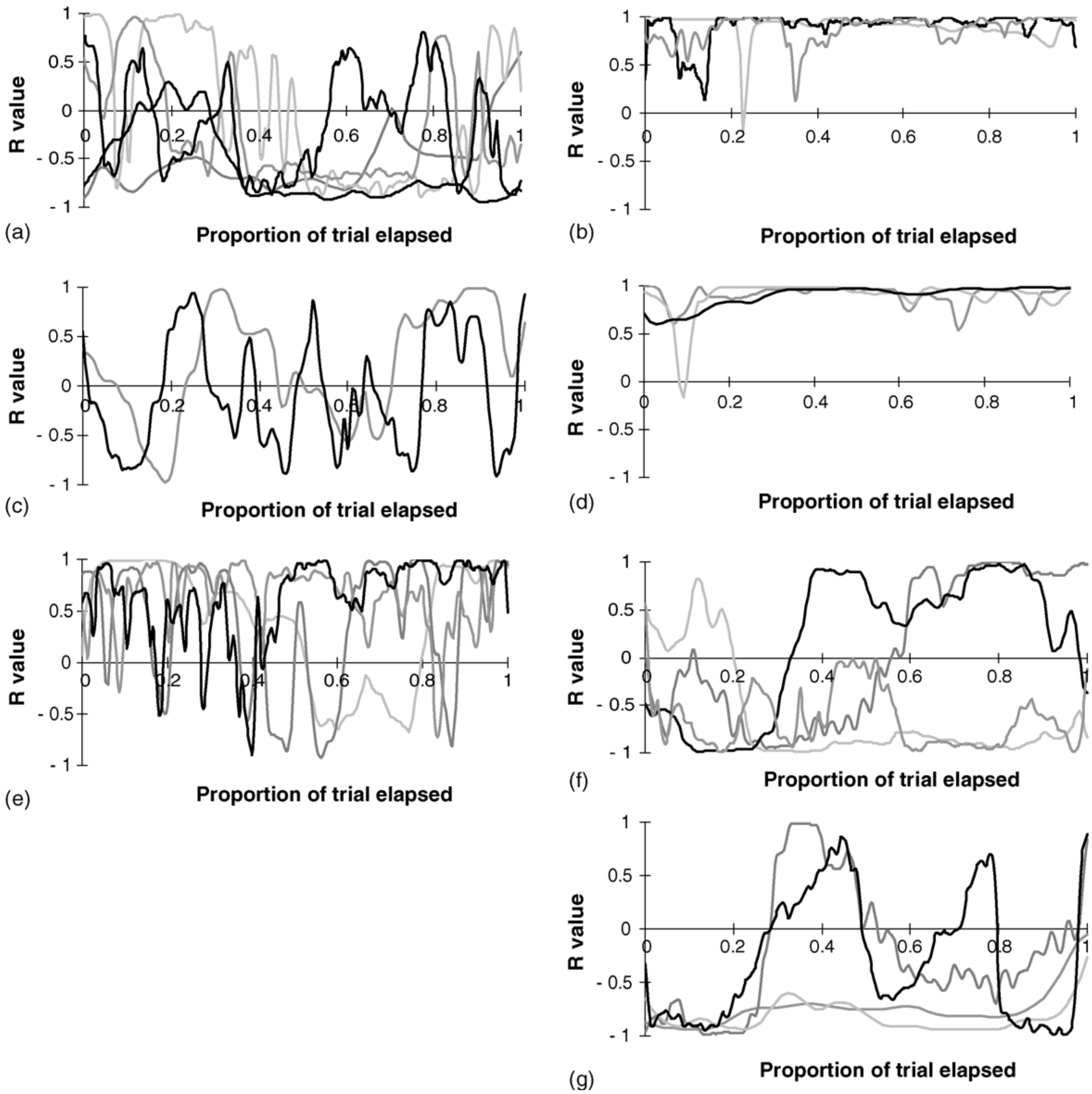

Fig. 8. (a–g) Cross-correlation functions for digitized bouts of the six children for whom such bouts were available. Each line represents the correlation between the right and left drumstick position for an individual bout; values at +1.0 indicate in-phase activity and those at −1.0 indicate anti-phase activity. Eighteen-month-old children's plots appear on the left (a, c and e); the plots on the right represent the 24-month-old children. The bouts on (f) and (g) were produced by the same child; the plots were separated to aid clarity.

