Analysis of motor skill acquisition in novice jugglers by three-dimensional motion recording system

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Abstract

In the acquisition of skills requiring periodic body movements such as in cascade juggling, the establishment of stable body movements seems crucial. We investigated the processes of developing stable body movements in each of the three learning stages defined by the framework established by Beek and Van Santvoord (1992). We focused on two types of stability: stability of the body's physical center, representing global structure of body movements, and that of arm swing, representing local structure. The experimental results revealed that the skills for establishing local and global structures were acquired sequentially; in this case, first local and then global. In addition, the analysis of verbal reports suggested that stable body movements and conscious attention are mutually related.

Keywords: Skill acquisition; three-dimensional motion recording

Introduction

Empirical investigation of learning in various fields has indicated that as development progresses, performance not only increases in a continual way, but also changes noncontiguously through multiple stages of development. In each developmental stage, learners use specific strategies to perform a task (Delaney et al., 1998; Rickard, 2004). These findings suggest that for developing expertise through skill acquisition in sports and traditional art performances, individual characteristics of body movements emerge in each developmental stage when performing a task. As Handford et al. (1997) showed, one such factor determining each learning stage is the transition toward stability of body movements.

In the current study, we investigate three-ball cascade juggling as an experimental task in which stability of periodic body movements is crucial for reaching a higher level of performance. Beek and Van Santvoord (1992) distinguished three stages of learning for skill acquisition in three-ball cascade juggling by focusing on schematic representations of the temporal sequence of events such as tosses and catches (Figure 1).

They defined hand cycle time (HCT) as the time between one toss and the successive toss (or one catch and the successive catch) in a hand. Additionally, HCT is divided into time loaded (TL), defined by time spent holding a ball, and time unloaded (TU), defined by time not spent holding a ball. On the basis of these three parameters, an index *k* is defined by the following equation.

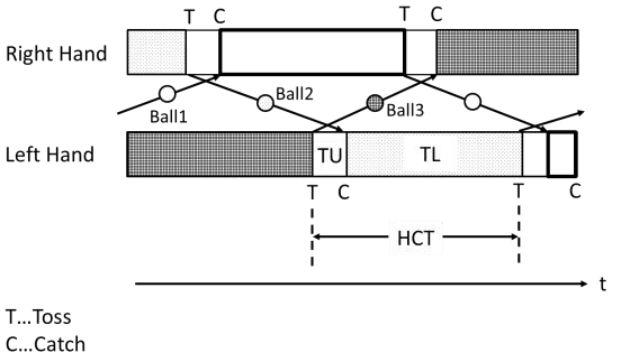

Figure 1: Schematic of the temporal sequence of events in three-ball cascade juggling (Hashizume and Matsuo, 2004)

$$k = \mathrm{TL} / (\mathrm{TL} + \mathrm{TU}) \text{ where } \mathrm{HCT} = \mathrm{TL} + \mathrm{TU} \quad (1)$$

In the initial stage of learning, Stage 1, the value of *k* is greater than 0.75, as learners discover how to perform three-ball cascade juggling through trial and error. In this stage, stability of body movements is not yet established. As the variability of HCT decreases, the learning stage moves to Stage 2, in which the value of *k* is maintained at almost 0.75, and does not decrease. Performers gradually learn to continue three-ball cascade juggling by establishing stable body movements. At this point, the value of *k* begins to decrease, and the learning stage shifts to Stage 3. Beyond Stage 3, performers have reached an expert level and are capable of performing five- and seven-ball cascade juggling. From the viewpoint of this analytical framework, Hashizume and Matsuo (2004) also showed that specific characteristics of body movements depend on the developmental stage; that is, the value of *k* and the variability of TU in body movements of those who reached Stage 3 are less than those still in Stage 2. In another analysis, Leroy, Thouvarecq and Gautier (2008) confirmed

that for expert jugglers, who can perform five-ball cascade juggling, a latency between the maximal flexion of the right elbow, and the maximal oscillation of the sacrum to the right is more firmly stabilized than in middle-level jugglers, who can perform three- but not five-ball cascade juggling.

