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Coordination changes in the early stages of learning to cascade juggle

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Abstract

The experiment was setup to examine the coordination changes in assembling the movement form of 3-ball cascade juggling. Eight adult participants learned to juggle over 4 weeks of practice. Juggling scores were recorded at each session and performance was videotaped at eight selected sessions for purposes of movement analysis. Once the basic spatial and temporal constraints on cascade juggling were satisfied, and the figure-8 juggling mode was established, temporal modulations of the relative motions of the hands were emphasized. All participants learned to juggle and the increase over practice in the number of consecutive balls caught was best fit with a power law. The non-proportional rate of performance increment was consistent with the qualitative changes in the form of the hand and ball movement kinematics that occurred over practice.

1. Introduction

The learning of a new movement form involves the assembly of a new spatial and temporal organization of the effectors. The skill of juggling affords both the learner and researcher a rich sensori-motor dynamic to search for the temporal and spatial

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constraints of hand and ball motions that are vital to learning and performing the task (Beek, 1989; Beek & Lewbel, 1995). Cascade juggling is a skilled act characterized by a coordination of cyclic motions of limbs and objects. The 3-ball cascade reflects a figure-8 pattern rotated by 90°. One hand tosses or "unloads" the object in such a manner that the ball is thrown in a parabolic arc at about eye level towards the other hand. The second ball is tossed just prior to catching the first ball with its parabolic arc corresponding to the opposite shoulder. With 3-ball juggling the individual has more time to allow for variation in the height of the tosses than in five- and seven-ball juggling, as well as for variation in tempo given a selected height of tossing (Beek & Turvey, 1992; Beek & Van Santvoord, 1996).

The number of balls caught has been the typical index of learning to juggle (e.g., Knapp & Dixon, 1950, 1952; Peterson, 1919; Swift, 1903), but the assembly of the task relevant spatial–temporal relations between hands and balls is the key to learning the skill of juggling. The hands must be coordinated so that a spatial–temporal pattern to the ball motions is established over the full juggling cycle. Although in cascade juggling the hands toss and catch the balls alternately, nearing an antiphase relation, the phase progression of the hands is not harmonic, as it contains distinct accelerations (leading up to the toss) and decelerations (in catching), resulting in a complex time-varying relative phasing between the hand motions. Obviously, bringing the limbs together into the new phase relations of juggling is achievable, but it takes practice to learn a new phase relation between limb movements (Zanone & Kelso, 1992).

Claude Shannon first derived an equation that has been interpreted as reflecting the temporal task constraint of juggling (Beek, 1989). It represented the number of balls being tossed to the number of hands:

$$B/H = (T_L + T_F)/(T_L + T_U), \tag{1}$$

where, B is the number of objects juggled, H is the number of hands (this is important for cases where there are more than one person juggling), T_L is the time each hand is loaded with an object, T_U is the time each hand is unloaded, and T_F is the flight time of each ball (Beek, 1992). The greater the number of objects being juggled, the greater the temporal and spatial constraints on performance. Since for real juggling Shannon's equation may be viewed as a statistical equation relating means of time components, a full $B \times H$ juggling cycle needs to be completed, or 2 ball cycles (six consecutive catches), to match the equation sufficiently closely (Beek, 1992).

Beek (1992) found a more defined timing component with an increased number of objects. The dwell ratio k was used as the timing measure for hand-cycle time ($k = T_L/T_L + T_U$). The range for k with skilled 3-ball cascade jugglers was between 0.54 and 0.83 with a mean of 0.71, and k was found to be smaller for higher juggling frequencies. In a series of experiments comparing k for skilled jugglers with 3-balls at three different frequencies, 3-balls of varying weights, 5-balls, and 7-balls, it was found that the range of k decreased substantially with increasing number of objects to be caught. With 3-balls the participants were able to vary the frequency at which the balls were tossed, however, the participants did not demonstrate this flexibility with 7-balls. The participants were also able to vary the frequencies with 5-balls but with less variability, k ranging between 0.66 and 0.76 as opposed to 3-ball cascade juggling ranging between 0.54 and 0.86 (Beek & Turvey, 1992).

The dwell ratio defines the ''fraction of time that a hand holds on to a ball between two catches''. The higher the dwell ratio, the smaller the probability that ball collisions will occur. This is due to the fact that as the dwell ratio increases the time-averaged number of airborne balls (B^*) decreases, according to the equation $B^* = B - Hk$ (Beek, 1989). When the hands have increased periods of contact with the balls, more time is available for an accurate throw to occur. Novice jugglers tend to opt towards a larger dwell ratio for enhanced proficiency of tosses, while expert jugglers may use smaller dwell ratios. Smaller dwell ratios allow more time to make corrections because the amount of time the balls are in the air averaged over time is larger, thus allowing the juggler greater flexibility (Beek & Lewbel, 1995).

In considering the acquisition of the coordination pattern of juggling, it would appear that there are several task specific factors that need to be considered before the dwell ratio can emerge. First, the hand goes through phases of loading and unloading, altering the phase relations between the two hands. Second, the catching hand must respond to the inaccuracies of the hand releasing a ball in order to maintain the progression of the tosses. When a toss has been made that is higher or lower than the previous catches, the spatial and temporal demands of the coordination mode have been altered. The opposing hand must compensate for the inaccurate toss to preserve the stability of the juggling pattern. For instance, if the toss is too high, the juggler may need to alter the next toss to compensate for the increased amount of time required for the high toss. If the ball is tossed at a decreased angle, without adjustment of its release velocity, then the juggler may need to take a step in order to make the catch.

This study investigated the assembly of the task relevant coordination mode for cascade juggling. Previous studies of the learning of juggling have not investigated the transition from an inability to juggle to the production of the cascade pattern of juggling. Beek and Van Santvoord (1992), for example, examined the learning of juggling from the point where the participants already could perform the task, and thus, by definition, already satisfied Shannon's equation. This experiment will examine the beginning phases of learning to juggle and in particular the formation of the spatial and temporal properties of the juggling coordination pattern prior to completion of the initial 6-ball cycle that produces the figure-8 limb pattern motion.

The examination of the assembly of the juggling coordination mode will be both qualitative and quantitative in an attempt to identify the primary factors that shape the formation of the juggling mode. Previous unpublished research and pilot testing suggested that the point of ball release in the cycle, angle and height of the ball toss, and the transition from the catch of ball 3 to ball 4 are critical features in learning the form of juggling. This transition is critical because at this point each ball has been tossed once, completing 1-cycle. In order to continue the juggling motion the toss of the non-dominant limb (assuming the pattern was begun with the dominant limb), will begin the second cycle. The study will also examine the quantitative changes in the spatial and temporal properties of the coordinative movement that occur as the juggler becomes increasingly skilled through initially satisfying the Shannon criterion to subsequently achieving a reduction in the dwell ratio and a reduction in the angle, height and range of the tosses. The experiment will assess the spatial–temporal properties of the juggling cycle (Beek, 1989; Beek & Lewbel, 1995) that do and do not change in the formation of the juggling coordination pattern.

