HOW VISUAL FEEDBACK AFFECTS MOVEMENTS

by

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Monkeys were well trained to perform a variety of point-to-point reaching movements in virtual reality. We systematically varied the timing and location of the visualized hand position to study the way that visual feedback is used during the initial phase of reaching. The results showed that the monkey learned a discrete strategy based on the information from vision of the hand during the reach. This information was used in a different phase of the task after a stereotypic processing delay to reach the target correctly. During the reach, vision of the moving hand was occluded except for a brief ‘flash’ period. Here, I demonstrate that reaching movement was affected by a gradual and orderly changed flash distance (at which point the flash was shown), but it was not affected when the order of the flash distance was randomly assigned. This suggested that the flash could not create a clear reaching effect every time. Second, I have shown that a misplaced flash location did not result in a hypothetical adjustment to counterbalance the imposed error. This suggested that the flash had to contain correct information in order to be used by the monkey. Finally, I have shown that the monkey was able to utilize the flash in a spatial rotation center-out task (the flash was displaced to either side of its proper location). This paper provides a novel movement correction experiment, and it is a useful tool for monkey experiments used to achieve long-term goals of understanding the connection between M1 neurons and early correction stimuli.

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1.0 INTRODUCTION

Every day people need to reach toward door knobs, light switches, or faucets. Although these tasks seem simple, the mechanisms behind these reaching movements are very complicated.

1.1 THE APPROACH AND TRANSPORT PHASE OF REACHING

Robert Woodworth was an early pioneer in the study of reaching. He established the importance of vision for reaching accuracy more than a hundred years ago [1, 2]. Subjects were required to move their hands between two targets in time with a metronome. The frequency of the metronome was set to be 20 to 200 strokes per minute. Those subjects performed the task with their eyes open and closed. Distal accuracy was much higher in the eyes-open condition at normal and slow speed conditions. However, distal accuracy was poor both with the eyes open or closed for the high speed condition. Woodworth did another experiment which was very similar to the first experiment, except 1) the frequency of the metronome was set to a constant value and 2) the subjects were instructed to move fast or slow during the task. He found that the speed of the movement affected the accuracy. From those two sets of experiments, Woodworth concluded that visual information was not useful when the inter-movement interval was less than 400ms. He found that the inaccuracy of fast reaching movement was due to a lack of final adjustment. This result was late confirmed by Keele and Posner [3].

Around half a century later, Craik designed an experiment which asked subjects to use a pointer to chase a moving object on a screen [4]. A 500ms delay was found between the subjects' action and the moving object. In addition, the subjects used a ballistic type of movement correction, which meant that the correction was discrete, not continuous.

Because of Woodworth and Craik’s experiments, it is now thought that reaching movement can be divided into two parts - the transport, or ‘ballistic’ phase and the approach phase [5, 11, 12, 13]. The transport phase occupies the first 90% of the reach. The main characteristic of the transport phase is its bell shaped speed profile; and it is planned before movement. The approach phase, on the other hand, uses visual feedback to guide the hand smoothly to the target zone; and it is adjusted mainly according to circumstances. Scientists thought that the reach consisted of a feedback-free transport phase and a feedback dependent approach phase. This idea was supported by Carlton [6]; he claimed that people focused on the targets, not the hands, during goal directed movements. Therefore, the visual error information might not be useful until the hands were close to the target zones [7].

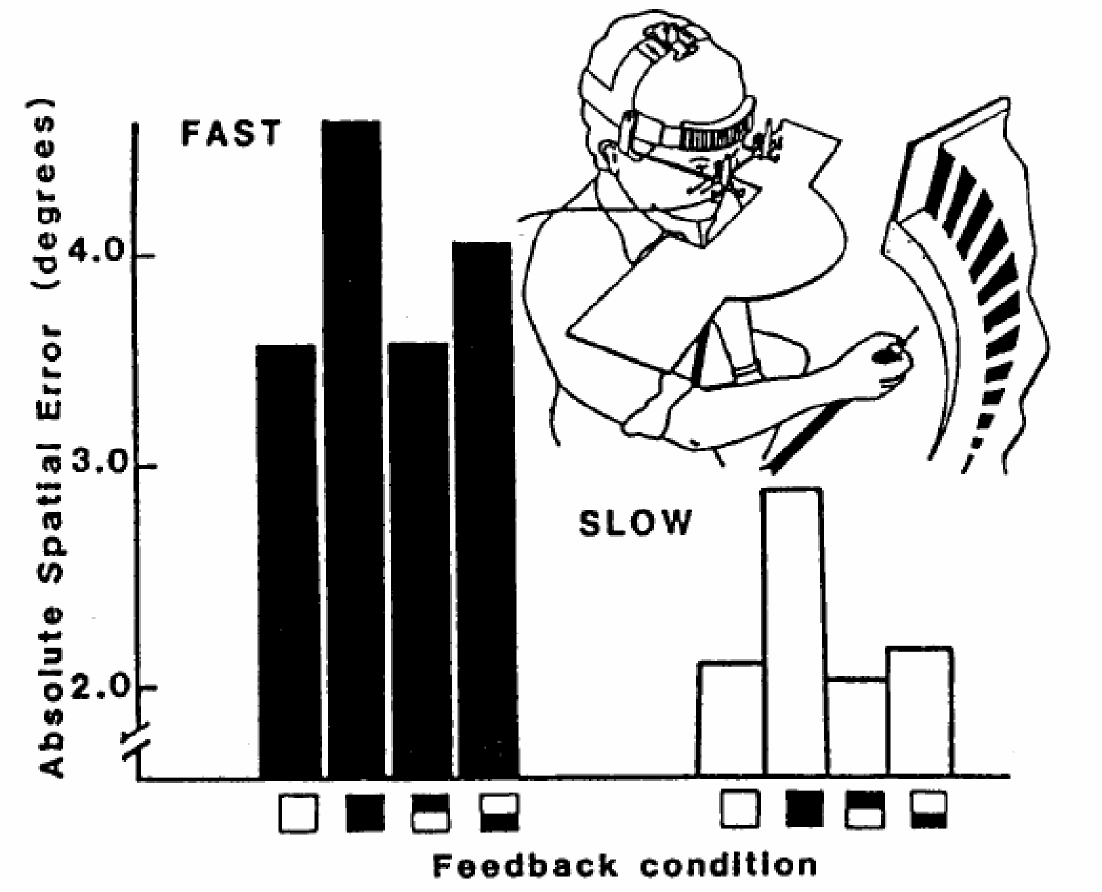


Figure 1. *Bard's experimental setup and result, this picture is copied from Paillard's paper[12]*

Until Conti and Beaubaton's [8] experimental result challenged the 'unusefulness' of visual feedback during the transport phase of pointing movement; it was considered not to be useful. However, their experiment results showed that early visual feedback can improve movement accuracy. In their experiment, subjects moved their hands under full, no, and partial vision. Under the partial vision condition, hand position was shown only in the early phase, the intermittent phase, or the final phase of the hand movement. The subjects also needed to move their hand toward the targets under three different levels of speed: fast speed (< 200ms), normal speed (between 200ms and 700ms), and slow speed (>700ms). They found that the movement accuracy in the early phase condition was greater than in the no-vision condition when the subjects' hands moved at normal and slow speed. This supported the idea that the visual information received during the ballistic phase of hand movement was useful. Bard's [9] aiming experiment also supported this finding. In his experiment (see figure 1), their subjects moved a joystick toward the vertical bars at two different speeds. The subjects' vision was restricted to full, no, and partial (1^{st} half or 2^{nd} half) vision. The experiment was different from other pointing experiments because they were not required to stop in the target. The result showed that the early phase of visual feedback in both fast and slow speed conditions improved the directional accuracy. Recently, Saunders and Knill [27] did a perturbation experiment to explore this area more. They asked subjects to move their fingers toward targets. A monitor was used to display their finger position which was given during the whole experiment. A displacement perturbation, which was a 2cm offset between the actual finger and virtual finger during the course of the movement, was given at 25% (early) or 50% (late) of the total distance to the target. The result showed that the response latencies in both cases were the same. This implied that the visual feedback information was used continuously during the whole movement. However, the success rate of the early perturbation trials was 10% greater than that of late perturbation trials. This implies that the continue process occurs at some time interval later that the feedback presentation.

