Role of Visual Information during Playing Ball-Juggling

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ABSTRACT

Three experiments on ball-juggling were carried out in order to clarify how our brain utilizes visual information in motor control. In Experiment 1, temporal relation between ball and eye movements were examined. The results suggested that visual information around the top of the trajectory seemed important, and that eye movements were controlled in an active fashion that our brain obtained necessary information in appropriate timing. In Experiment 2, where movement of the left-hand (i.e., catching hand) were analyzed, it was shown that spatial movement to the catching position, catching action and return movement were performed as a continuous movement. Experiment 3 examined how juggling performance was affected by restricting visual information. Results were compared among three conditions, 1) vision was always available, 2) vision around the top of the trajectory was deprived of, and 3) vision of the left eye was always unavailable. The result showed that the performance was impaired a little in the second condition, and further more in the third condition, meaning that binocular information was quite important. A schematic model was proposed for understanding the general structure of control of ball-juggling.

1. INTRODUCTION

Ball-juggling has attracted many scientists since long time ago. Shannon, Father of information theory, was also interested in juggling and left an article [1].

The present study examined the role of visual information in playing "Otedama", Japanese-style ball-juggling (called "showering" in English), through behavioral experiments. The fundamental purpose here is to understand the mechanism of motor control of our brain, especially how our brain utilizes visual information in performing complex motor tasks.

Our brain realizes efficient sensory processing with limited resources by directing attention to specific information source which is likely to provide useful data for achieving the current task [2,3]. Such an attentional and active strategy of sensory processing must play an important role not only in perception and cognition, but also in motor control [4].

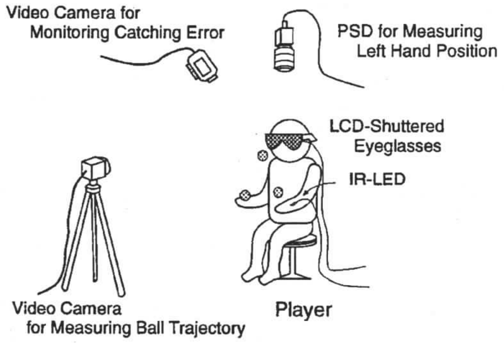

Figure 1 Experimental Apparatus

Ball-juggling seems a heavy task for our brain because we have to handle multiple balls simultaneously. Thus, it is expected that characteristics of such attentional processing appear remarkably in performing this task.

As a related study, Beek and their colleagues has examined the role of visual information in playing "cascade juggling" (another style of ball-juggling) [5–7]. They examined what visual information was essential for performing this task. In the present study, the authors measured temporal relation among hand, ball and eye movements (in Exps. 1 and 2), and examined the effect of restriction of visual information in a more quantitative manner (in Exp. 3) [9].

2. APPARATUS

Figure 1 depicts schematically the experimental system. It consisted of four sub-systems, which measured ball trajectory, hand position, catching-error and eye movement, respectively. In addition, LCD-shuttered eyeglasses were utilized for restricting visual information in Experiment 3.

Ball movement was observed with a video camera. Parameters of ball movement were estimated from several frames of video image and its future trajectory was predicted by extrapolation. Movement of the left hand (i.e., catching hand) was measured with an IR-based 2D position sensitive device (PSD). The left hand was

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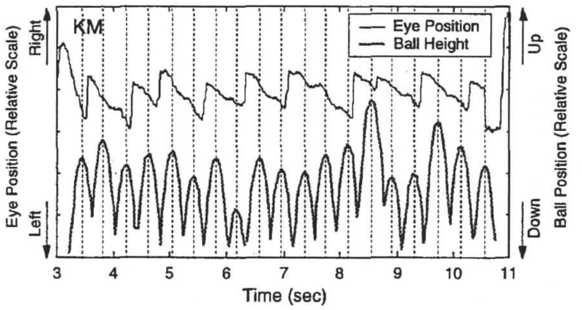

Figure 2 Relation between ball and eye movements

monitored by another video camera which mainly measured "catching error", the distance between the hand center and ball center in catching. Eye movements were detected based on change in the skin potential around the eyes (EOG method). Although player's visual field was secured with this method, its stability was too poor to measure absolute eye position. Thus, in the present study, the author focused mainly on the timing of eye movements.

Two subjects, KM (middle-class player) and KY (expert-class player) participated in all experiments.