Finally, the qualitative changes in the formation and refinement of the limb movement patterns with practice will drive the increase in the performance variable of the number of balls juggled. Hence, it was hypothesized that the performance curves of number of balls juggled will increase with multiple rates of change, reflecting the qualitative and quantitative changes in the limb dynamics throughout the learning process (Newell, Liu, & Mayer-Kress, 2001). Thus, learning the movement form of a juggling task would be captured in a power law function of the individual's performance level over practice time, as opposed to an exponential change for an individual learning a single limb positioning or timing task, that is based on the rate of change of growth/decay functions relaxing to a fixed point without reorganization of the dynamical landscape (Liu, Mayer-Kress, & Newell, 2003).

2. Methods

2.1. Participants

Eight adults (five males, three females) from State College, Pennsylvania were paid for their participation in this study. They ranged in age from 19 to 28 years and were recruited based upon the condition that juggling presented a completely novel task for them. All participants identified themselves as right-hand dominant. The Institutional Review Board of the Pennsylvania State University approved the protocol of this study.

2.2. Task

The task to be learned in this study was to juggle three balls in a cascade pattern for as many consecutive catches as possible. To successfully juggle in a 3-ball cascade pattern, one must satisfy the Shannon criterion (Horgan, 1990), previously defined as $B/H = (T_L + T_F)/(T_U + T_F)$. Participant's practiced with 1- and 2-balls before the laboratory sessions to familiarize themselves with the tasks of tossing and catching. The participants then came into the laboratory for eight sessions over a period of 4 weeks to practice 3-ball cascade juggling in front of a video recorder. The sessions included 15 min of juggling with no warm-up trials.

The participants were further instructed to continue practice outside of the laboratory and to log the details of such practice. They were instructed to practice three times per week for a period of 20 min per practice session. It was assumed that the participants completed the outside practice as instructed and logged their performance accurately. It was also assumed that the participants devoted their full attention to the task at hand without outside influences affecting their performance. If the participant was able to catch six consecutive catches, they were given a bonus of $20 over the initial $30 for participating in the study. To give a further incentive, the participant who was able to complete the task with the most consecutive catches and highest average catches for the final two sessions received a further bonus of $20.

2.3. Apparatus

Three Klutz® brand juggling balls were used as the objects juggled in this study. Each participant received a set of these balls for practice outside the laboratory. Each participant wore a pair of thin white gloves with a black band wrapped around the second digit to allow a contrast for the digitizing process. An 8 mm commercial video camera/recorder (60 frames/s) was used to obtain kinematic information. The video recorder was placed upon a tripod 4.5 m from the participants in the frontal plane. This configuration allowed a full-body anterior view of the participants given that the participants maintained minimal locomotion during juggling. The video recorder was set to allow the fullest view of the parabolic arcs of the juggling balls without missing the apex of their flight paths. Hence, the video recorder was adjusted to the flight pattern of each individual participant so as to afford optimal viewing during the digitizing process.

2.4. Procedures

Prior to the study the participants were given two juggling balls and instructed to practice 1-hand juggling followed by 2-hand juggling for a period of 2 weeks. At this time, each participant received a brief written explanation of the study including the experimental protocol and signed the informed consent form. The instruction for the 2-ball juggling was to practice producing two separate parabolic arcs, allowing the participants to adjust both to the tosses for 3-ball cascade juggling as well as to familiarize them with catching the balls. The participants were strongly discouraged to participate in any practice of 3-ball juggling.

After 2 weeks of 1- and 2-ball juggling practice, the participants came into the laboratory for their initial 3-ball juggling session. The participants were each given a set of juggling instructions for 3-ball cascade juggling. They also viewed a video segment of a professional juggler completing a 3-ball cascade juggling pattern so that each participant had the same visual representation of the juggling pattern to be learned. The sessions began as soon as the participants began practice and continued for 15 min. Trials varied individually according to how much time elapsed between trials and the number of balls caught.

2.5. Data analysis

The number of consecutive balls caught was recorded for each trial throughout the laboratory sessions. A successful catch was one that passed through a parabolic arc through its apex from one hand to the other. The successful catches were counted by an investigator and recorded for analysis. Task performance and the data on the number of balls caught per trial were quantified using the highest number of consecutive catches and the mean number of catches. The performance curves and line graphs were plotted for each individual and across participants. This allowed comparison of performances on both an individual as well as a group basis for each variable.

Peak Motus was used to digitize six segments of the particular juggling trials, the two hands, three balls and the torso. Individual trials were analyzed after the juggler was averaging 1, 2, and 3 cycles, as well as their final performances in the laboratory. A cycle was considered tossing and catching each ball 1 time. The cycle begins at the toss of one of the balls and ends after the catch of the third ball. In other words, there are three tosses and catches involved in 1-cycle. These trials were assessed because they allow a comparison of the individual's initial changes in movement coordination. The digitized points were the middle phalange of each hand, the center of each ball, and the torso. The torso was assessed by placing a black dot on the manubrium of the sternum.

These kinematic data provided for a portrayal of the phase relations between the hands and the balls, and one hand against the other. The phase relations were calculated as the positional deviation between the two oscillating variables. The analysis strategy also provided an assessment of the range and mean of the lateral torso movement. The calibration method in Peak Motus allows the ability to compare heights of ball tosses, ball release height, and ball catch height. The range of the ball motion was analyzed as a function of plane. The time between tosses was assessed through Peak Motus by taking the time between the instant the ball was released from one hand to the instant the next ball was released. The height of the ball tosses were measured from the point of release to the zenith. The ball release and catch height were analyzed by measuring the location in space of the hand at the point in which the ball first left the hand and when it first made contact with the hand.

3. Results

3.1. Ball juggling performance

Fig. 1 illustrates the individual performance curves for the mean number of balls juggled per trial as a function of practice session. The individual performance curves revealed variable rates and levels of improvement. All participants learned to juggle more than 2-cycles of balls fairly early in the investigation. One participant surpassed the 6-consecutive catch requirement on the first day of testing, however, most participants reached this mark on the second day. Most participants showed an increasing rate of gain in performance, but two participants displayed unstable patterns of change in performance over time. These unstable patterns were marked by increases in performance followed by a subsequent decline and continued in such a manner over practice sessions.