These findings suggest that different characteristics of body movements may emerge depending on the stage of motor skills learning acquired. Previous studies have mainly focused on the temporal sequence of events in three-ball cascade juggling. In skill acquisition that needs periodic body movements such as cascade juggling, the establishment of stable body movements seems crucial. The current study investigates the processes of developing stable body movements by identifying specific characteristics in each of the three stages defined by the framework established by Beek and Van Santvoord (1992). We focus on two types of stabilities: stability of the body's physical center, which represents global structure of body movements, and that of arm swing, which represents local structure. In almost every sport, such as baseball and tennis, the establishment of both local and global stabilities is required for skill acquisition.

First, to establish global stability, the variability of movement in the body's physical center should be minimized. For example, the fundamental walking motion's stability is characterized by the flow and variability of the center of mass (Stokes, Andersson and Forssberg, 1989). It was confirmed that in complex body movements in sports and traditional art performances, a lower level of movement is a crucial factor that greatly affects smooth and stable movements of the whole body (Abe, Yamamoto and Fujinami, 2003; Escamilla et al., 2009).

Second, to establish local stability, each local part of the body should be coordinated. Yamamoto and Gohara (2000) confirmed that the variability of both physical center of the body and individual arm swing of expert tennis players is minimized, and that those spatial flows converge to fixed patterns. In three-ball cascade juggling, the balls are directly controlled by the movements of both hands. This systematic ball control requires the establishment of stability of both physical center of the body and individual arm swing.

In the current study, we investigate whether local and global stabilities are established in parallel or sequentially. Specifically, Beek and Van Santvoord (1992) showed that in moving from Stage 2 to Stage 3, the value of k remains constant at around 0.75 until the preparation for entering Stage 3 is completed, and begins to decrease in moving toward the Expert stage. We confirm how the two types of stabilities are established around this crucial development point.

Experimental Task

We investigated motor skill acquisition in three-ball cascade juggling. The skills required for performing this juggling are regarded to be among the fundamental ball juggling skills. The following describes how to perform three-ball cascade juggling (Beek and Van Santvoord, 1992).

(1) If a juggler is right-handed, he has two balls in the right hand and one in the left hand.
(2) Toss the ball in the right hand toward the left hand.
(3) As the first ball falls, toss the second ball in the left hand underneath toward the right hand. Catch the first ball in the left hand.
(4) As the second ball falls, toss the final ball in the right hand underneath toward the left hand. Catch the second ball in the right hand.
(5) As the final ball falls, toss the first ball in the left hand underneath toward the right hand. Continue with this sequence to perform three-ball cascade juggling.

The performance of jugglers was evaluated by the number of successive catches of balls according to the above procedure. In the experiment, we had the participants practice three-ball cascade juggling over one week. Hashizume and Matsuo (2004) suggested that novices reach Stage 1 when they are able to perform about 10 successive catches, Stage 2 is reached when about 50 successive catches are performed, and Stage 3 is reached by performing more than 100 successive catches.

Experiment

Method

Participants Eleven right-handed male undergraduates and graduates participated in the experiment (M = 20.3 years); all were novices in juggling. In addition, three expert right-handed jugglers (M = 20.0 years) involved in a juggling club in Nagoya University joined the experiment. They had acquired complete skills for performing five-ball cascade juggling.

Procedure Over a period of one week, the novices attended six training sessions while the experts received no training. On the first day, the novices were given three juggling balls (diameter: 63 mm, weight: 90 g), and were instructed to train themselves while referring to an instruction sheet on how to perform three-ball cascade juggling and a video demonstrating expert performance of three-ball cascade juggling. They were informed that they could refer only to the given materials. In each session, they were required to train themselves to perform three-ball cascade juggling for at least 60 min.