1.2 TIME OF PROCESSING VISUAL INFORMATION

Keele and Posner did an experiment in 1968, 69 years after Woodworth's. Keele and Posner's central idea [10] was similar to Woodworth's which used different lighting conditions to determine the time duration of processing visual information. In their experiment, subjects moved a pointer toward targets which had a 50% chance of self-illumination (P = 0.5); and were required to move the pointer at four different speeds. The result showed that proportion of the error decreased when the visual feedback was given and/or the movement duration increased. Moreover, errors were related to visual feedback only when the movement duration was more than 200ms. Thus, Keele and Posner believed that the visual feedback was effective for reaching accuracy, but it took about 200ms to elicit a correction based on visual input. Zelaznik [7] repeated Keele and Posner's experiment with an extra condition: the target was always illuminated (P = 1). Errors decreased even though the movement duration was 120ms. The latency difference between these two experiments might be due to the expectation of feedback in the P =1 case. However, extra time may be required to process the feedback in the P =0.5 case because the feedback was not expected. This can be explained by a movement processing model which will be introduced later.

1.3 THE CHARACTERISTICS OF A MOVEMENT ANALYZING SYSTEM (MAS) AND DISPLACEMENT ANALYSIS SYSTEM (DAS)

In the first section, the transport and approach phases of movement were introduced. Before those phases had been brought to our attention, Woodworth [1, 2] had claimed that the visual feedback reduced the positional error during the ending phase of the reaching. Bard [9], on the other hand, found that the visual feedback improved the directional accuracy of movement in the initial phase of reaching.

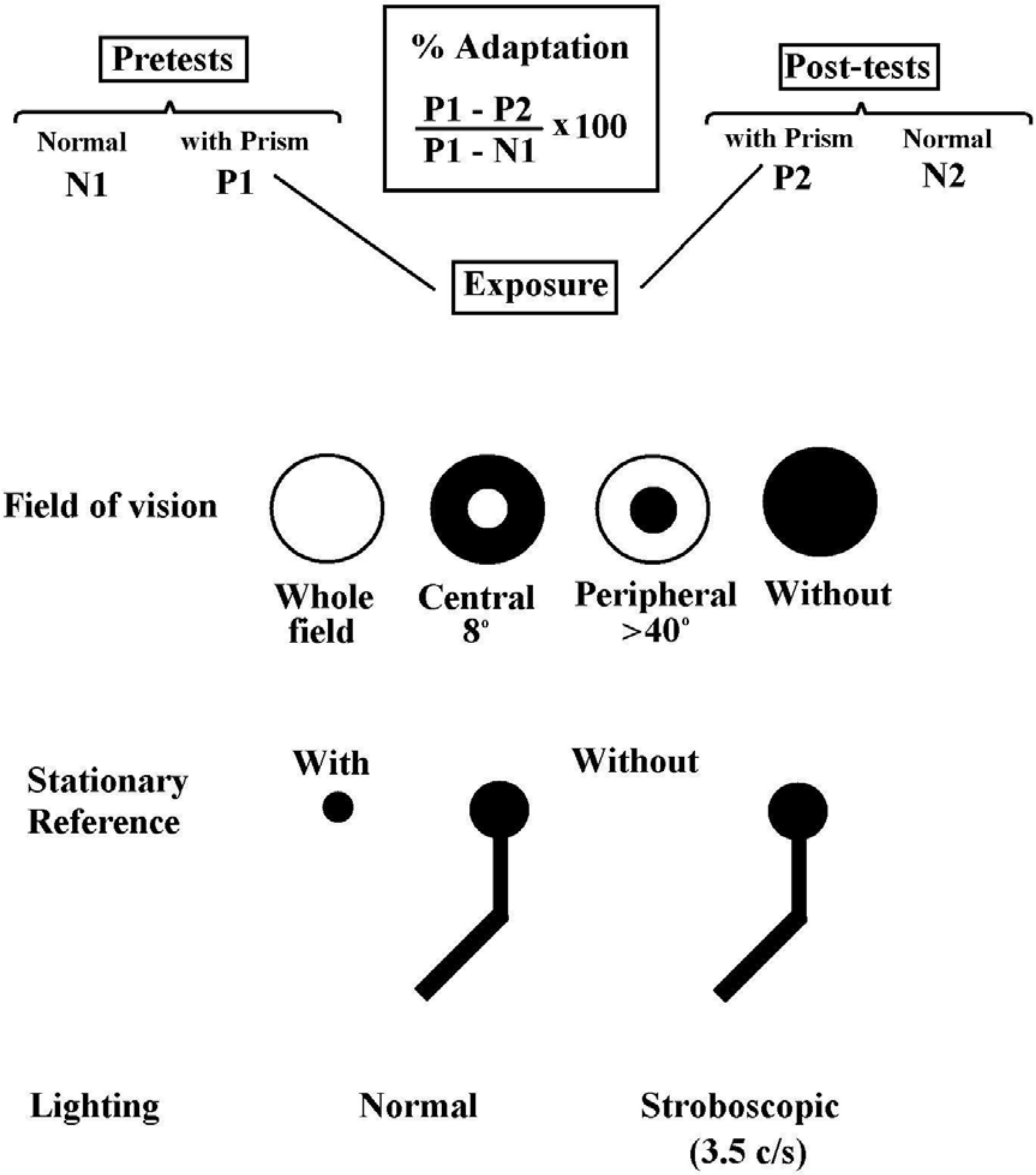


Figure 2. *General procedure of Paillard's experiment. P1 and P2 are the average error for pretest and post-test conditions respectively. N1 and N2 are the average error before the pretest and after the posttest condition.*

Visuomotor activity involves both visual and motor systems. However, few scientists focused on the functionality of the visual system during reaching movement until the 1960s. Paillard carried a series of experiments in this period. He believed [11-17] that two different systems, the Movement Analyzing System (MAS) and the Displacement Analyzing System (DAS), processed visual feedback information separately and designed a visual perturbation experiment to prove the existence of the two systems [11]. Subjects wore prismatic goggles which shifted visual flied to the left. The subjects' view was also limited to the central 90 degree (whole field vision), central 8 degree (central field vision), the visual periphery; or they had no vision at all (See Figure 2).