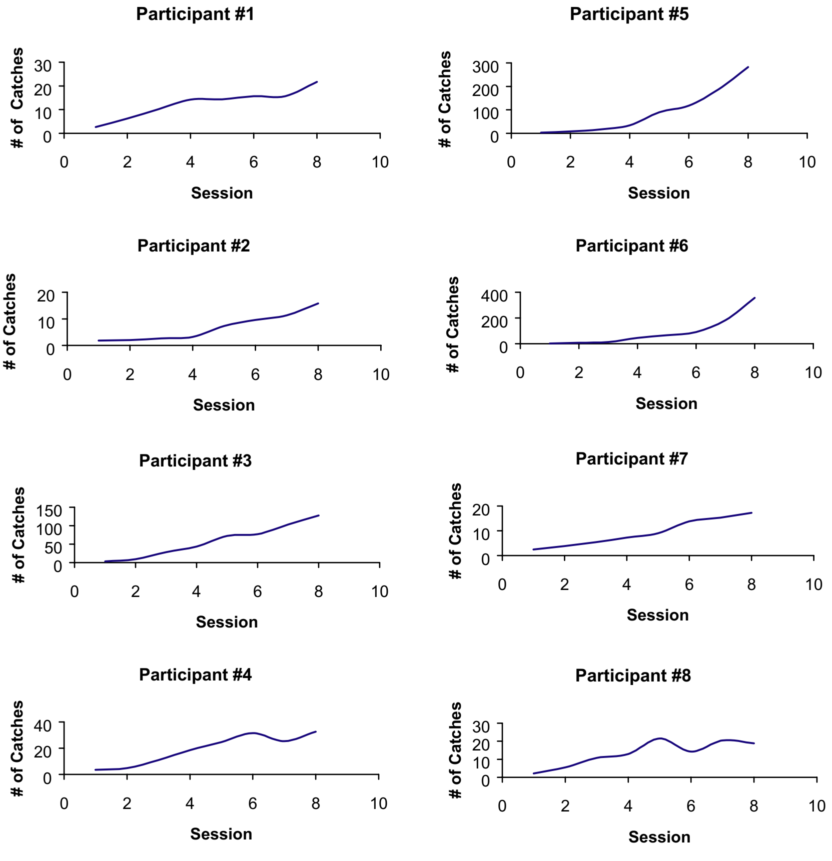

Fig. 1. Individual performance curves for the mean number of consecutive catches.

The group of participants significantly increased their performance outcome over all sessions, $F(7,56) = 3.07$, $p < 0.01$. The highest mean number of consecutive catches in a session was 357.25 and the highest number of catches within a single trial was 858. Both of these scores were achieved during the same practice session by participant #6. Although this participant finished the experiment with the most successful performance, he began with one of the lowest performances, averaging 2.42 catches in session 1. Outside practice was comparable for all subjects according to the practice logs taken by the participant; however, these data were not analyzed.

All participants improved from 1 catch to 2 catches within 1 lab session; 2 catches to 3 catches within 1 lab session; 3 catches to 4 catches between 1 and 5 sessions; 5 and 6 catches between 1 and 2 sessions; and 5 and 6 catches within 1 session. These results indicate that the major hurdle in acquiring the skill of juggling is the transition from 3 catches to 4 catches.

The individual performance curves for the mean number of balls juggled were curve-fitted using 2 and 3 parameter power law and 2 parameter exponential fits.

The *R*-squared values and parameters for these function fits to the individual data are displayed in Table 1. The individual performance curves were assessed using the average juggling performance for each lab session. The exponential curves were calculated using the equation $y = ae^{bx}$, where a and b are constants and e is the base of the logarithm. The 2 and 3 parameter power law curves were calculated using the equations $y = ax^b$ and $y = y_0 + ax^b$, respectively, where a, b, and y_0 are constants. Six out of eight of the participants' best fit were with a three parameter power law function, and there was essentially no difference in the fit of the three functions in the remaining two participants. There was an overall significant difference between the three functions fitted, $F(2,21) = 7.45$, $p < 0.01$. Post-hoc tests revealed a significantly better fit for the 2 and 3 parameter power law functions than the exponential function.

3.2. Movement coordination pattern

3.2.1. Hand/ball motions prior to the assembly of one cycle

The very initial trials of each participant were analyzed to determine how the first juggling cycle of three consecutive tosses and catches was assembled. The particular focus was the changing pattern of the spatial and temporal properties of the hand

Table 1
The R^2 value for each participant when the mean number of balls juggled per session was fitted with a power law (2 and 3 parameter (p) equations) and with an exponential function

Participant	Power law	Parameters	Power law	Parameters	Exponential	Parameters
1	0.9298	$a = 4.04$ $b = 0.775$	0.9427	$y_0 = -12.1$ $a = 14.7$ $b = 0.371$	0.8514	$a = 5.37$ $b = 0.174$
2	0.9697	$a = 0.383$ $b = 1.78$	0.9807	$y_0 = 1.34$ $a = 0.134$ $b = 2.25$	0.8334	$a = 1.25$ $b = 0.319$
3	0.9853	$a = 5.28$ $b = 1.53$	0.9891	$y_0 = -6.52$ $a = 7.72$ $b = 1.37$	0.9144	$a = 12.7$ $b = 0.295$
4	0.9028	$a = 4.28$ $b = 0.998$	0.9177	$y_0 = -1.10$ $a = 12.3$ $b = 0.613$	0.8018	$a = 6.87$ $b = 0.205$
5	0.9948	$a = 0.841$ $b = 2.79$	0.9935	$y_0 = 52.4$ $a = 7.55e{-8}$ $b = 1.08$	0.776	$a = 7.31$ $b = 0.459$
6	0.9846	$a = 0.00877$ $b = -4.82$	0.9885	$y_0 = 4.76$ $a = 4.56e{+9}$ $b = 21.8$	0.9945	$a = 2.43$ $b = 0.623$
7	0.9801	$a = 1.57$ $b = 1.16$	0.9844	$y_0 = 1.44$ $a = 87.7$ $b = 1.41$	0.758	$a = 2.84$ $b = 0.235$
8	0.8013	$a = 4.43$ $b = 0.756$	0.8481	$y_0 = -63.3$ $a = 64.8$ $b = 0.123$	0.6667	$a = 6.07$ $b = 0.162$

and ball motions in the progression of learning the form of juggling. Thus, the pathway from tossing the first ball through to the completion of a complete cycle was investigated. Table 2 shows the frequency of events with trials having only one successful catch and trials having two successful catches.

In the 1-catch trials, 19% of the mistakes were realized due to a lack of a parabolic trajectory in the second toss, the "hand-off" category. Stated another way, the first ball was tossed with a trajectory peak at approximately head height and falling toward the opposing limb. However, the second ball toss had no parabolic trajectory and was essentially "handed-off" to the opposing hand. For the 2-catch trials, the "hand-off" category referred to a hand-off of the 3rd ball. This problem was nearly eliminated at this stage of learning with less than 1% of occurrences.

The hand full category occurred when the subject did not release the third ball for the 1-catch trials and no release of the fourth ball (or Ball 1 for the second toss) for the 2-catch trials. This caused difficulty in the ability to catch because the hand was already loaded. This occurred in approximately 20% of the trials for both 1 and 2 catches.

The vertical toss trials included those in which the balls were tossed at or near a 90° angle in relation to the horizontal ground, causing the continuation of the cycle to become increasingly difficult. A vertical toss would force the other limb to cross the midline of the body in order to make the catch. These angles were measured from the videotape of the juggling lab sessions. Most of the mistakes found for the 1-ball catches were due to vertical tosses (44%); however, this only caused 21% of the destruction of the continuation of the juggling pattern in the 2-catch trials.