The participants' performances were measured on the first day (Day 1), the fourth day (Day 4), and the last day (Day 7). Five trials took place on Days 1 and 4, and 10 trials were performed on Day 7, where the participants tried to achieve their best record while performing inside the frame border (70 cm × 70 cm) on the floor. All experts were able to perform three-ball cascade juggling without any difficulty; therefore, on Day 7, they performed five trials, in which their complete performances were confirmed within 30 s. After the performance measurements, interviews were conducted, where the participants were required to explain the points they thought to be the most important for

performing three-ball cascade juggling. Explanatory gestures and demonstrations with balls were allowed. When the reports were incomplete or, difficult to understand, the experimenter encouraged more detailed explanations by requesting the participants to "give more specific explanations on that point."

On Day 7, during the performance measurement, a three-dimensional motion recording system recorded the position of seven light-reflecting markers in three-dimensional space with nine infrared cameras at a sample rate of 100 Hz (Hawk type, Hawk: five; Hawk-i: four, NAC Ltd., California, USA). The cameras were applied to the following anatomical sites: the left and right wrists, the left and right elbows, the left and right shoulders, and the chest. Anterior deviation (X-axis), lateral deviation (Y-axis), and vertical deviation (Z-axis) of each site were recorded in three-dimensional space.

Results

Best Performance Table 1 lists each participant's best performance on Days 1, 4, and 7. The table shows considerable differences in performance among the participants. On the basis of their best performances on Day 7, the participants were categorized into three groups according to the framework suggested by Beek and Van Santvoord (1992), and Hashizume and Matsuo (2004). The Stage 3 group included the participants who performed over 100 successive catches (No.5, No.7, No.9, No.11, M = 266, SD = 62.24), the Stage 2 group included those who reached 50 successive catches (No.1, No.6, No.10, M = 42, SD = 11.15), and the Stage 1 group included those who completed no more than 10 successive catches (No.2, No.3, No.4, No.8, M = 9, SD = 1.12).

Figure 2 indicates the transition of the means of the best performances on Days 1, 4, and 7 in each group. The horizontal axis shows the dates of measurement (Days 1, 4, and 7), and the vertical axis shows the means of successive catches as best performances with the log scale. Mixed ANOVA with Group (Stages 1, 2, and 3) as a between-subject factor and Day (Days 1, 4, and 7) as a within-subject factor was performed on the successive catches. It revealed a significant effect for both Group and Day (Group: F (2, 8) = 17.24, p < .005; Day: F (2, 16) = 9.67, p < .005). The interaction between Group and Day was also significant (F (4, 16) = 5.89, p < .005).

The post-hoc Ryan test showed that on Days 4 and 7, the best performances of the Stage 3 group were significantly higher than those of the Stage 1 and 2 groups (Day 4: MSe = 2904.01, p < .05; Day 7: MSe = 2904.01, p < .05). In addition, in the Stage 3 group, the successive catches on Day 7 were significantly greater than those on Days 1 and 4 (MSe = 2617.59, p < .05).

Table 1: Best performance of each participant on Days 1, 4, and 7

Participant (No.)	Day 1	Day 4	Day 7
No.1	5	18	40
No.2	6	7	7
No.3	2	3	9
No.4	3	5	8
No.5	27	80	242
No.6	4	10	30
No.7	19	101	354
No.8	4	5	10
No.9	10	334	283
No.10	2	4	57
No.11	21	36	183

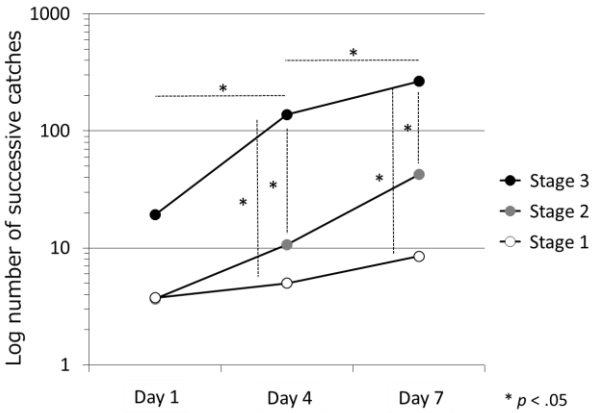

Figure 2: Transition of the means of the best performances on Days 1, 4, and 7 in each group