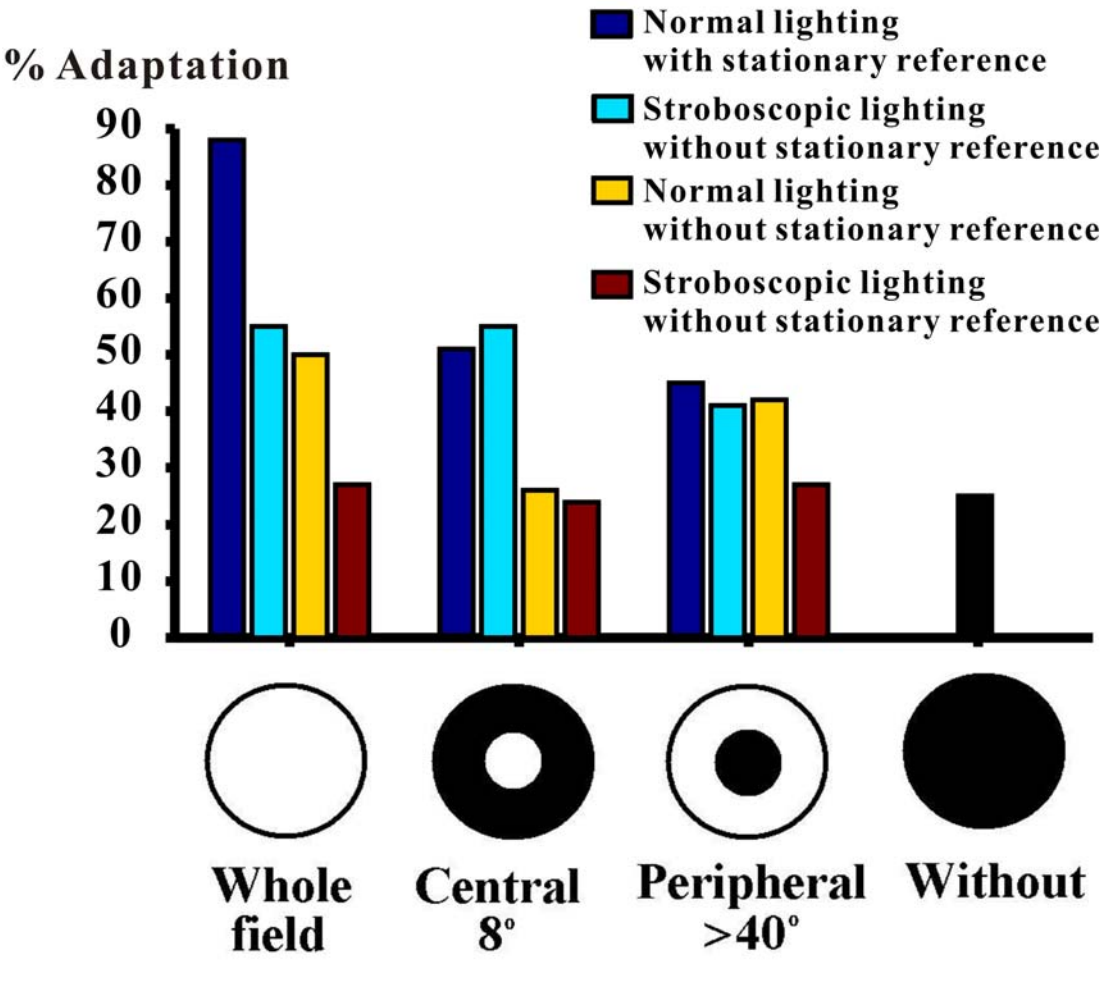


Figure 3. *The adaptation scores of Pillard's experiment in each condition*

In the pretest and the posttest periods, those subjects needed to point to designated targets in an open loop condition (without seeing their hands). Between the pretest and the posttest period, those subjects pointed either to stationary targets or moved freely under normal or stroboscopic illuminations. Then Paillard calculated adaptation scores (See Figure 2), which represented the rate of improvement, in each condition (See Figure 3). The data showed 1) the highest adaptation score when subjects moved their hands under normal whole field vision with stationary targets; 2) that when only the central field vision was allowed, the presence of the stationary targets improved the adaptation scores; 3) that with peripheral vision and absent stationary targets, the stroboscopic illumination (which affected the operation of MAS) decreased the adaptation score.

Therefore, Paillard [11-17] confirmed his hypothesis that two systems, MAS and DAS, controlled two different visual feedback loops to reduce the movement error. MAS mainly used peripheral vision (above 15 degrees of eccentricity and sensitive to high velocity); it detected the directional difference between the trajectories and a stable reference frame, using information from the initial part of the trajectory. DAS mainly used central vision (below 15 degrees of eccentricity and sensitive to low velocity); hand – target distance was use to reduce landing error. Moreover, Paillard concluded that the MAS suppressed the DAS peripheral vision since the stroboscopic illumination decreased the adaptation score under the peripheral field vision only when the stationary targets were absent.

1.4 INFORMATION PROCESSING

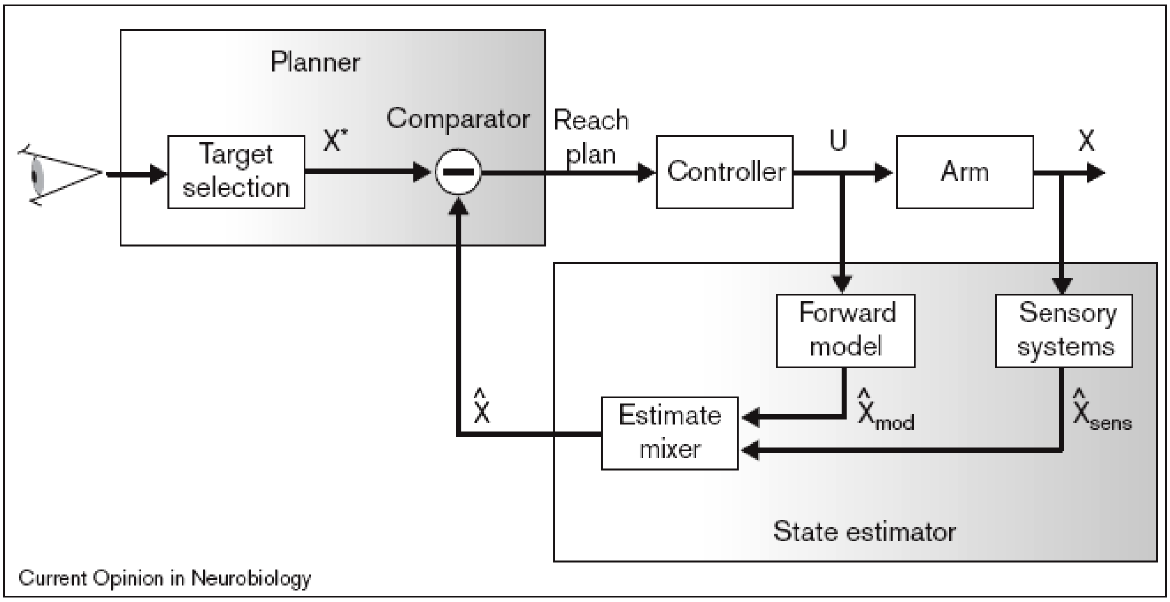


Figure 4. *Information processing model. X* is the target location. Controller converts the reach plan (trajectory plan) to the joint angles signals which is U. Arm receives the joint angles signals to produce X (the trajectory). Inside the estimator, estimate mixer receives the signal from sensory system and forward model (which creates the predictive sensory feedback). Then the estimator creates the single state estimation X^ which will compare to the X*. This figure is copied from Sabe's paper [18]*

In typical feedback models, sensory information is used to calculate the current state of reaching movement and compared to the desired movement. Correction signals are generated if any error is found.

These models were proposed more than a hundred years ago. Woodworth's simple model [1] was a pure-delay-feedback-loop to calculate movement error with a controller to correct the reaching trajectories. However, the pure-delay-feedback-loop must compare the desired command to delayed feedback; errors will occur because of signal latencies. To reduce this error below the threshold level is a lengthy process. His model does not match with the fact that we can produce smooth and fast movements. Therefore, movement information processing in our brains is not a simple pure-delay-feedback-loop. Some other components should exist to help the movement control. The sensory forward internal model, provides prediction of feedback to overcome the feedback latency problem, in the information processing model (see Figure 4). This model can explain how we reduce our movement errors in short time periods. Nowadays, each information processing models contain two major components which are forward and inverse internal models; the feedback predictor and movement controller respectively.

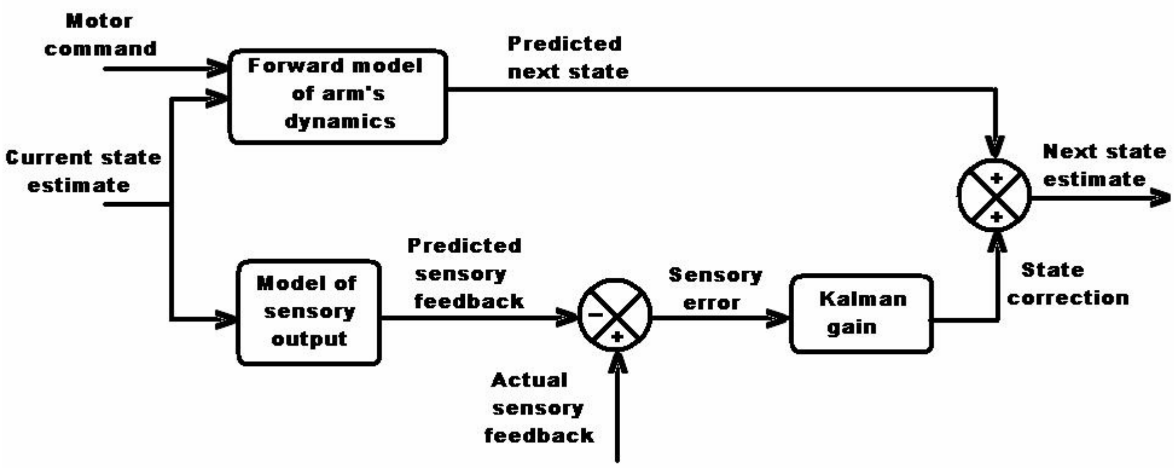


Figure 5. *The model of Wolpert's state estimator. In the upper part, the prediction of the next state is based on the current state and the motor command. In the lower part the actual sensory feedback is compared to the predicted sensory feedback. The relative weighting of those two parts is controlled by a gain function.*

Feedback latency is not the only problem in movement control. How to handle different sensory feedback signals of different quality is another problem. For example, we may ignore unreliable feedback. However, the state estimator in the previous movement control model (See figure 5) does not show this functionality. Wolpert [23] suggested another state estimator which includes a component to control the weight of sensory information (See figure 5). By reducing the weight of using the sensory component (the lower part of the figure 5), the unreliable feedback will have less significance. Then, the only primary contributing to next state estimation will be the forward model of the arm's dynamics. This can explain how our brains process noisy/unreliable feedback information. Moreover, the weight of using the sensory component will change dramatically when the condition of the movement is suddenly changed; more time is needed for processing the feedback information. Therefore, Wolpert's state estimator can also explain why movement error decreased even though the movement duration was only 120ms [7] in Zelaznik's experiment. (See page 6).