"Skipping ball #2 catch" occurred when the individual initiated a toss with parabolic arcs, but neglected to make the second catch. It appeared that the jugglers were concentrating on the future catch (Ball #3) and "forgot" to make the 2nd catch. It was often observed that the ball would simply fall beside the hand with no attempt to catch it. For the 2-catch trials, they were catching the 1st and 3rd balls, while ignoring the 2nd. This rarely occurred (2%) in the 1-catch trials since the 3rd ball was generally not tossed or tossed vertically. However, a lack of attention given to the 2nd ball catch was the most common cause (41%) of the destruction of the 2-catch trials.

The "other" category included mostly volleying and premature tosses for the 1-catch trials. Volleying occurs when the hands tap or hit the ball back into the air without making an actual catch. Premature tosses were tosses initiated

Table 2
The number and percentage of categorical events in 1-Catch trials and 2-Catch trials

Event	1-Catch	Event	2-Catch
Hand-off	23 (20%)	Hand-off	1 (<1%)
Hand Full (3rd ball)	21 (17%)	Hand Full	38 (22%)
Vertical Toss	51 (44%)	Vertical Toss	36 (21%)
Skipping ball 2 catch	2 (2%)	Skipping ball 2 catch	69 (41%)
Other	18 (15%)	Other	25 (15%)

immediately following the 1st toss. This category also included several ball collisions, which occurred more often in the 2-catch trials.

3.2.2. Initial cycles of juggling

Each participant's hand and ball movement data were analyzed according to the initial progressive increase in the number of cycles of balls consecutively caught. A cycle corresponded to three consecutive tosses and catches and was completed when the number of balls in the hands had each been thrown with a parabolic arc across the body. This allowed an examination of the progressive change as the participants acquired the movement pattern of juggling. A further comparison was made with 4-cycles taken from the final session. A number of variables that characterize the kinematics of the hand and ball motions of juggling were analyzed.

3.2.3. Ball motion

Fig. 2a shows the maximal range of ball motion as a function of direction. There was a main effect on the maximal range for both practice, $F(3,56) = 4.96$, $p < 0.01$ and plane of motion, $F(1,56) = 91.38$, $p < 0.01$. There was no interaction between the plane of motion and practice for the maximal range of motion ($p > 0.05$), but post-hoc analysis showed that the ball range effect largely arose from a change in the vertical plane, the absolute height of the ball toss was reduced by about 50% in the vertical plane.

The spatial orientation of the ball kinematics is depicted for a single participant and the expert in Fig. 3. An emerging figure-8 structure for the learner can be seen through practice. The figure-8 pattern is the structure that defines the cyclic pattern of cascade juggling. When this pattern is maintained, the performer is able to continue the sequence for an increasing amount of time (or balls tossed). The trajectories of the tosses become tighter and better reproducible as the participants become increasingly skilled.

The expert juggler (bottom Fig. 3) maintained a very stable pattern of limb motion structure with reproducible limb motion patterns, which the learning participant is emerging towards. There is a repetitive cyclic pattern that is sustained in the juggling action. The final sessions of the participants reveal a much more constrained, repetitive pattern similar to that of the expert.

3.2.4. Hand motion

The maximal range of horizontal hand motion as a function of practice is shown in Fig. 2b. There was a main effect for practice, $F(3,56) = 4.76$, $p < 0.01$, with the range of hand motion decreasing over practice. There was no significant effect for hand or a hand by practice interaction (p's > 0.05). The coefficient of variation also decreased as a function of skill in the horizontal range of hand motion $F(3,28) = 10.77$, $p < 0.001$.

The vertical relative motion of the limbs also showed a reduction in range of motion (see also Fig. 4). Due to increased accuracy of the tosses, the limbs were required to compensate for excess spatial motion in the ball to a much lesser degree. When comparing the relative motion of the left versus the right hand, a figure-8 pattern

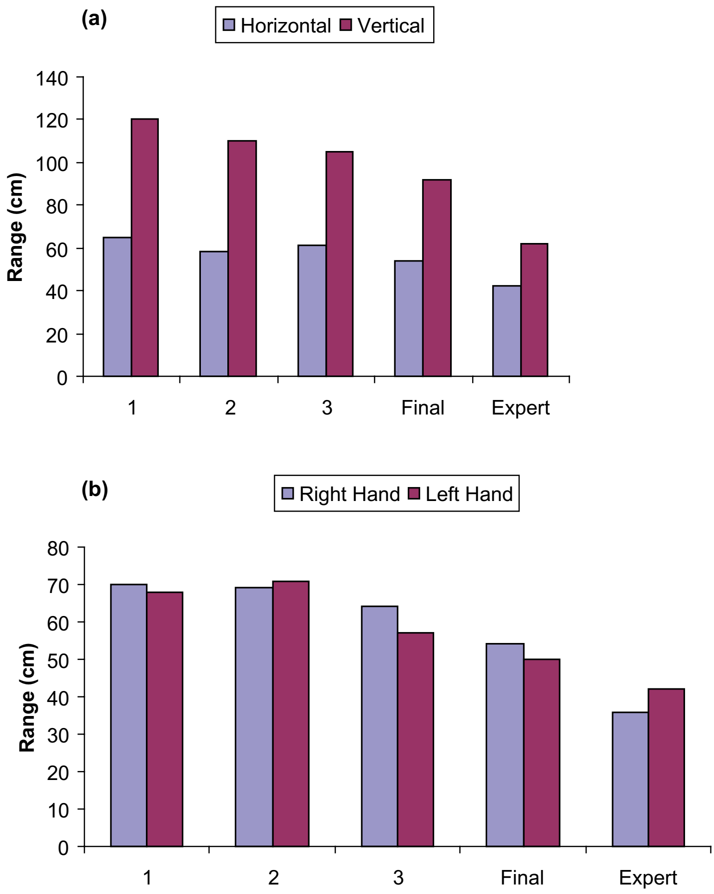

Fig. 2. (a) Maximal range of ball motion for both the vertical and horizontal planes, (b) maximal range of hand motion in horizontal plane for right and left hands as a function of achieving a 1, 2, or 3-cycle performance. The expert values on these variables are provided for comparison.

emerges through practice (see Fig. 4). This kinematic pattern appears to be critical in maintaining the structure of the juggling movement. This pattern does not require the cycles to overlap the past cycles, but a more repetitive motion aids in the stabilization of the juggling pattern. The final session shows a less variable cyclic pattern that emerged through hundreds of trials. The first 3-cycles illustrate the emerging figure-8 pattern. Furthermore, the heights of the toss $F(3,56) = 4.96$, $p < 0.05$; as well as the lateral motion of the limbs $F(3,56) = 4.76$, $p < 0.05$, decreased throughout the sessions. By the final session, the participants were able to perform with more constrained movements, similar to that of the cyclic pattern of the expert. The variability of the vertical range of motion was assessed with coefficient of variation, displaying a significant decrease through increasing skill level, $F(3,28) = 32.86$, $p < 0.001$. The coefficient of variability of each hand, left versus right, was also assessed exhibiting the same results, $F(3,28) = 33.45$, $p < 0.001$, and $F(3,28) = 33.71$, $p < 0.001$.