3. EXPERIMENT 1

3.1 Purpose

Watching jugglers' eyes, we can readily notice that their eyes move periodically in horizontal direction. Though jugglers themselves feel as if they fixated at the top of the ball trajectory, such eye movements are commonly observed for all jugglers, independent of their skill.

Considering that visual attention and eye movement are tightly related to each other, measuring eye movements may provide us some clues to elucidate what visual information our brain selectively utilizes. Therefore, Experiment 1 examined the relation between ball and eye movements.

3.2 Result

Figure 2 illustrates a typical result obtained in 3-ball juggling. Top and bottom curves show the position of the right eye and the height of balls, respectively. Vertical broken lines indicate the time when balls passed the tops of their trajectories. It took about 800 ms from throwing a ball to catching it.

The result shows that the eyes alternatively repeated a smooth leftward movement and a quick rightward movement (saccade), approximately synchronized with ball movements. It seems that the leftward movement was for tracking a ball (Note that balls moved leftward because jugglers threw a ball by the right hand and caught it by the left hand) and the rightward movement was for preparing for the next ball.

Looking at the result more closely, it can be found that timing of saccadic eye movements varied cycle by cycle. To illustrate this fact clearly, distribution of saccade onsets with respect to the time when a ball passed the top of the trajectory (we call this "top-passing time" below) is shown in Figure 3.

The distribution of the onsets is rather broad and there are two peaks in the distribution: One is between 0 and 180 ms after the top-passing time and the other is between 100 and 200 ms before that time. Considering that balls were thrown one after another (cycle time was about 400 ms), however, it should be regarded that the right end of the horizontal axis is connected to the left end. Then, it is quite possible that the secondary peak is included in the slope of the primary peak.

Thus, it can be concluded that distribution of saccade onsets made a peak around 0 – 180 ms after the top-passing time and smoothly decreased with the time.

3.3 Discussion

First, the result that saccade onsets distributed rather broadly suggests that eye movements were not determined in a passive fashion, exactly synchronized with ball movements, but controlled in an active fashion, that is, to get necessary visual information. This view is consistent with the fact that saccades were not made in all ball cycles. Perhaps, our brain acquires selectively information helpful for motor control.

Next, let us speculate how our brain determines saccade timing. Experimental results show that most saccades occurred between the top-passing time and 200 ms after that. This implies that in most cases, our brain had acquired necessary information before or around the top-passing time. In other words, visual information in the first-half of the trajectory contained enough information for motor control.

What if our brain fails to gather enough information by the top-passing time (e.g., in the case that ball goes out of the visual field) ? In such a case, our brain must try to track the ball for longer time in order to get more information, which results in delayed saccades. The slope of the distribution found in Figure 3 may be formed by such delayed saccades.

The view that visual information around the top-passing time is important is also supported by the fact that saccades were less likely to occur between 0 and 100 ms before this time (See Figure 3): Our brain may prevent from making saccades around this period not to miss the most important information.