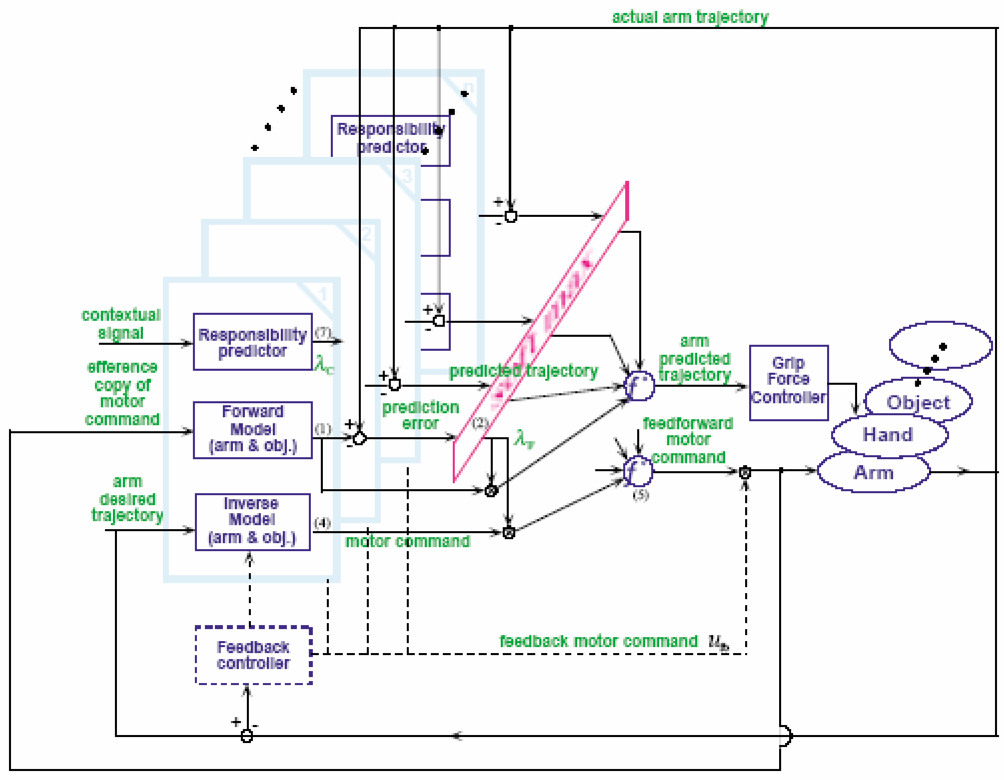


Figure 6. *Haruno's reaching movement model [22]*

Haruno's information process model [22] (Figure 6) is complex because of many math equations. However, his model is more advanced and realistic and is characterized by that 1) individual modules for each type of movement; 2) a combination of all modules used in every signal movement; and 3) a responsibility controller that governs the contribution of each module.

2.0 EXPERIMENT

Perturbation of visual feedback can be used to study the relation between visual feedback and hand movement. For example, Woodworth [1, 2] asked his subjects to close their eyes during reaching movements to find movement accuracy in a no visual feedback condition. Moreover, Paillard [11] asked subjects to wear prismatic goggles to alter the visual feedback to study the two channel systems. In other words, Woodworth and Paillard were using physical objects to create the perturbation. Nowadays, virtual reality systems are very common, so the latest experiments have changed to use 3D monitor displays with computer systems. Saunders [27] used computers to control the virtual pointer’s position in his visual perturbation experiment to study the possibility of online movement correction. In this section, our experiment setup will be introduced.

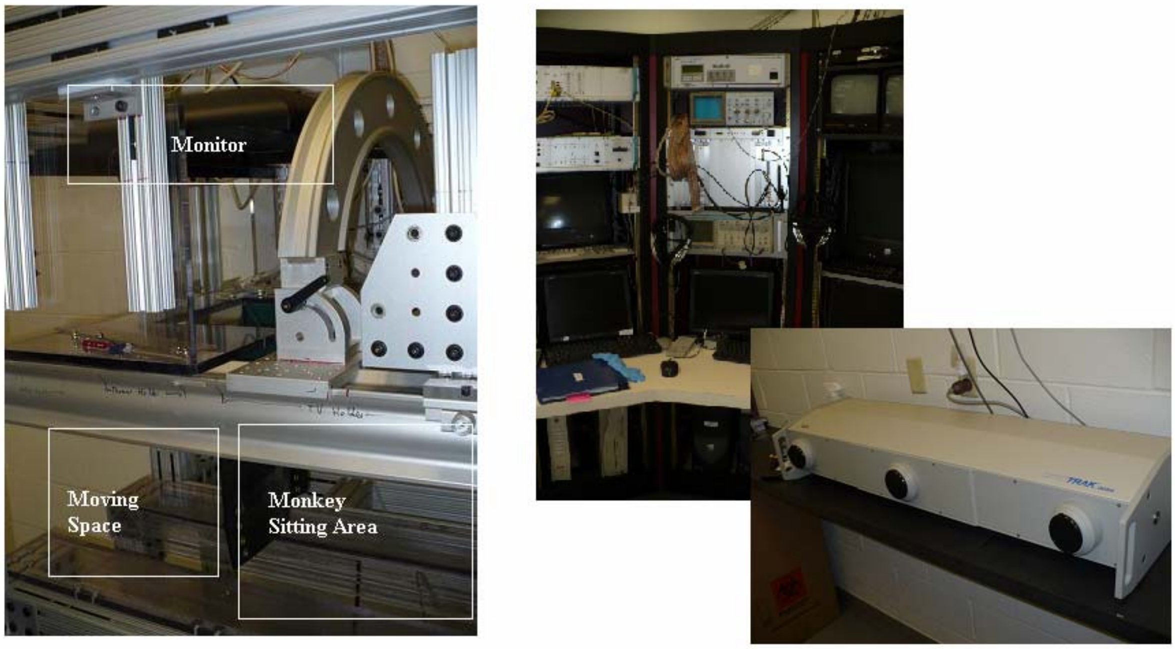


Figure 7. *The setup. The middle picture shows the computer which controls the visual feedback. The right picture shows the system which tracks the hand position.*

Figure 7 shows a setup for visual perturbation experiment. During the experiment, a monkey sits in a restraint chair. One of its hands is restrained and the other hand is allowed to move within the work space. A mirror is set in front of the monkey, replacing the view of its hand. Hand position is detected by a tracker; and its 3D position is sent to a computer. A cursor representing hand position is displayed on the monitor. By charging the value of the transform matrix (matrix that converts the hand coordination to visual coordinate), the cursor position can be altered. The advantage of using this setup is that the position and duration of visual feedback can be controlled precisely.

2.1 EXPERIMENT 1

2.1.1 Method and Material

Our aim of the experiment was to decide a behavior task that to understand information processing in our brains We used flash center-out task, so the visual feedback during the movement can be well controlled. Our hypothesis was that the monkey used the flash during its movement. The flash center-out task was modified from the regular center-out task with the visual feedback withheld until the hand reached the flash distance at which 66ms of visual feedback was given. The experiment was intended to determine whether gated-visual-feedback can be used by the monkey during the movement.