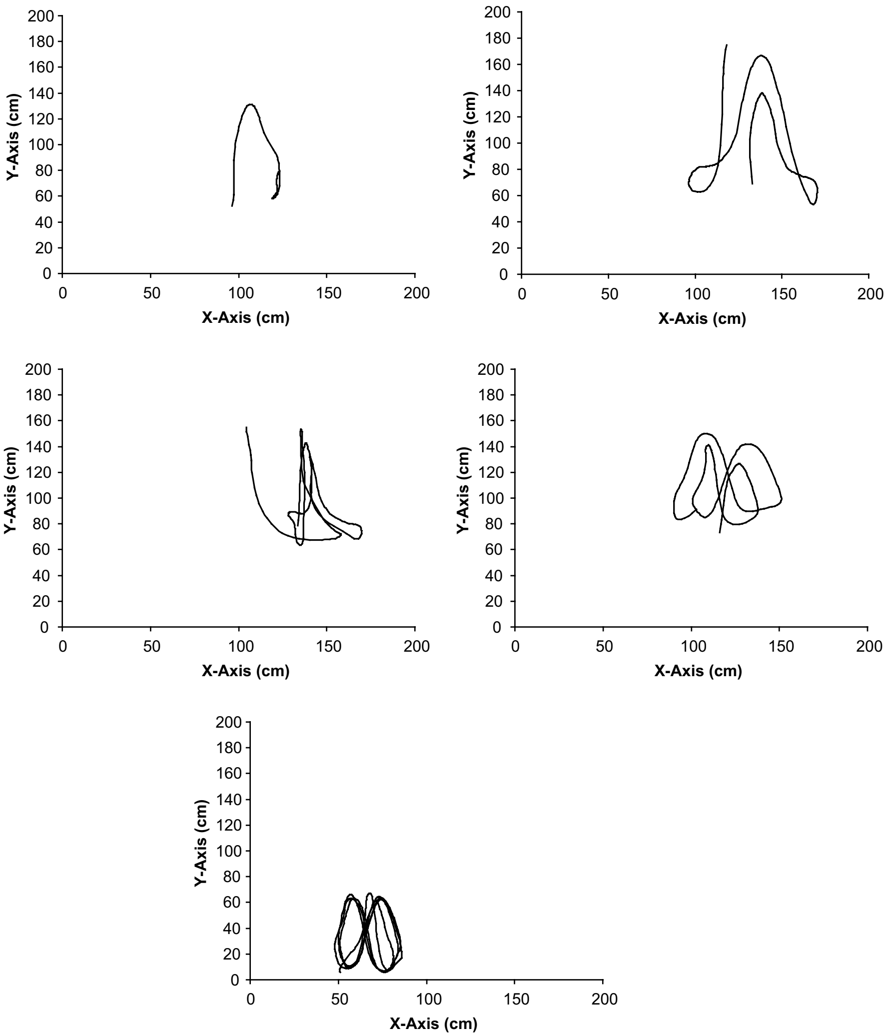

Fig. 3. Motion of Ball 1 (Participant #8) for (upper left) 1-cycle; (upper right) 2-cycles; (middle left) 3-cycles; (middle right) 4-cycles from final session; (bottom) expert. Range of motion in vertical and horizontal planes were significantly reduced, $F(3,56) = 4.96$, $p < 0.01$.

3.2.5. Ball-hand relations

The phase relations between the ball and the right hand changed significantly, $F(3,472) = 19.86$, $p < 0.01$. The phase relations actually significantly increased $F(2,355) = 26.70$, $p < 0.01$, from the performance of 1 cycle to that of 3 cycles, however, decreased slightly, when the participants performed the juggling pattern skillfully, the final juggling patterns exhibited by the jugglers. The left hand and the ball revealed similar results with a significant effect across skill level, $F(3, 460) = 20.92$, $p < 0.01$. An increase was found from 1 to 3 cycles, $F(2,346) = 31.16$,

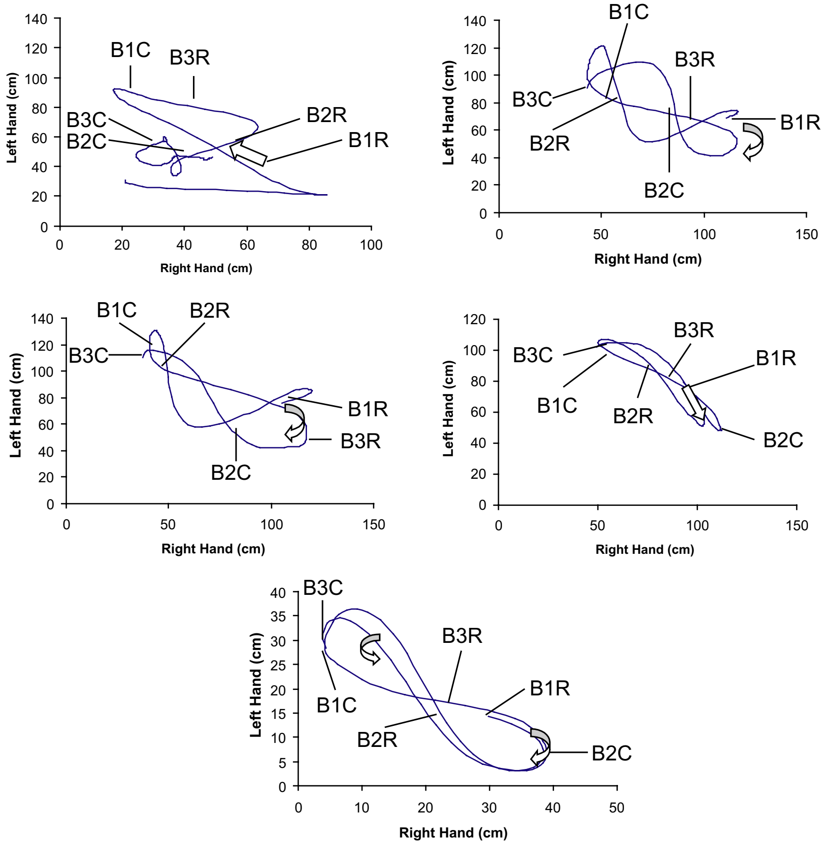

Fig. 4. Relative motion of participant #8 and expert data marked for pertinent cycle points. B1, B2, and B3 correspond to Ball 1, Ball 2, and Ball 3. *R* is the release of the ball, and *C* the catch, the point, which the ball was in grip of the hand. By the final session a distinct transition has occurred from that of the first three cycles. (upper left) One complete cycle; (upper right) two complete cycles; (middle left) three complete cycles; (middle right) four complete cycles; (bottom) expert data.

$p < 0.01$, as in with the right hand, however, a near significant reduction was found from three cycles to the final session $F(1, 230) = 3.76$, $p = 0.054$. Ball 1 was used for the phase relations since it has more time in motion than the other balls. The phase relations were calculated as the positional deviations between the two oscillating bodies of interest, the left hand and ball 1, and the right hand and ball 1.