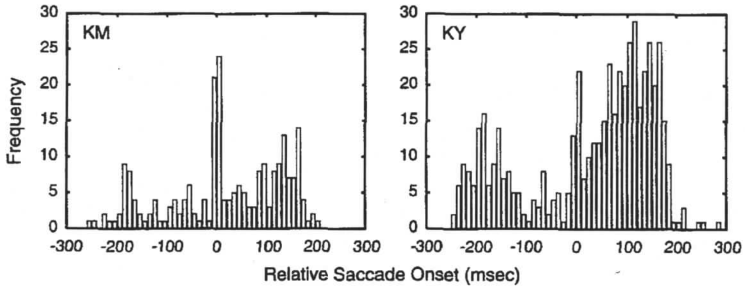

Figure 3 Distribution of saccade onsets

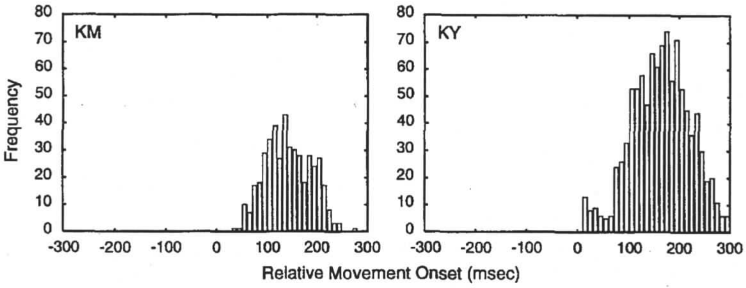

Figure 4 Distribution of onsets of left-hand movements

Then, why is such visual information important for our brain ? Two reasons can be thought. First, the top of the trajectory has a particular meaning in a physical sense. Actually, if the throwing time and top-passing time are exactly known, the catching time can be easily estimated. Second, it is plausible that our visual system can measure the ball position most accurately at the top of the trajectory. It is difficult for our visual system to know the position of an moving object whose retinal image changes fast, because our visual processing is slow. If a retinal image of an object is stabilized, to the contrary, our visual system can know its exact position. In ball-juggling, a ball moves in a constant speed in horizontal direction and in a constant acceleration in vertical direction (i.e., parabolic movement). Assuming here that our eyes tracks only the horizontal component of ball movement, retinal image of a ball moves only in vertical direction and stops at the top-passing time. That is why the top of the trajectory is easy for our brain to measure.

Therefore, the top of the ball trajectory has a special meaning for visual processing and motor control. It is consistent with the jugglers' subjective report that they keep directing attention to this position.

4. EXPERIMENT 2

4.1 Purpose

It is necessary to bring the left hand exactly to the position to which a ball falls, for stable juggling. Although such hand movement can be regarded as a sort of reaching movement, its destination is not explicitly given, different from visually-guided reaching movements. Therefore, our brain has to estimate it based on internal prediction.

Here, the authors wondered if visual information of the ball trajectory was utilized for this estimation. To answer this question, the authors analyzed temporal relation between ball and left hand movements.

The rationale is as follows. If onsets of the hand movement are in advance of the top-passing time, our brain does not utilize visual information at least for initial motor planning of the hand movement. If the onsets are enough behind the top-passing time, to the contrary, it is possible that our brain reflects visual information to the motor plan.

4.2 Result and Discussion

Figure 4 shows the distribution of movement onsets with respect to the top-passing time.

In contrast to the saccade onsets, onsets of arm movements distributed only in a restricted range (50 – 250 ms after the top-passing time). This was because players could not start left-hand movements until the left hand passed the previous ball to the right hand.

The result that the onsets were behind the top-passing time seems favor for the view that visual information was utilized for controlling the left hand. However, considering that the latency of arm movement is at least 200 ms, it cannot be said that the onsets were

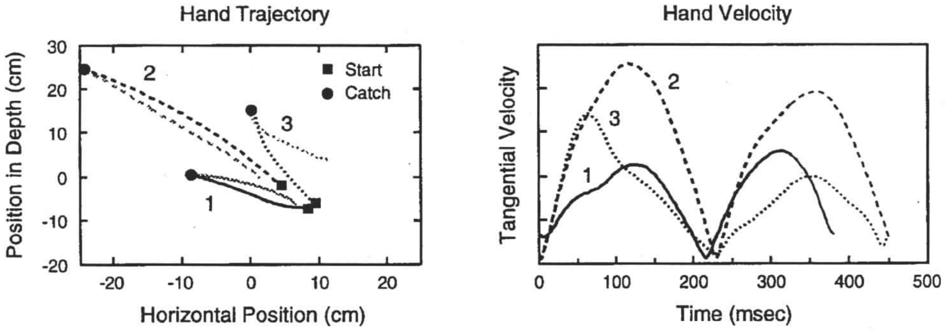

Figure 5 Trajectory and velocity profile of left-hand movement

"enough" behind the top-passing time.

Thus, we cannot get a definitive answer to the question. Of course, there remains a possibility that visual information is utilized for controlling the left hand. That is, it is possible that the hand movement is first triggered based only on prior information, but is updated using visual information.

By the way, the authors examined the trajectory and velocity profile of the left-hand movement, in addition. Figure 5 shows three examples of trajectories in a horizontal plane and corresponding tangential velocities. In the left panel, trajectories of "go" movement to catch a ball (thick line) and of "return" movement to pass the ball to the right hand (thin line) are drawn together. The first example (1) is a typical trajectory commonly observed in the experiment. The second one (2) shows the case that the hand traveled far leftward, and the third one (3) shows the case that the hand moved mainly in depth direction. The right panel shows velocity profile of each movement. The first (0 – 240 ms) and second (240 – 500 ms) curves correspond to "go" and "return" movements, respectively.