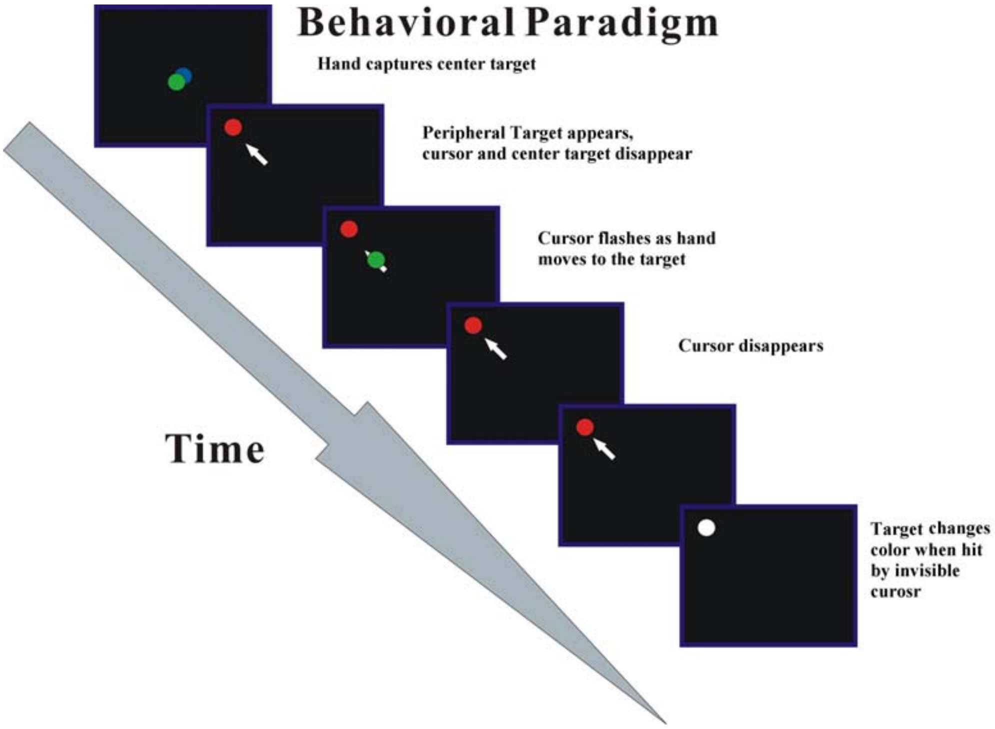


Figure 8. *behavioral paradigm of the first experiment (arrow – the hand movement direction, green circle – the cursor, blue circle – the center target, red circle – peripheral target, white circle – the peripheral target when touch)*

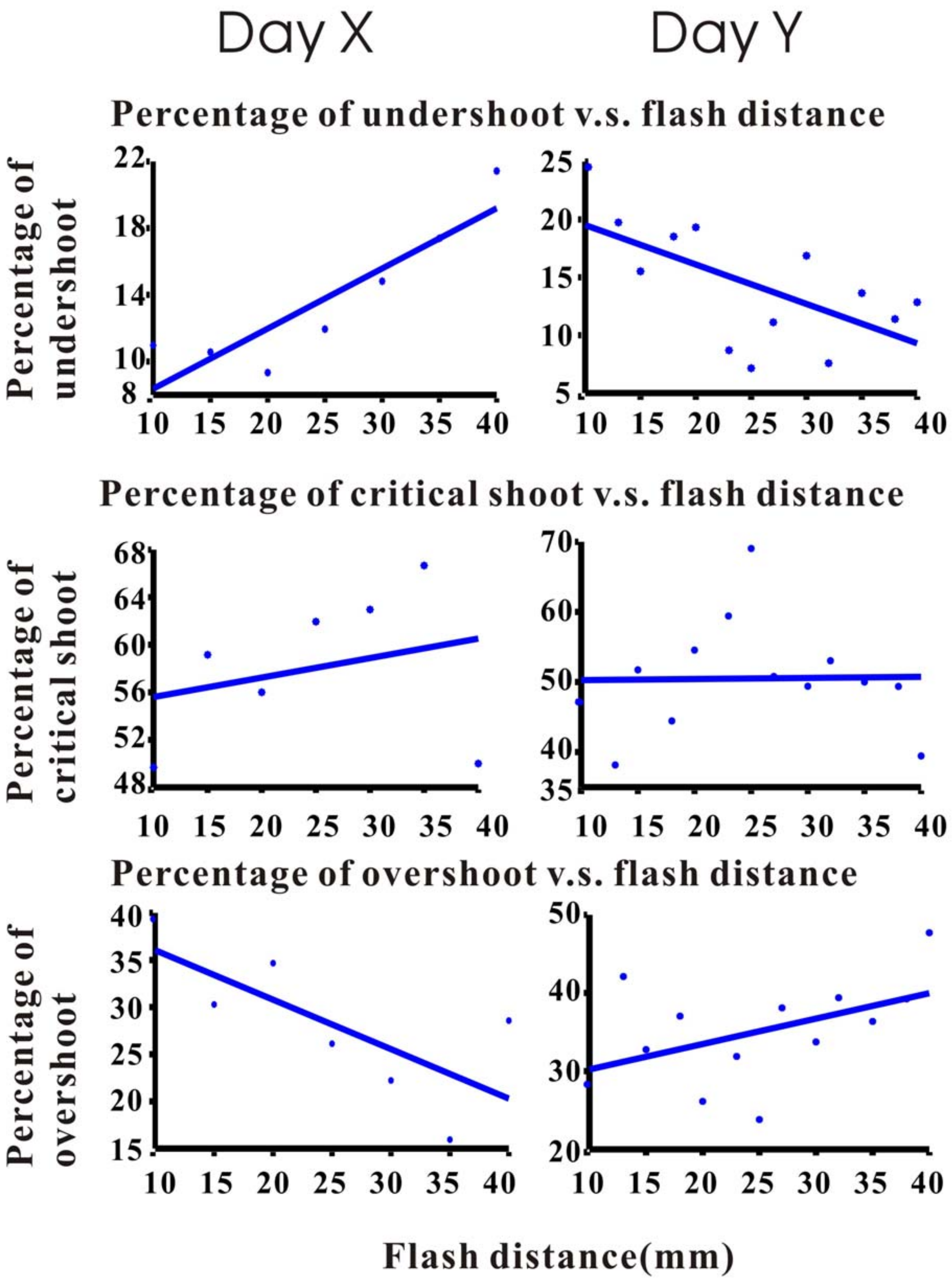


Figure 9. *The percentage of undershoot, critical shoot, and overshoot at different flash distance on day X and day Y respectively*

Table 1. *R square values and P values from multiple linear regressions.*

		Day X	Day Y
Undershoot	R square	0.7994	0.3886
	P value	0.0066	0.00228
Critical Shoot	R square	0.074	0.0004
	P value	0.5547	0.9515
Overshoot	R square	0.534	0.2233
	P value	0.0621	0.103