The first window started at frame 1, the second at frame 2, and so on until the final window included the last frame of the bout as its terminal point. A correlation coefficient between the vertical amplitude of the two drumsticks was computed for each window, and a cross-correlation function for the entire bout was mapped. Figures illustrating all of the children's bouts appear in Fig. 8. Note that the younger children's coordination is highly erratic, with frequent and variable swings between positive and negative correlations between the hands' positions. This is especially true of the children represented in Fig. 8a and e, although the child in Fig. 8c appears to be regulating activity somewhat more successfully; indeed this was the only 18-month-old child who produced anti-phase action (see Fig. 6e). By contrast, two of the older children exhibit very stable in-phase activity, with only a few lapses that represent brief pauses in action. The third 24-month-old child, illustrated in Fig. 8f and g, had more variable activity in many bouts, but the transitions between phase relationships appear much smoother than is the case with the younger children. Looking at this child's individual displacement plots (e.g., Fig. 6d), it becomes clear that these

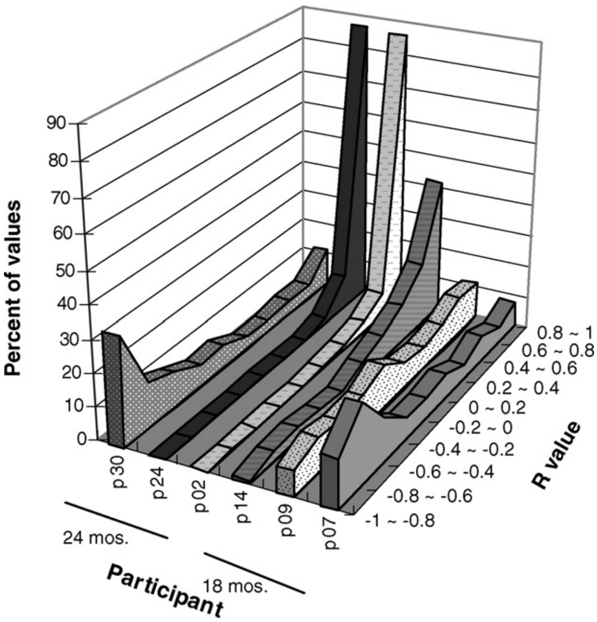

Fig. 9. Distribution of Pearson cross-correlation values across bouts for each of the six participants for whom bouts were digitized.

transitions represent well-regulated shifts from in-phase to anti-phase activity, which is not the case for most of the 18-month-olds.

These correlation functions can be summarized across bouts for each child, and a plot of the distribution of r values produced. Such a plot appears in Fig. 9. A high percentage of values in the 0.8–1.0 range indicates consistent in-phase activity. Values between −0.8 and −1.0 indicate anti-phase activity. As the plot illustrates, two 24-month-old children (P02 and P24) strongly preferred in-phase activities, while the other children's coordination patterns were more variable, although most of the children exhibited some tendency toward preferring in-phase or anti-phase activity.

4. Discussion

Children readily engaged in the drumming activity and displayed a variety of behavioral patterns within this context. As predicted, a shift from primarily unimanual to more heavily bimanual activity was apparent between 12 and 24 months of age. The bimanual activity of the oldest group of children also appeared to "settle into" the two attractor states—in-phase and anti-phase—exhibited in similar actions produced by older children and adults. This suggests that children at both ends of the age range being studied are capable of producing and attending to sustained bouts of percussive activity, but that facility in coordinating the two hands in specific, stable phase patterns within this context emerges during the second year of life.

At 12 months, activity was primarily unimanual and only one child engaged in two-handed drumming. This child usually led with the right hand but also produced some in-phase activity. In both cases the behavior appeared highly routinized and stable within bouts of activity, suggesting strong coupling between the limbs but with some lateralization. At 18 months, just over half of the children produced bimanual drumming bouts. These bouts were quite variable in form, with half being coded as in-phase, and most of the rest as either off-phase or as having no consistent pattern exhibited within the bout. Many children in this middle age range appeared to be novice two-handed drummers for whom an adaptive 'solution' to the challenge presented by this task had not yet emerged. By 24 months, most children engaged in bimanual drumming and the behavior appeared much more regular in form than at 18 months. Bouts of 'inconsistent' phase activity had disappeared, and fully 90% of bimanual bouts were produced in in-phase or anti-phase form, the two forms consistently preferred in adults in a variety of tasks. At the same time, the behavior of the older group appeared more volitional and less routinized than that of younger children. These observations were supported by kinematic analysis of a subset of the bimanual bouts produced by 18- and 24-month-olds, and are consistent with the notion of alternating periods of stability and variability during the process of developing motor skill.

Of particular interest to those investigating coordination is the ratio of in-phase to anti-phase activity in children who engage in bimanual drumming. In-phase activity appears to be strongly preferred by some children at each of the three ages included in this study; however, anti-phase action emerges relatively quickly, appearing only at 24 months but then preferred equally to in-phase motion. The results from this study and follow-up ones with older children will have implications for the field of bimanual dynamics, in that they speak to the universality of different motor-action systems self-organizing into preferred coordination patterns.

As noted by Swinnen and Wenderoth (2004), a wide variety of nonlocomotor behaviors that have been studied to date reflect the tendency to self-organize into in-phase coordination patterns. We initially expected our percussion activity to follow this trend in the young children we studied, and in fact some children did strongly prefer in-phase activity at 2 years of age. Others, however, started incorporating anti-phase activity into their drumming bouts. The gross-motor activity examined in this project may not be fully analogous to the fine-motor actions that have been the focus of previous studies with older participants. Indeed, there may be greater linkage between drumming and the locomotor system than between drumming and fine-motor actions such as finger-tapping. In particular, the main muscle systems used in drumming are also those used to effect rapid reciprocal arm swing during walking. During the second year of life, children are learning to walk efficiently, and typically begin to swing their arms rather than hold them out statically for balance after 10–15 weeks of independent walking experience (Ledebt, 2000). It may be that from this time forward, the self-organized reciprocal arm swing used during walking becomes such a strong attractor state, that the preference for this coordination pattern carries over in to other, non-locomotor, contexts such as drumming. Indeed, Swinnen and Wenderoth (2004) also remark on the adaptability and context-dependency of bimanual movements; this may be a good example of both.