Although go and return movements seem distinct in the left panel, their velocity curves are connected continuously (i.e., there is no zero-velocity interval between two curves). Actually, when watching the left-hand movement from the side, it was observed that the left hand moved in vertical direction when catching a ball and that the hand drew an elliptic trajectory in a vertical plane. Such vertical movement must be helpful not only for minimizing the shock of ball-catch, but also for smoothing the movement itself. That is, go movement, catching action and return movement were performed as one continuous movement.

Looking at the catching action closely, moreover, it was found that the hand were closed almost at the same time as the hand touched the ball. This suggests that catching action was triggered not by sensory signal telling that the hand touched a ball, but by motor program planed in advance.

This behavior is closely related to "pre-shaping" observed in grasping an object: We form our hand posture according to the object shape in advance of touching it. Presumably, our brain determines when and how to close the hand in a similar manner.

In sum, two conclusion can be drawn in this experiment. First, "go" movement (to the catching position), catching action (vertical movement and hand closing) and "return" movement (for passing a ball to the right hand) are performed as a continuous movement. Second, our brain pre-programs not only where but also when we catch a ball.

5. EXPERIMENT 3

5.1 Purpose

The result of the previous experiment gave us no clear answer to the question whether visual information was utilized for controlling the left-hand movement. Experiment 3 tried to answer this question from another point of view: It examined whether the accuracy of the hand movement (and total performance of juggling) was impaired by restricting this information.

The authors used LCD shuttered eyeglasses to this end. The shutters were closed synchronized with ball movements so that players could not see a specific part of the ball trajectory.

In the previous study [8], the authors tried to show the effect of visual restriction, using average consecutive numbers of juggling (i.e., how long players could continue juggling) as a performance index, but failed to show any significant effect. This might be because this index did not reflect the accuracy of the left-hand movement: Players could continue juggling so long as the error was not fatally large.

In the present study, thus, the authors used "catching error", the distance between the hand center and ball center as a more direct measure of the movement accuracy. Subjects' performance was compared among

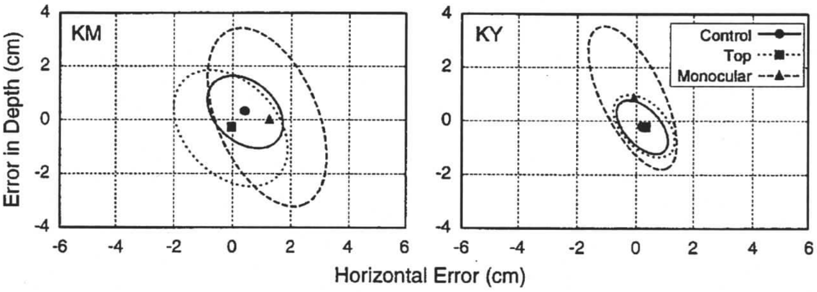

Figure 6 Error ellipse in three experimental conditions

the following conditions:

1. *Control* condition: Visual information was always available,
2. *Top* condition: Visual information for both eyes was unavailable for 100 ms when a ball passed the top of the trajectory, and
3. *Monocular* condition: Visual information for the left eye was always unavailable.

In *top* condition, the shutters were closed either between 0 and 100 ms before or after the top-passing time. *Monocular* condition was prepared to examine whether our brain relied on binocular information.

5.2 Result

First, average consecutive numbers for three conditions were 14.5, 12.3 and 7.0 for subject KM and 32.3, 32.3 and 13.6 for KY, showing that this index somehow indicated the effect of vision restriction.

Next, error ellipses in three conditions are shown in Figure 6. The hand center corresponds to (0, 0) on the figure. A larger ellipse means that variance of the error was larger (i.e., catching was less stable). Generally, size of the error ellipses were correlated with the average consecutive numbers: The number was reduced as the ellipse was larger.

Looking at the result for KM, the ellipse is larger in *top* condition and even larger in *monocular* condition, compared to *control* condition. As for KY, on the other hand, there is little difference between *control* and *top* conditions while the ellipse is remarkably larger in *monocular* condition. In *monocular* condition, moreover, the ellipse is expanded and its center is shifted in depth direction, meaning that the movement accuracy was impaired in depth condition. Therefore, movement accuracy were affected more by continuous lack of binocular information, rather than lack of a specific phase of visual information.

As for the *top* condition, there was no clear difference between the cases that the shutters were closed before and after the top-passing time, meaning that there was no specific "critical period" for acquiring visual information.

5.3 Discussion

First, the catching error increased significantly in depth direction when binocular information was always unavailable. This strongly suggests that binocular information (binocular disparity and/or vergence angle) is essential for controlling the left-hand movement, together with that visual information is surely utilized for controlling the left-hand movements.