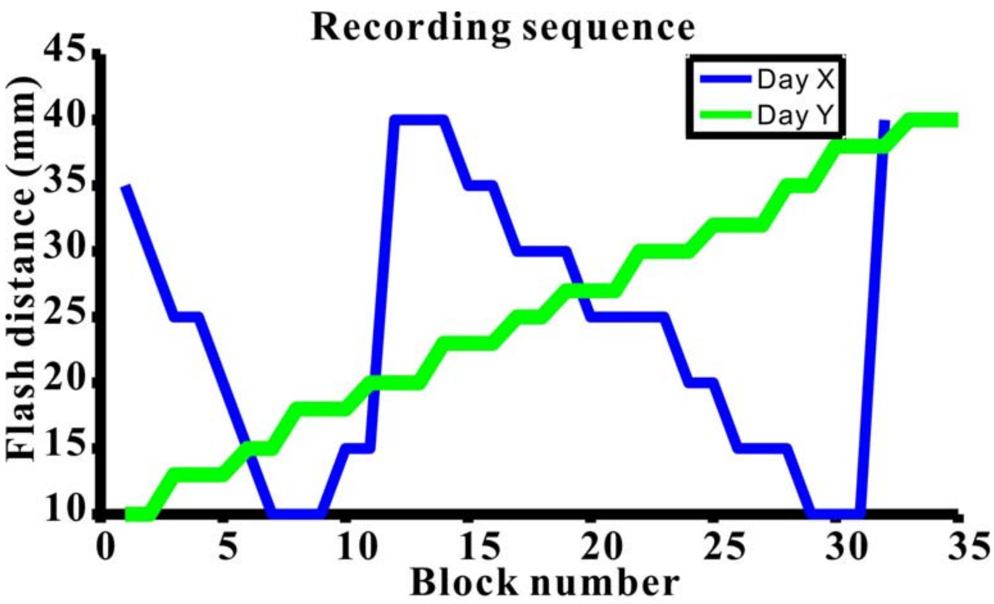


Figure 10: *The flash distance sequence across block number on day X and day Y.*

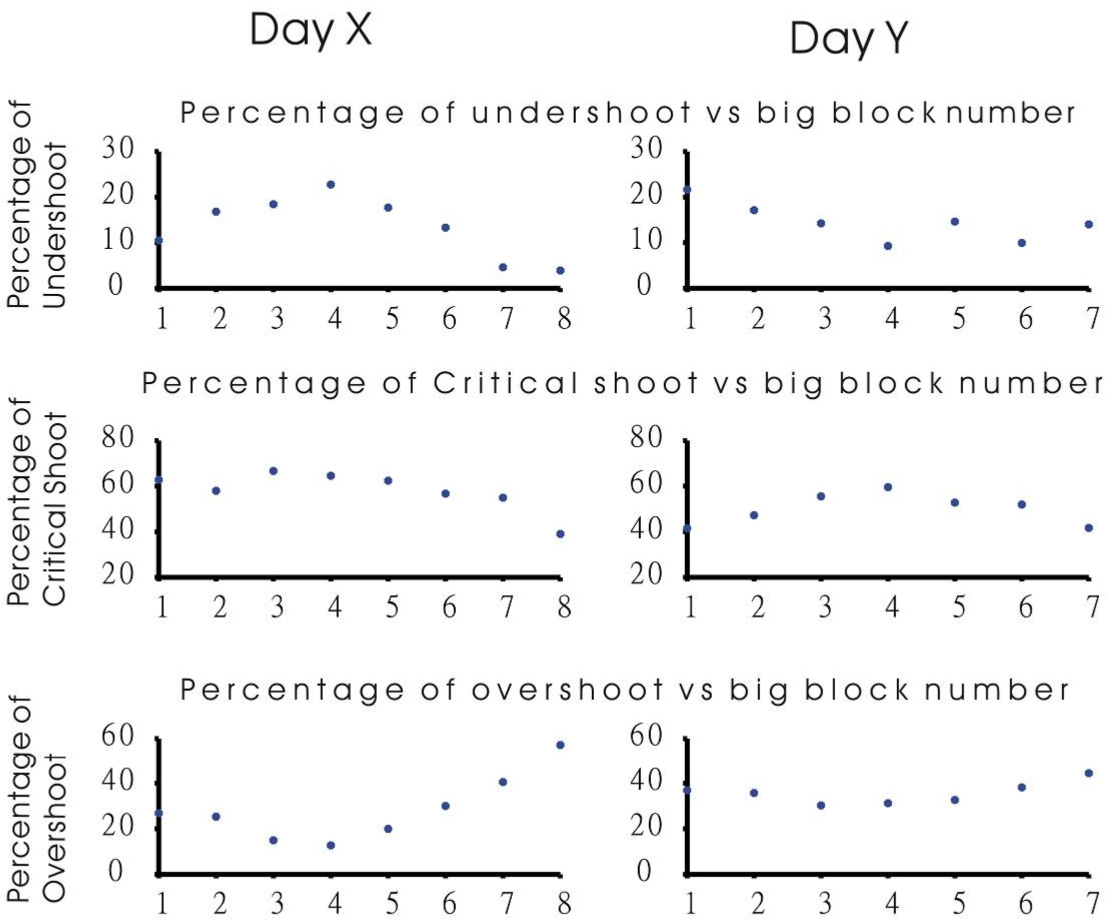


Figure 11: *block number vs percent undershoot and percent overshoot, each big block is averaged from at least 4 regular blocks*

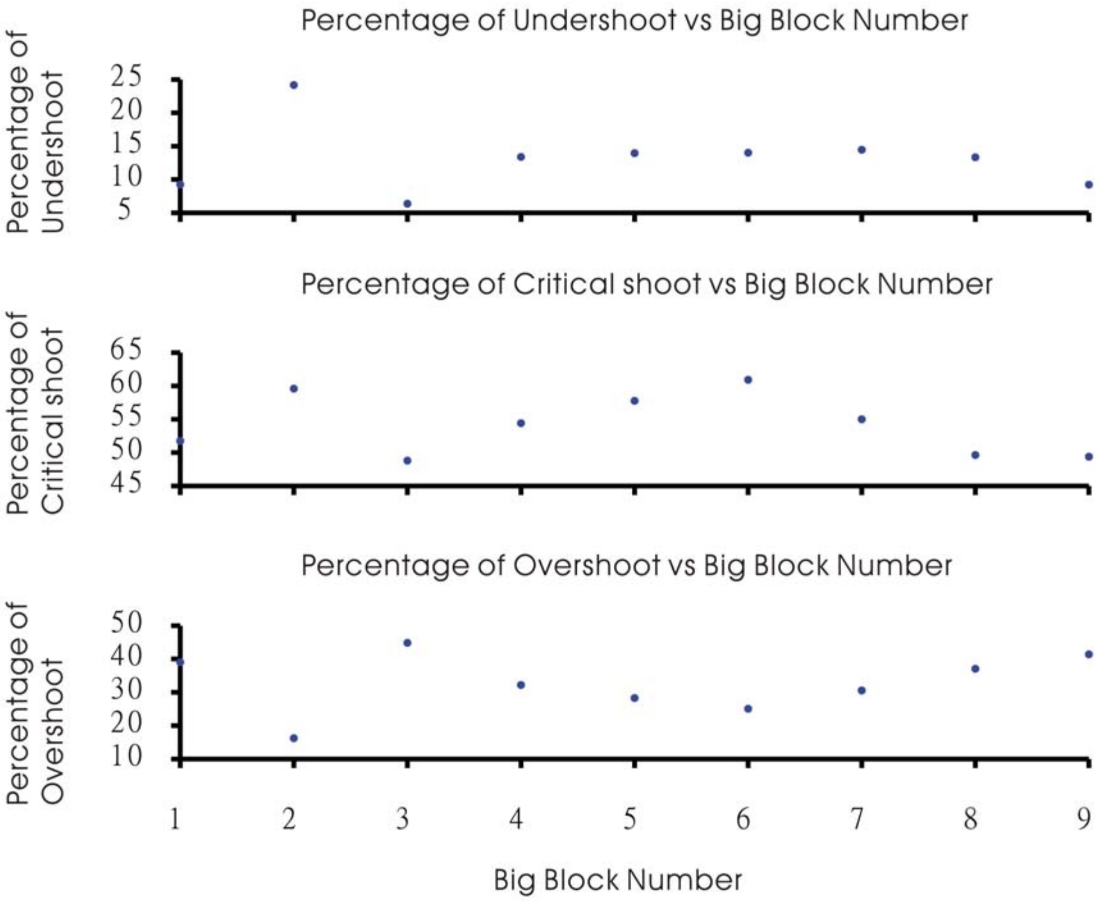
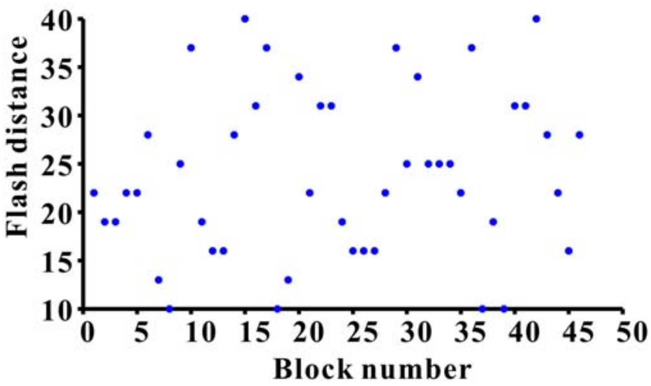


Figure 12. *block number vs percent undershoot and percent overshoot, , each big block is averaged from at least 4 regular blocks*



Day Z		
Undershoot	R square	0.0122
	P value	0.7468
Critical shoot	R square	0.1414
	P value	0.2544
Overshoot	R square	0.1129
	P value	0.3124