A breakdown of the pertinent points in the temporal-spatial domains in the maintenance of the cyclic pattern is displayed in Fig. 4, revealing the progressive development of the figure-8 patterning. There is a particular boundary of the limb trajectory in both the vertical and horizontal planes in which the juggler must toss and catch the ball in order to maintain the temporal–spatial orientation. The most stable area for the release is amongst the inner swing phase of the figure-8 pattern. However, the catches occur with higher probability when completed in the outer boundaries of the pattern. In the beginning trials of the novice, displayed in Fig. 4, a structure is lacking in the timing of the tosses and catches. The positions of the balls relative to the cyclical patterns were analyzed in two dimensional space. If the position of the ball was located along the outer curvature (the lateral 50%) of the ball trajectory at the moment of the catch, it was labeled as being in the outer boundary. Analysis of all of the participants revealed a gradual increase in the number of catches that occurred in the outer boundaries with increasing skill, $p < 0.01$. When the participants were only able to perform 1-cycle, only 38% of the catches occurred in the outer boundaries, for 2-cycles 67%, for 3-cycles 79%, and 100% of the catches occurred in the outer boundaries during the final session. There was a steady transitioning of the position in the trajectory where catches occurred with increasing skill. Analysis of variance revealed that the position the ball catches for the left and right hand changed significantly as a function of practice, $F(3,28) = 2.94$, $p < 0.05$.

The novice is not giving him or herself adequate time to sustain the structure of the movement, which results in fewer consecutive catches. The points of release and catch occur in all areas of the movement trajectory, both in the crossover as well as the outer boundary. However, during the final session, displayed in Fig. 4, the participant has discovered the preferred areas for the movements. The tosses and catches are occurring around the same zones as in the expert's data. When the toss is delayed or expedited beyond these boundaries the cycle may easily be destroyed. The boundaries for 3-ball cascade juggling allow movement variance of the limbs and balls, but the structure of the coordinative action must be confined in the figure-8 sequence.

The timing between the hand movements were assessed by measuring the amount of time between release and catch of the same ball, release and release of subsequent balls, and catch and catch of subsequent balls (see Fig. 5). There was a main effect for practice, $F(3,84) = 4.47$, $p < 0.01$, with the time between release and catch decreasing with practice. Another main effect was found between the different timing components, $F(2,84) = 103.71$, $p < 0.01$. The time between the release and catch, $F(3,84) = 2.44$, $p < 0.05$, and catch and catch, $F(3,84) = 2.16$, $p < 0.05$, decreased throughout practice resembling the performance of the expert. The time between releases remained stable over practice, $F(3,28) = 0.75$, $p > 0.05$, appearing to be an invariant in the acquisition of cascade juggling. However, this result is most likely a product of marginal statistical fluctuations rather than an invariant, as the intervals between the points of release and catch remain relatively constant.

The variability of these component times was also assessed (Fig. 5b). There was a significant, $F(3,28) = 2.44$, $p < 0.05$, reduction in the variability of the time between release and catch and time between catch and catch, but no decrease in that of the release to release. This timing pattern allows a quite variable range in the flight trajectory of the balls, yet the motion of the limbs maintains the timing for the subsequent ball flight.

The timing of the hands being empty and loaded was also assessed (see Fig. 5c). The amount of time in which the hands were fully decreased as a function of practice $F(3,56) = 6.67$, $p < 0.01$, nearing that of the expert by the final session. There was

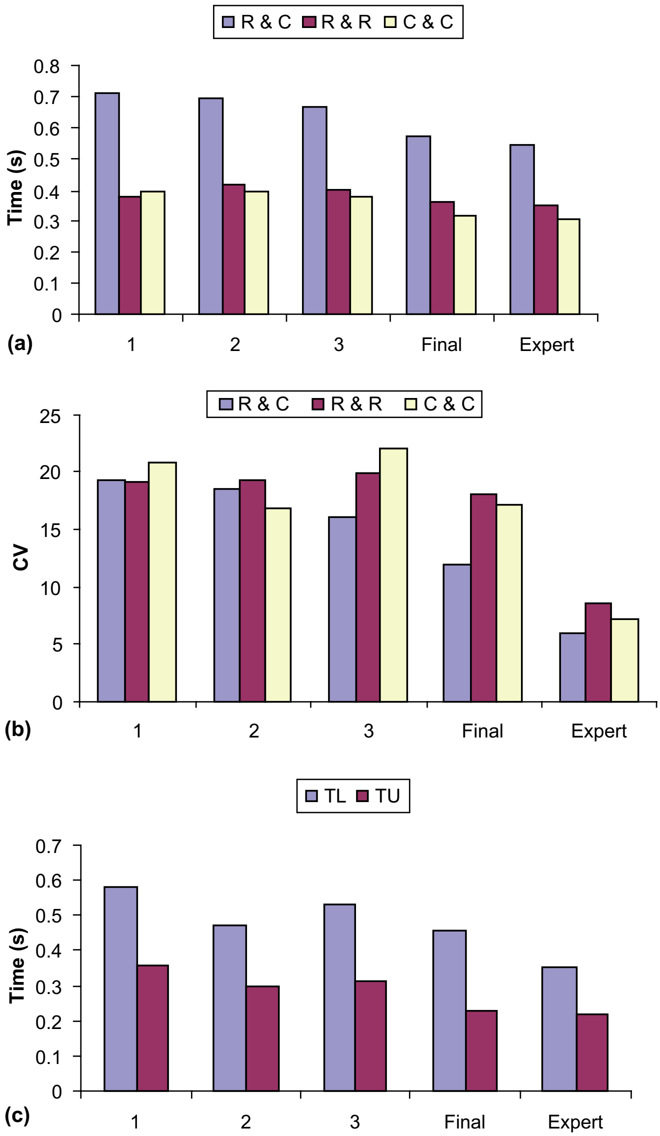

Fig. 5. Temporal constraints of juggling (a) time between release (*R*) and catch (*C*), release and release, and catch and catch; (b) variability of timing in coefficient of variation; (c) time loaded (T_L) and time unloaded (T_U).

also an effect between the condition of the hand, $F(1,56) = 59.42$, $p < 0.01$, with the amount of time in which the hands were unloaded remaining essentially invariant $F(7,28) = 1.58$, $p > 0.05$, and similar to that of the expert. The time in which the hands are unloaded is the amount of time between the release of one ball and the catch of the next. There was no interaction between practice and the condition of the ball, unloaded or loaded. The dwell ratio, ($k = T_L/(T_L + T_U)$), was also computed with a mean of 0.63 across all trials. A significant reduction was not found in the dwell ratio with increasing skill, $F(3,28) = 0.29$, $p > 0.05$.