Stability of Movement Analysis

Analysis Procedure To evaluate the stability of body movements, the following three indexes were examined. The values of the indexes when tossing were analyzed because the timing of body movements was expected to determine the balls' trajectories. First, the stability of arm swing was examined using two indexes, standard deviation (SD) of the wrist positions and that of the elbow positions. Second, the physical center's stability was examined using the third index, i.e., SD of the chest positions.

The following procedure was utilized in the analysis. For identifying the timing of tossing, we focused on the movement of the wrist positions. The movement of the wrists periodically repeated upward and downward motions; and we regarded the top point in the vertical movement as the tossing point. At the tossing point, we captured the positions of three sites (the wrist, elbow, and chest) and calculated the values of the three indexes. For the Stage 2, 3, and Expert groups, to capture stable body movements that had reached a steady state, we excluded the initial three successive catches from the analysis. Twelve successive catches (from four to fifteen) were analyzed. Meanwhile, for the Stage 1 group, since the number of catches was much lesser, an analysis based on the above requirement was

impossible. Therefore, for this group, we analyzed body movements from the initial toss to the final catch. Two of the four participants in the Stage 1 group were excluded from the analysis because the recording system failed to capture their body movements.

Basically, the trial that had the best performance recorded was analyzed. However, when the recording system failed to capture the positions of the three sites in the best performance trial, we analyzed another trial in which the second or third best performance was recorded.

Stability of Movement Result Figures 3, 4, and 5 show the values of the three indexes in the four groups. The horizontal axis shows Group (Stages 1, 2, 3, and Expert) and the vertical axis indicates the means of *SD*s of the positions of the three sites (the wrist, elbow, and chest, in mm) at tossing timing. The error bars indicate the standard errors. The participants in the Stage 1 group were excluded from the statistical analysis because the criterion for capturing data in that group was different, and the values of each index were much larger than those in the other groups. First, we evaluated the stability of arm swing for local body movement. The ANOVA revealed a significant effect of the Group factor on the *SD*s of the wrist positions (F (2, 7) = 6.97, $p < .05$). The post-hoc Ryan test showed that the *SD* in the Stage 2 group was significantly larger than those in both Stage 3 and Expert groups (*MSe* = 78.51, $p < .05$). The ANOVA on the *SD*s of the elbow positions also revealed a significant effect of the Group factor (F (2, 7) = 14.03, $p < .005$). The post-hoc Ryan test also showed that the *SD* in the Stage 2 group was significantly larger than those in Stage 3 and Expert groups, respectively (*MSe* = 2.26, $p < .05$).

Meanwhile, for stability of the body's physical center, an ANOVA on the *SD*s of the chest positions revealed a significant effect of the Group factor (F (2, 7) = 6.84, $p < .05$). The post hoc-Ryan test also showed that the *SD* in the Stage 3 group was significantly larger than that in the Expert group (*MSe* = 2.66, $p < .05$).

The overall results showed that the variability of body movements in the Stage 1 group was much larger than that in the other three groups. As for arm swing, representing local structure of body movements, there was a significant development from Stage 2 to Stage 3 in the stabilities of both wrist and elbow movements; meanwhile, movements at the chest's physical center, representing global structure, emerged between Stage 3 and the Expert stage. These results imply that developmental stages in which local and global structures are established are different. This also suggests that the skills for establishing local and global structures are acquired sequentially; in this case, first local and then global.