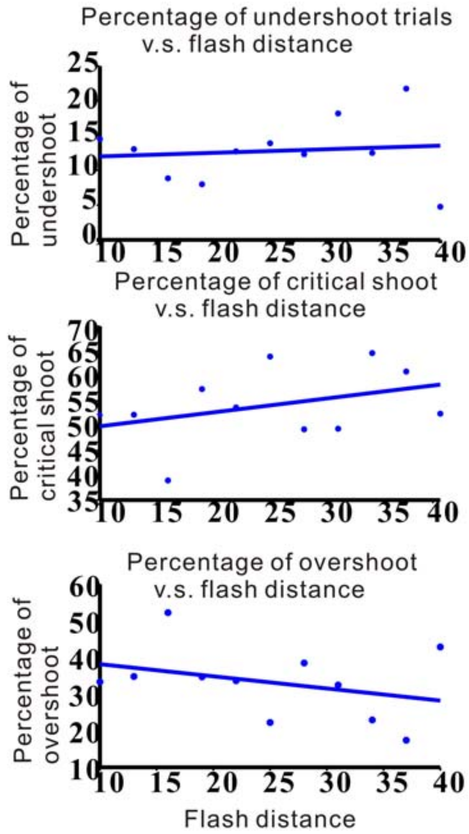


Figure 13 (left upper figure): *the flash distance sequence across block number on day Z.* **Figure 13 (right figure)**: *The ratio of undershoot, critical shoot, and overshoot to total trials at different flash distance on day Z. Figure 13 - Table 2: R square values and P values from multiple linear regression*

In the first experiment the cursor was flashed at different positions along the trajectory. Effectiveness of the visual cue was assessed by measuring the position of the hand at the end of the trial when the animal was attempting to acquire the target. The target was located 60 mm from the start position. The position of the terminal hand position (15% of max velocity) was quantified by three categories; undershoot (41.6- 56.3 mm), critical shoot (56.3-71 mm) and overshoot (71-85.6 mm). On the first day of the experiment (Day X), the flash position was decreased in distance from the start position (double sequence- Figure 10, blue line). The percentage of trials that displayed an undershoot varied directly with the flash distance (Figure 9 , r sq = .7994). The percent of trials in the target zone did not show a significant effect with flash distance (middle panel, r sq = .074) and this was the most common result for the entire experiment. The percent of overshoot tended to decrease with flash distance (r sq = .534). On the second day (Day Y), the order of the stimuli was reversed (Figure 11, green line). Now the tendency to undershoot decreased with flash distance (r sq = .39), while that for overshoot increased (r sq = .22). These results can be explained by the following scenario. The monkey had a slight tendency to undershoot without visual feedback. As the trials progressed through the day, the monkey learned to predict where the flash would occur and this corresponded to increased likelihood of overshooting and a decreased tendency to undershoot. In experiment #1, we found that the visual feedback could not consistently be used by the monkey. The monkey used the flash as a distance cue to tell itself where its hand located was only if the flash is consistently reliable. Therefore, we could not use it as a behavior task for any further recording

2.2 THE SECOND EXPERIMENT:

2.2.1 Method and material

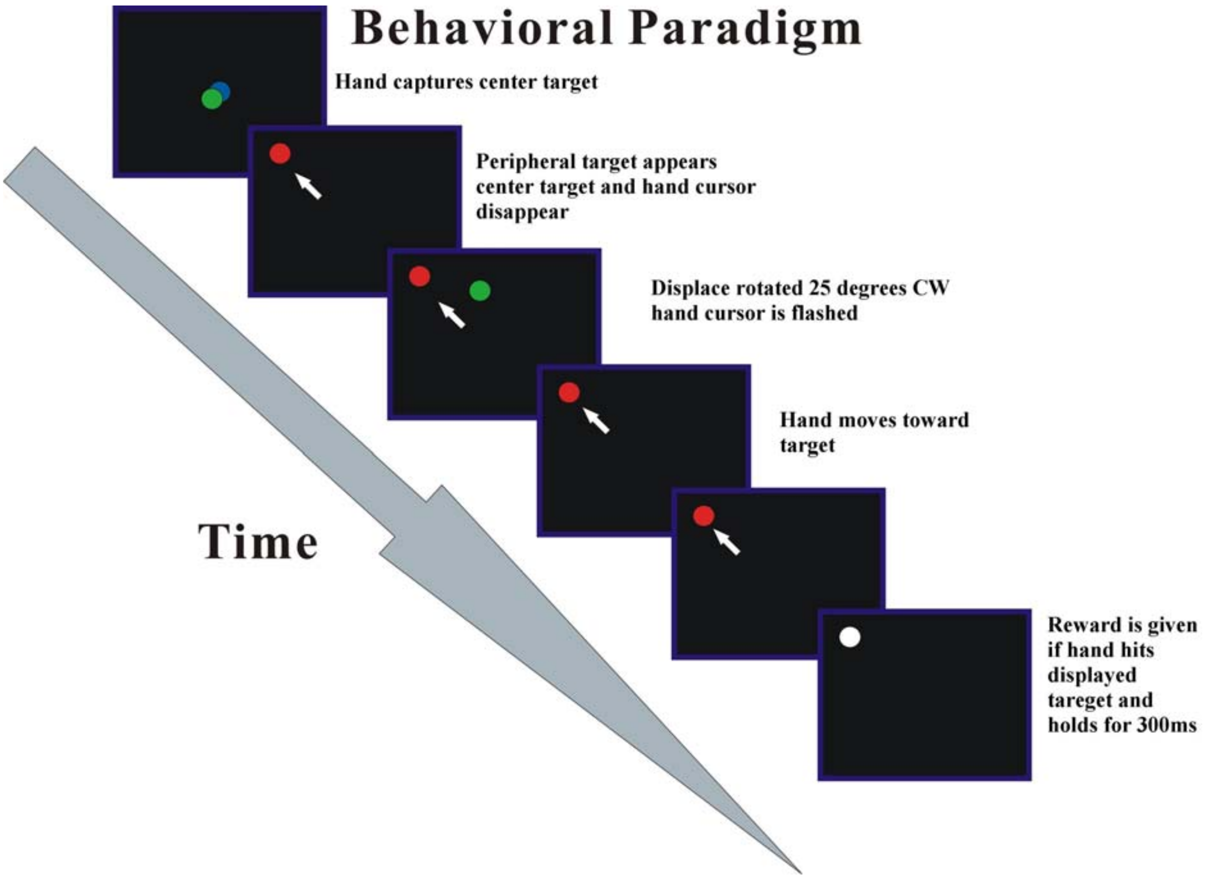


Figure 14. *behavioral paradigm of the 2nd experiment (arrow – the hand movement direction, green circle – the cursor, blue circle – the center target, red circle – peripheral target, white circle – the peripheral target when touch)*

From the previous experiment, we found that the monkey learned where to expect the flashed cursor, but we could not be assured that the monkey used the gated-visual-feedback every time. Therefore, we set up the following experiment to see how the monkey responded to angular perturbed, gated, visual feedback during the movement. Our hypothesis was that the monkey would create a physical adjustment to counterbalance the directional perturbation of the cursor.

The behavior diagram is shown on Figure 14. The monkey moved a cursor to the center target (based on the coordinate system with (0, 0, 0)). As the peripheral target appeared, the cursor and center target disappeared. The monkey moved its hand toward the target. The cursor disappeared when the movement began. The cursor reappeared for 66 ms at the flash distance, but the flash location was rotated clockwise by 25 degrees along visual Z axis[{5}]. If the monkey hit the target, the sphere changed color to begin the hold period. A reward was given if the monkey could hold the cursor in the target for 300 ms.