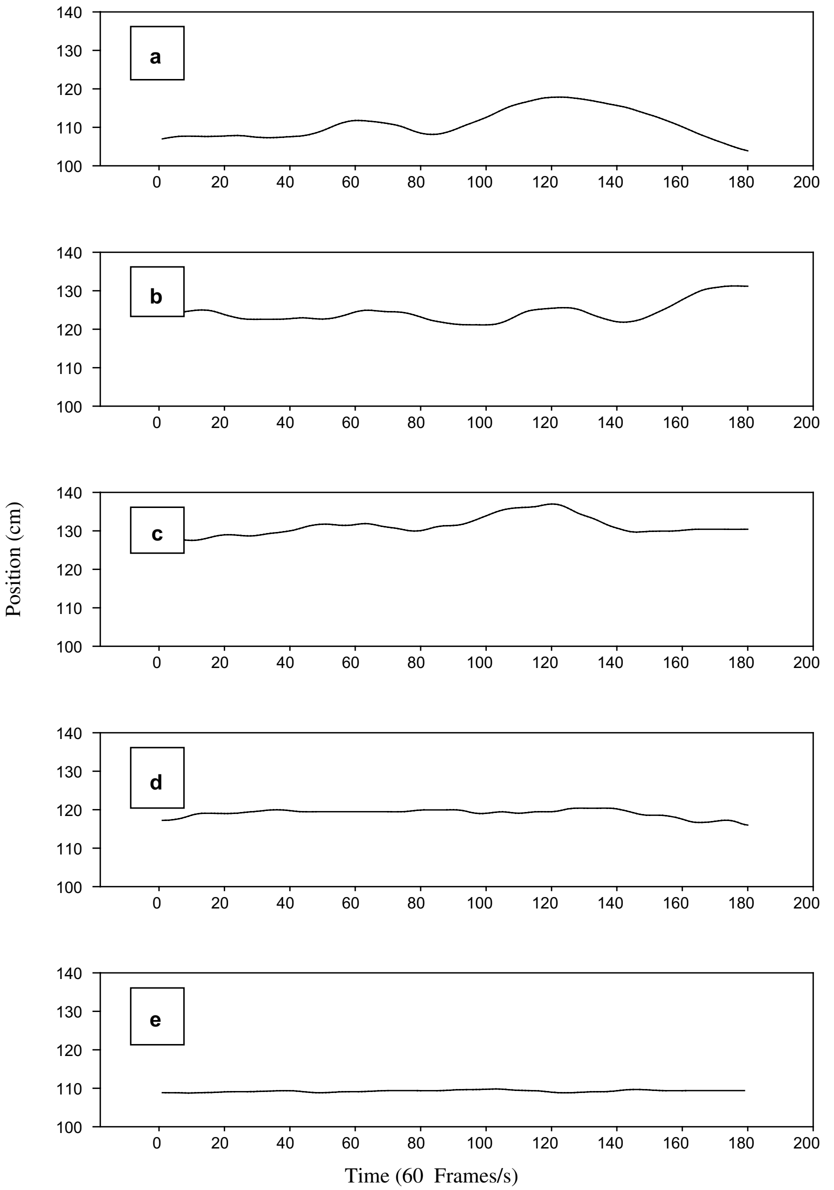

Fig. 6. Range of lateral torso motion for 1-cycle from each period of learning (Participant #6) (a) 1-cycle, 14 cm; (b) 2-cycles, 10 cm; (c) 3-cycles, 9.5; (d) final, 3 cm; (e) expert, <2 cm.

The participants' timing data from the juggling cycle were placed into the Shannon equation ($B/H = (T_L + T_F)/(T_L + T_U)$). The means of the temporal side of the equation across participants were not different from one another with values 1.39, 1.53, 1.44 and 1.51 for the first, second, and third successful cycles, and the 4-cycle segment from the final session, respectively. The results were similar to that of the expert who had a value of 1.5. It appears that although the time loaded and the flight trajectory times were significantly reduced throughout the sessions, this did not influence the participants' ability to complete juggling cycles.

3.2.6. Torso motion

The range of the lateral torso motion decreased as a function of practice comparing the initial trials to the final session, $F(3,28) = 41.39$, $p < 0.001$. Fig. 6 shows the reduction of body motion as a function of learning. The novice begins with considerable torso motion to compensate for the trajectory of the ball toss but as the tosses become more constrained and accurate, the torso movement is minimized, similar to that of the expert. Forward body motion was not analyzed due to the limits in the calibration of the system used. However, the taking of steps, which was prevalent in the earlier sessions, ceased in the later trials as participants were able to maintain more accurate tosses.

4. Discussion

This study investigated the acquisition of a new movement coordination pattern through examination of the acquisition of cascade juggling. The focus was the development of the coordination pattern *prior to* the point at which one would identify the learner as satisfying the task goal of juggling, as defined by the Shannon criterion (Beek, 1989). Juggling is, in effect, one of those tasks, like standing, bicycle riding and so on, that are characterized initially in a qualitative manner by whether the performer does or does not perform the task. There have been many studies of the acquisition of juggling (e.g., Knapp & Dixon, 1950; Swift, 1903), including from a dynamical systems perspective (Beek, 1992; Beek & Van Santvoord, 1992), but none have examined directly the assembly of the movement coordination pattern that defines the activity. This limitation is, perhaps, a reflection of the general de-emphasis historically in motor learning of the acquisition of the new coordination modes, in deference to emphasizing the acquisition of the task relevant parameterization of an already established attractor dynamic (cf. Newell, 1985).

The completion of six consecutive catches, or 2-cycles, was used as an index of whether the individual had acquired the ability to juggle (Beek, 1989). This criterion affords the completion and coordination of all of the component movements required for the juggling task. Most participants were able to successfully produce six consecutive catches and tosses through a parabolic arc across the body by the second laboratory practice session, and all participants were able to complete this task criterion by the fourth session. As a consequence, the participants had considerable further practice time to become quite skilled jugglers by the end of the recorded sessions. This progression over the practice period allowed for analysis of both the assembly of the movement form of the individual participants *prior to* producing six consecutive catches and the subsequent refinements in the relative motion pattern of hands and balls, as enhancements in performance outcome took place.

The findings showed that there are particular regions in both the temporal and spatial domains of limb motion where the tosses and the catches must occur. Through practice the participant is able to produce these spatial–temporal relations and subsequently further enhance the stability of the juggling pattern. To complete six consecutive catches, and thus satisfying Shannon's equation, one must be able to bring together the motions of the limbs and balls into a particular phase relation. The critical relative motion of the limbs depicts a figure-8 motion for the tossing of the objects, allowing a cyclic behavioral pattern of hands and balls, which is crucial to sustaining the act of juggling.

During the earliest performances of 1- and 2-ball catches, the juggler was learning how to appropriately toss the ball in order to allow an efficient amount of time to make the catch and continue the cycle. The most prevalent errors in this stage of learning occurred due to poor tosses, including extreme angle/height errors, premature tosses, and straightly upward tosses. Another common error in this early phase of learning was the failure to initiate a toss. This particularly occurred when the participant was consistently catching two balls and was attempting to assemble three catches, and even more so during the subsequent transition from three catches to four catches.

Thus, the initial assembly of the juggling mode is learned through a collection of spatial–temporal factors and constraints that are perhaps inappropriate to separate to a single dimension of either spatial or temporal, given their inherent interdependence. Changes in the spatial pathway of the ball trajectory lead inherently to changes in the temporal aspects of the flight and on future hand motions; however, this is not the case for lateral ball motion. Similarly, Newtonian mechanics dictate that changes in the temporal aspects of the ball flight, through changes in the initial ball impulse on release, are tightly linked to the spatial aspects of the ball flight. Juggling is a problem of coordinating the balls and hands in space-time.