In addition, the timing of catching action tended to be disordered in *monocular* condition (Unfortunately, the authors have not succeeded to show this tendency as objective data). Since catching action seemed triggered by internal estimation, as mentioned in the previous section, this tendency also supports that visual information contributes to the motor control.

On the other hand, it was shown that restricting visual information around the top of the trajectory had little effect, especially for the expert-class player. This result is against the conclusion of Experiment 1 that visual information around the top of the trajectory seems important. What made us fail to show the effect ? The following fact may give us a hint to answer this question.

The authors analyzed temporal change in catching error though no concrete data is shown here. In *control* condition, the error always remained within a certain range, and that is why the performance was stable. In *monocular* condition, on the other hand, the error remained small for a while, but once it started to increase, it was not recovered and reached a fatal level. This fact suggests that visual information is required only when the control is disordered. In other words, our brain does not rely on visual information while the control works well.

Therefore, the reason for the little effect in vision restriction in *top* condition may be in our flexible sensing strategy to refer to visual information only when needs arise.

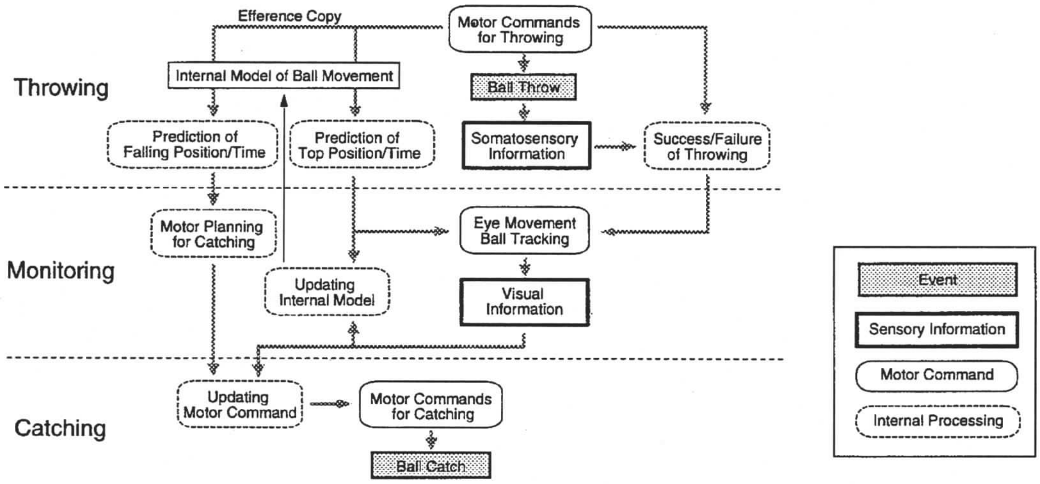

Figure 7 Schematic information flow in control of ball-juggling

6. CONCLUDING REMARKS

The present study showed that visual information played a certain role in ball-juggling. First, visual information around the top-passing time seemed important (Exp. 1). On the other hand, it was also suggested that out brain refers to visual information only when the control was disordered (Exp. 3). In other words, visual information was utilized not constantly, but intermittently according to the requirement. Presumably, such flexible and dynamic strategy of visual information processing makes it difficult to show a clear-cut experiment result. Moreover, it was shown that the left-hand movement for catching balls was controlled in a pre-programmed manner (Exp. 2).

It seems difficult to sketch the global control structure of ball-juggling in a bottom-up fashion based on individual experimental data. Finally, thus, the authors try to build a schematic model (Figure 7) in a top-down fashion.

The authors think that internal prediction based on motor commands for throwing plays a key role in control of ball-juggling. The most essential difference between beginners and experts is in the stability of throwing. If throwing is stable, that is, if we succeed in throwing a ball as we intends, our brain can predict the ball trajectory based only on its internal model. Thus, our brain can send proper motor commands to the left hand without relying on visual information. If we failed to throw a ball, to the contrary, our brain has to re-calculate or update motor commands based on visual information. Since beginners cannot throw balls in a stable manner, they have to often refer to visual information, which results in heavy load of sensory and motor processing.

In future study, the authors plan to measure 3D positions of hands and balls, and absolute eye positions to clarify more detailed characteristics of players' behavior. It is hopeful to understand the mechanism of motor control including attentional sensory processing though such attempts.

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