The percussion task explored here is just one of many possible cyclic bimanual activities we could have elicited from our young participants. Indeed, although we have not reported the results here, we also asked them to engage in a cymbal-banging activity, and most children in all of our age groups readily did so. Other investigators have reported bimanual block-banging along the body's midline by children shortly after the onset of duplicated babbling (approximately 6–8 months of age) (Ramsey, 1985). Other actions such as bimanual arm waving and hand-clapping are also commonly observed during the first year of life and are well-established by 18–24 months, when two-handed drumming appeared in most of the children we observed. There are clearly different time-courses for the emergence of each of these skills. How might one account for these differences in actions that are in some ways very similar?

It is important to remember that, to a young child, drumming with sticks on a defined surface represents a new skill context (albeit one which they may have encountered before their test session). Connolly and Dalgleish (1989), in their examination of children's mastery of spoon-feeding, note that even what appears to be such a simple task contains multiple elements that must be mastered. In the case of spoon-feeding, the components that must be coordinated include the hand, mouth, spoon, and food. With bimanual drumming, elements that must be integrated into the task include both upper limbs, two sticks, and the drum surface. The problem for the child becomes one of attentional load as well as motor function. In mastering such tasks, as outlined by Case (1985), children will often attend first to a single dimension of the problem, then as the task context becomes familiar, will expand his or her conceptualization of the problem to include its multiple dimensions. When considered from this perspective, the task demands in this study were more complex than actions such as block-banging or clapping, which have fewer elements to coordinate.

From the cross-sectional data available from these participants, it appears that children first master unimanual drumming, then as they get older, they incorporate action with the second arm as they are able into the ongoing activity of the lead arm (often the right). This was evidenced by the actions of our 18-month-olds, who sometimes placed the left drumstick on the drum's surface and held it there while moving the right stick, or moved the left stick intermittently or with reduced amplitude relative to the right. That attentional load can influence performance of bimanual tasks has been demonstrated repeatedly in the adult literature (Peters, 1985; Temprado et al., 2002), which characterizes attention as a control parameter that can affect the stability and timing of preferred coordination patterns. In other motor learning contexts as well, children will master one component of a task before adding in additional aspects. Ledebt (2000) longitudinally examined changes in children's arm positions as they were learning to walk. She reported that as children took their initial steps, they tended to hold their arms extended in a 'high guard' position, then over the course of several weeks they first lowered their arms then began to swing them while walking. The initial 'freezing' of the arms, claims Ledebt, serves at least two purposes. First, it assists in maintaining balance as the child learns to shift weight from leg to leg. However, it also serves to reduce the degrees of freedom of the walking task by holding the upper limbs still while focusing on the movement of the legs. As this becomes practiced, the child can incorporate simultaneous arm movement along with alternating the legs, and quickly becomes a more efficient walker. A similar process may occur with drumming: the degrees of freedom are initially frozen for one limb, then gradually are incorporated into the overall activity as it becomes mastered in play or other contexts (e.g., locomotion). Indeed, this process of learning to exploit multiple degrees of freedom has been a central pillar of dynamic motor analysis since Bernstein (1967).

Although we recognize that we are limited to description and not explanation of behavior without identification of control parameters that must be in place for coordinated behavior to occur, these regulating factors must be determined experimentally. Clearly, in maturing children, some candidates for such control parameters are organismic. These may include neural structures or pathways and associated skills related to interhemispheric transfer, visuomotor processing, attentional resources, and so on. The literature clearly documents changes in each of these areas between 1 and 2 years of age (e.g., Case, 1992; Diamond & Gilbert, 1989; Ruff & Rothbart, 1996; Thatcher, 1997), and identification of neurological correlates of developing bimanual skill is important. However, as Thelen and Smith (1994, p. 16) point out, “Whatever the course of brain development, *behavioral expression* is entirely context-dependent” (emphasis original). Thus, task dynamics (e.g., use of drumsticks, size and orientation of drum, absence of timing cues) and environmental context (e.g., presence of parent and other adults, unfamiliar laboratory) must be considered as well. Indeed, constraints at all of these levels likely interact to determine how the bimanual motor system self-organizes in the situation that we studied and we defer a discussion of the nature of bimanual control at this age until we have a greater range of data to build upon. For now, we propose that the simple drumming activity that we have used to assess coordinated behavior in young children provides a rich context in which to address the same issues that confront investigators of bimanual activity in older children and adults, and that such activity is highly amenable to dynamic systems analysis using the collective variable of relative phase and the in-phase and anti-phase attractor states.

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