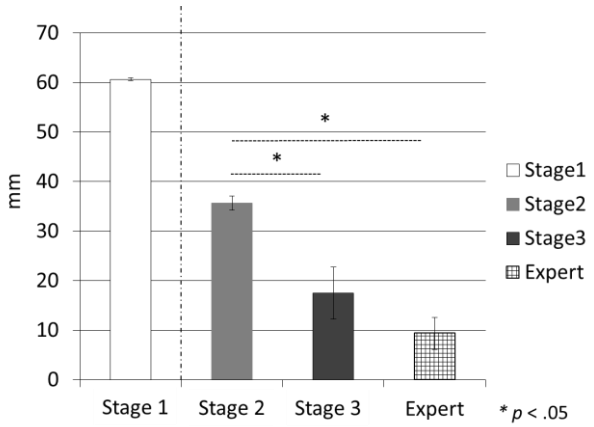

Figure 3: Standard deviation of the wrist positions

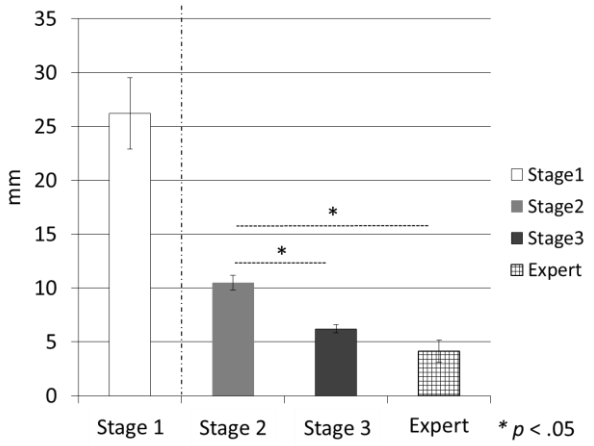

Figure 4: Standard deviation of the elbow positions

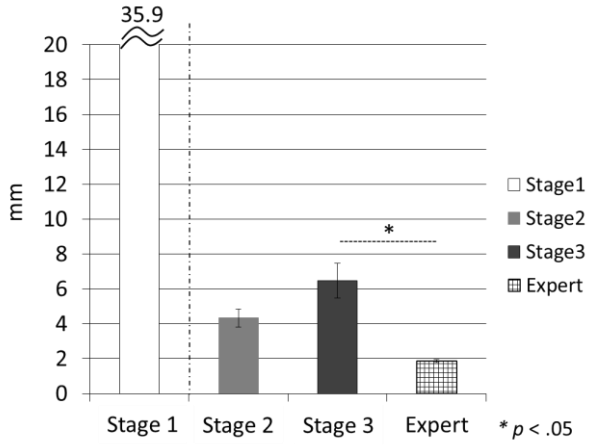

Figure 5: Standard deviation of the chest positions

Discussion and Conclusion

In this study, we investigated what characteristics emerge in each of the three learning stages defined by Beek and Van Santvood (1992), focusing on the development of stable body movements. The results showed that first, the stability of arm swing is established from Stage 2 to Stage 3, and

then, the stability of the body's physical center develops to reach the Expert stage, beyond Stage 3. This implies that the two types of skills, global and local stabilities, for performing three-ball cascade juggling are acquired sequentially. Our result, according to which an increase in the stability of arm swing occurs with the development of learning stages, is consistent with the findings of Mapelli et al. (2012).

The shift in the stability of body movements from Stage 2 to Stage 3 in the current study may correspond to the change in the value of *k* in Beek and Van Santvoord (1992). Our results showed that first, the stability of arm swing is established, and then the variability of the body's physical center is minimized. This implies that strategies for performing the task are different at each learning stage. Specifically, the participants who reached Stage 2 may use a strategy for tossing and catching balls by controlling their arms while those who reached Stage 3 may use a different strategy for controlling the body's physical center, with whole body movements from side to side while maintaining the stability of arm swing.

We also recorded the participants' verbal reports mentioning intentional concerns for achieving optimum learning and reaching their best performance on Days 1, 4, and 7. We also found differences in the reports among those who reached each of the three stages. We categorized the reported content into three categories.