The 3- to 4-catch progression appeared to be a major transition in the juggling cycle, as the hands were required to reverse the movement. The second cycle, or ball 4 toss, initiates a cycle originating in the opposing hand and motion in the opposing direction. If the juggling pattern began in the right hand, ball 4 toss occurs in the left hand. Each of the three balls have been tossed and caught once before this transition. The fourth toss is the second toss of ball 1 using the hand that did not begin the juggling pattern. This transition was noted as the most difficult because it took between 1 and 5 lab sessions to surpass, whereas all of the other transitions were accomplished within 1 or 2 sessions. The transitions from ball 4 to 5 and 5 to 6 also occurred more quickly (for most participants, within one session) than the initial transitions of incremental catches (from ball 1 to 2 and 2 to 3). Once six consecutive catches had been produced, all movement components of the juggling pattern had been performed, and subsequent improvements in the phasing of the coordination pattern occurred rapidly as can be viewed in Fig. 1. It should be noted that the findings of the initial phase of learning to cascade juggle in this study may have been influenced by the 1- and 2-ball prior practice experienced by the participants.

The amount of time in which the hand is unloaded is an invariant structure in the act of juggling. However, throughout the learning process the time between the release and catch revealed the most significant reduction with less time necessary for the flight trajectory time of the objects. The participants adopted a shorter flight trajectory time as they became more skilled, although they were able to extend beyond the 2-cycle criterion with lengthier ball flights.

The findings also provided additional evidence that the unloaded time of the hands is an important temporal feature in the juggling movement pattern (Beek, 1989). Although the spatial pattern of the ball tosses was over a narrower range with practice, the time in which the hands were empty was not altered in the early phase of acquiring the movement pattern. For higher tosses, the loaded hand carried the ball to a higher point before releasing and catching the ball at a higher point. As the juggler became more skilled, the height of the tosses was reduced by decreasing the amount of time in which the limbs were loaded before the release and making the catch with the same time interval between the of the flight trajectory.

No significant reduction in the dwell ratio was found in the present study. The dwell ratio includes the time in which the hand is loaded with the first catch, through the release, plus the time that the hand is unloaded before the catch. The dwell ratio ranged from 0.61 to 0.66 from the initial trials to the final trials. This range is much shorter than in the Beek and Lewbel (1995) study; however, the goal of the investigation was not to propose a variety of juggling frequencies. The participants in the present investigation were simply attempting to improve the number of ball catches, so they were most likely searching for the most comfortable speed in order to perform this task. These different findings are also expected due to the skill level of the participants. In the present investigation, the jugglers began as novices and progressed to an intermediate status, however, in the Beek and Lewbel (1995) study, experts were analyzed. Compared to novice and intermediate jugglers, expert jugglers are better able to vary the juggling frequency, including very high juggling frequencies with low dwell ratios, and to adopt a hot-potato and delayed styles of juggling resulting in low and high dwell ratios, respectively.

The variability that is intrinsic in the juggling motions decreases throughout the learning process but is always present even at the expert level (Beek & Lewbel, 1995), a feature that is general to movement in action (cf. Newell & Corcos, 1993). In achieving skilled juggling, it is critical to reduce the variability of the tosses, and to learn to compensate for errors. The most skilled of the participant learners were able to produce similar phase relations to that of the expert, but were not able with the level of practice provided to substantially vary the toss heights and velocities with the same functional adaptability. It appears that the novice jugglers were able to learn how to coordinate the movements of the hands and balls, but needed further practice to search for the boundaries to the basic movement pattern of balls and hands.

Increasing the accuracy of the tosses is an essential aspect of learning to juggle, as it allows the juggler to set up an invariant time basis for the hand movements, such as a spatial clock (Beek, 1989; Van Santvoord & Beek, 1996), within which the proper phasing between the hand movements is subsequently learned. The learner discovered the phase relations that allowed enough time to catch the objects, but not too much time that the flight trajectory was jeopardized due to its potential error. As each participant learned the skill, they began to minimize torso movement, concentrating on the cyclic movement of the limbs. This minimized torso is related to the decreased variability of the toss, allowing the individual to stand in one area as opposed to "chasing the balls", while, conversely, a stable posture may be a prerequisite for accurate tossing.

Although we did not formalize the analysis of visual attention it is clear that the catching errors occurred more readily in the early 1–4 ball catch sequences when the attentional focus of the learner was drawn towards the hands. Mechsner, Kerzel, Knoblich, and Prinz (2001) reported this phenomenon in another bimanual coordination task involving a frequency ratio of 4:3 and that occluded vision of the hand movement. The task could only be accomplished when the attentional focus was drawn towards a stimulus other than the hands.

Although not quantitatively assessed in the present investigation, the visual cues used by the learners appeared to change throughout the learning process. For instance, the participant who finished with the highest number of catches began with one of the poorer performances and appeared to visually follow each ball's entire trajectory. As the sessions continued through qualitative assessment, his visual attention became more and more fixed on the upper portion of the parabolic arc. By the final session, this juggler, like the others, was observed to be limiting his view to the upper portion of the parabolic arcs and incorporating what he learned through, trial and error, to limit attention to the most important aspect to continue the juggling sequence. An expert is able to detect slight deviations in the ball's angle or energy of release, whereas a novice needs to visually detect changes in angle or velocity (Beek & Lewbel, 1995).

The function for the change in the mean number of balls caught in the trials over sessions showed that a power law (three parameters) accounted for more of the variance than an exponential function, opposing a finding by Huys where the number of consecutive throws increased at an exponential rate (Huys, Daffertshofer, & Beek, 2004). This pattern to the change in the outcome data with practice is consistent with the best fitting function in a large number of motor learning studies (cf. A. Newell & Rosenbloom, 1981). A dynamical systems interpretation of learning curves holds that this function of performance change is due to the changing and different time scales of the evolving attractor landscape, bifurcations between attractor organizations and the transient phenomena associated with moving toward and away from fixed points (Newell et al., 2001). The examination of the spatial and temporal motions of the limbs and balls over the practice sessions showed varying time scales to the rate of change in performance outcome (number of balls juggled), and the associated qualitative changes in movement dynamics. In contrast, for example, the rate of performance change associated with the acquisition of single limb positioning tasks, reflects an exponential time scale (Liu et al., 2003), a finding that is consistent with parameter changes of an attractor dynamic.

Our study has shown that there are many factors that drive the assembly of the juggling coordination pattern and its subsequent adaptation over practice. Fundamentally it would appear that the form of juggling emerges from the channeling of the spatial and temporal properties of the ball tosses and this in turn provides the basis for the pick up of the task relevant information that affords the assembly of the juggling cycle. Learning to juggle, i.e. learning to satisfy Shannon's equation, reflects the interdependence of information and movement in the perception–action cycle (Kugler adn Turvey, 1987).

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