- Physical: references to specific body movements. The following are representative examples:
  - Catch a ball with the palm of the hand, not with fingertips.
  - Continue three-ball cascade juggling while fixing the position of the elbows.
  - Note the other hand, and try to throw a ball to the place of that hand.
- Temporal: references to temporal structures of body movements. The following are representative examples:
  - Throw a ball at the time when another ball begins to fall from the zenith of its parabolic arc.
  - Let the ball be in space, and lengthen that time as much as possible.
  - Try to perform rhythmic throws and coordinate the rhythm to the movements of both hands.
- Spatial: references to spatial structures of manipulated objects (i.e., balls). The following are representative examples:
  - Throw a ball to a consistent place.
  - When throwing a ball, predict the place, where the ball will fall by watching the zenith of the parabolic arc continuously.
  - Try to fix the pathway of the ball to attain a consistent parabolic arc shape.

Table 2 indicates the category of the participants' reports based on the above criteria. The table indicates that the participants in the Stage 1 group mainly referred to the first category (physical), maintaining such references until the interviews on Day 7 (three of four). The participants who reached Stage 2 similarly referred to the first category in their reports on Day 1 (three of three), but the rate of the first category of reports gradually decreased from Day 1 to Day 7 (zero of three on Day 7), and instead, references to the second category (temporal) about the temporal structures of body movements increased (three of three on Day 7). Those who reached Stage 3 did not refer to the first category from Day 1, maintaining this tendency until Day 7 (zero of four on Day 7); and consistently referred mainly to the third category (spatial) (about 47 % of the total). This tendency was also observed in the Expert group.

The verbal reports reflect the intentional findings consciously noted by the participants in each learning stage.

Table 2: Category of the participants' reports

Physical | Temporal | Spatial

Participant (No.)		Day 1	Day 4	Day 7
Expert	No.12			Spa.
	No.13			Ohter
	No.14			Spa. Tem.
Stage 3	No.5	Spa. Spa.	Phy.	Spa.
	No.7	Spa. Phy.	Spa.	Other
	No.9	Tem.	Spa.	Spa.
	No.11	Tem.	Tem. Phy.	Tem.
Stage 2	No.1	Spa. Phy.	Phy. Tem. Other	Tem.
	No.6	Phy. Other	Tem.	Tem.
	No.10	Phy.	Other	Tem.
Stage 1	No.2	Phy.	Spa.	Phy.
	No.3	Phy.	Spa.	Spa.
	No.4	Spa. Spa.	Phy.	Phy. Spa.
	No.8	Spa. Phy.	Phy.	Phy.

The systematic distribution of the reports reflects that such conscious attention in training may relate to regularly phased unconscious skill acquisition of stable body movements captured in the current experiment. Beilock et al. (2002) confirmed that in training novice performers, efforts of continuous intentional attention to a series of specific behaviors cause rapid development of performance. Beilock and Carr (2001) reported that monitoring activities with intentional attention to one's own behaviors improves performance in choking situations when under mental stress. Additionally, Zentgraf and Munzert (2009) confirmed that the instructor's guidance causes improvements in both body movements and ball trajectory; specifically, information about body movements reduces the displacement of behaviors, and that about ball trajectory around the body decreases the variability of ball location at the zenith of the parabolic arc.

These findings imply the possibility that stable body movements and conscious attention are mutually related. Our initial trials in the current study have started a trial to propose an instructional program for skill acquisition that reflects the cognitive mechanisms necessary at each learning stage.

In the current study, the analysis was performed on a between-subject design basis. In the future, we should confirm similar shift patterns captured in the current study over individual learning processes. Additionally, we focused only on stability of body movements at the time of tossing. However, catches are also crucial for continuing cascade juggling. Stability seems crucial in tosses, but in catches, other factors may be important because in catches, adaptive behavior for responding to the variability of falling balls is required, in which we should find another significant factor besides stability.

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