2.2.2 Results

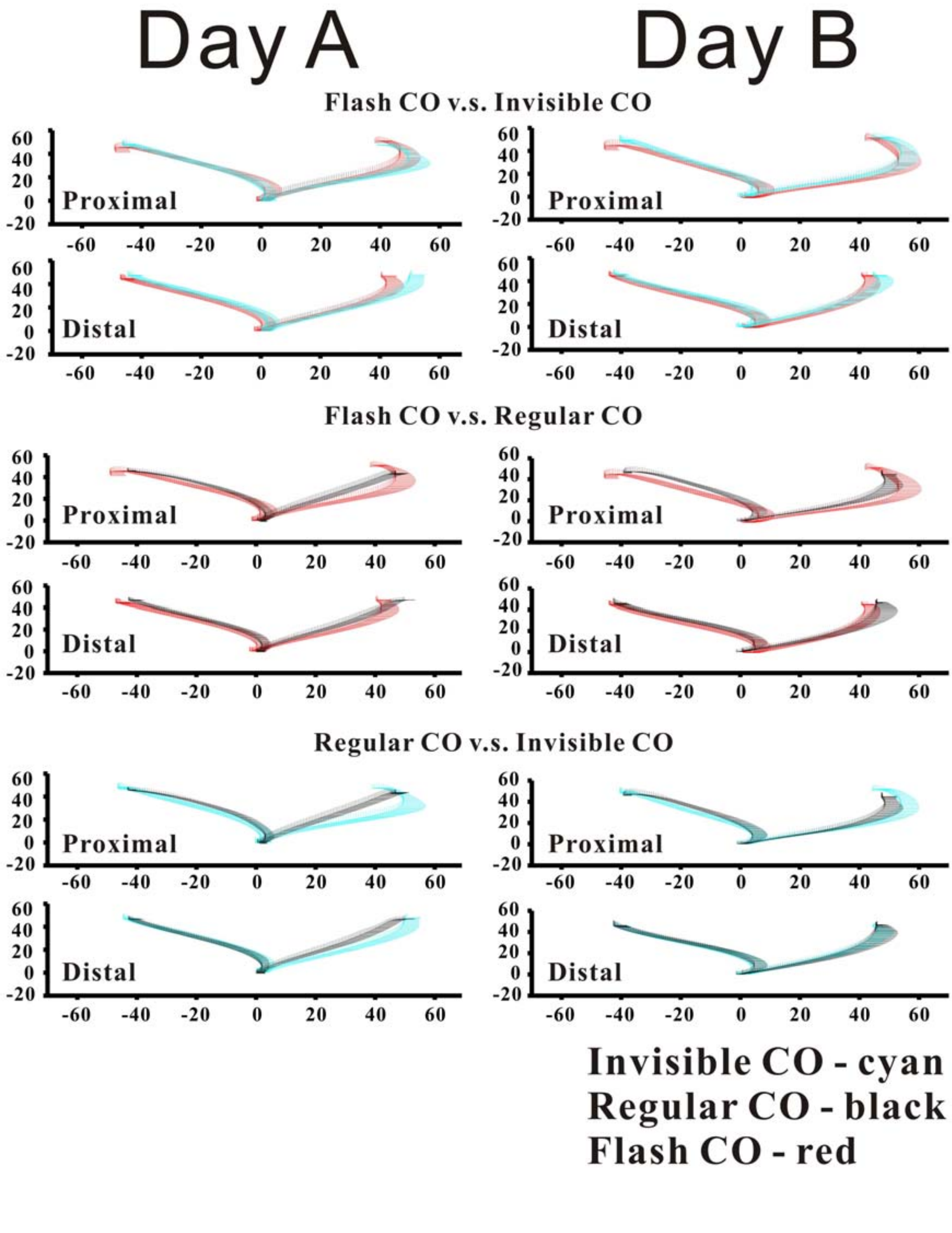


Figure 15. *Different pairs of Day A and Day B trajectories*

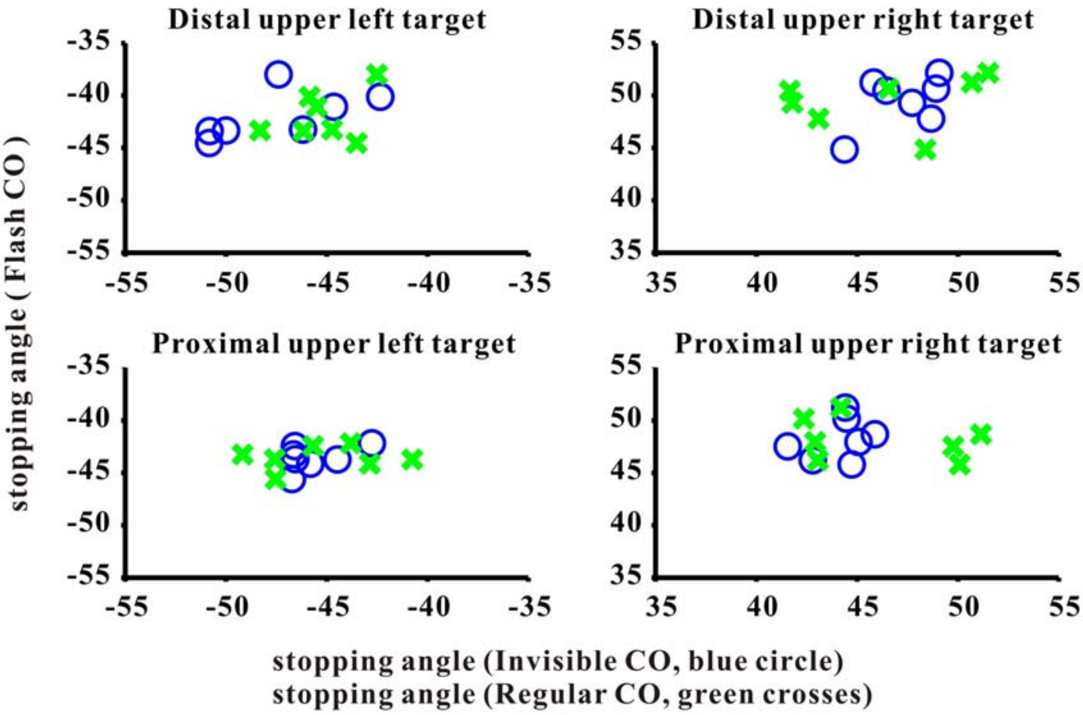


Figure 16. *The average stopping angles of all three conditions in seven recording sessions. The blue circles represent the average stopping angle of invisible and flash center-out for the same session. The green crosses represent the average stopping angle of regular and flash center-out on the same recording session*

It was thought that if the animal was attending to the cursor cue, that the displacement would lead to erroneous movement and its terminal hand position would be further from the target than normal. Three conditions were tested in this experiment. The cursor was on throughout the movement in the ‘normal’ trials, it was flashed at a displaced location in the ‘flash’ trials and it was completely absent in the ‘invisible’ trials. Each condition was repeated in blocks through during the daily experiments. Figure 16 shows results from two different days. Trajectories to the four targets are shown as mean + 1 SD (shaded region). The abscissa is left-right distance in mm from the start position, the ordinate is elevation and the panels are arranged so the proximal targets are above the distal targets. Paired comparisons are shown for the different conditions. The major differences are seen for the rightward targets in Day A. The invisible trials tend to be longer than those of the other two conditions. The regular trials tend to be straighter. Both of these differences were less obvious on Day B where the regular trials showed similar curvature to that seen in the other conditions. This day-to-day variability made it difficult to draw conclusions, but the main comparison– between the invisible condition and flashed cursor did not show a clear difference. In retrospect, a better design would have been to randomly intersperse a few trials in which the cursor was displaced with those that were normal. We would then expect performance to the displayed target to be degraded when the erroneous cursor position was used. The lack of effect in the collected data is summarized for all the data in Figure. 16. Here, each symbol represents the average result of an experimental day. The lack of effect in the collected data is summarized for all the data in Figure. 16. We concluded that the noise of hand movement was larger than the effect, so this experiment paradigm was not useful. Here, each symbol represents the average result of an experimental day. Based on these results we designed Experiment 3 (below) which addresses the possibility that the animal ignored the erroneous cursor cues

2.3 EXPERIMENT 3

This experiment also used a displaced cursor, but this time the animal was rewarded for moving its hand to an unseen virtual target that was displaced to the position the hand should be in if the indicated cursor position was correct (see Figure 17). On each trial the flashed cursor was displaced CW or CCW and the animal was rewarded for capturing the corresponding displaced, unseen target, by moving its hand to one side or the other of the displayed target.

After the first two experiments, we understood that the feedback information had to be important for the monkey to generate success trials. In the third experiment, we used a spatial rotation perturbation center-out task. We hypothesized that the monkey needed to use the information to correct its hand movement to hit the target zone. This is detailed in the following section.

2.3.1 Method and material

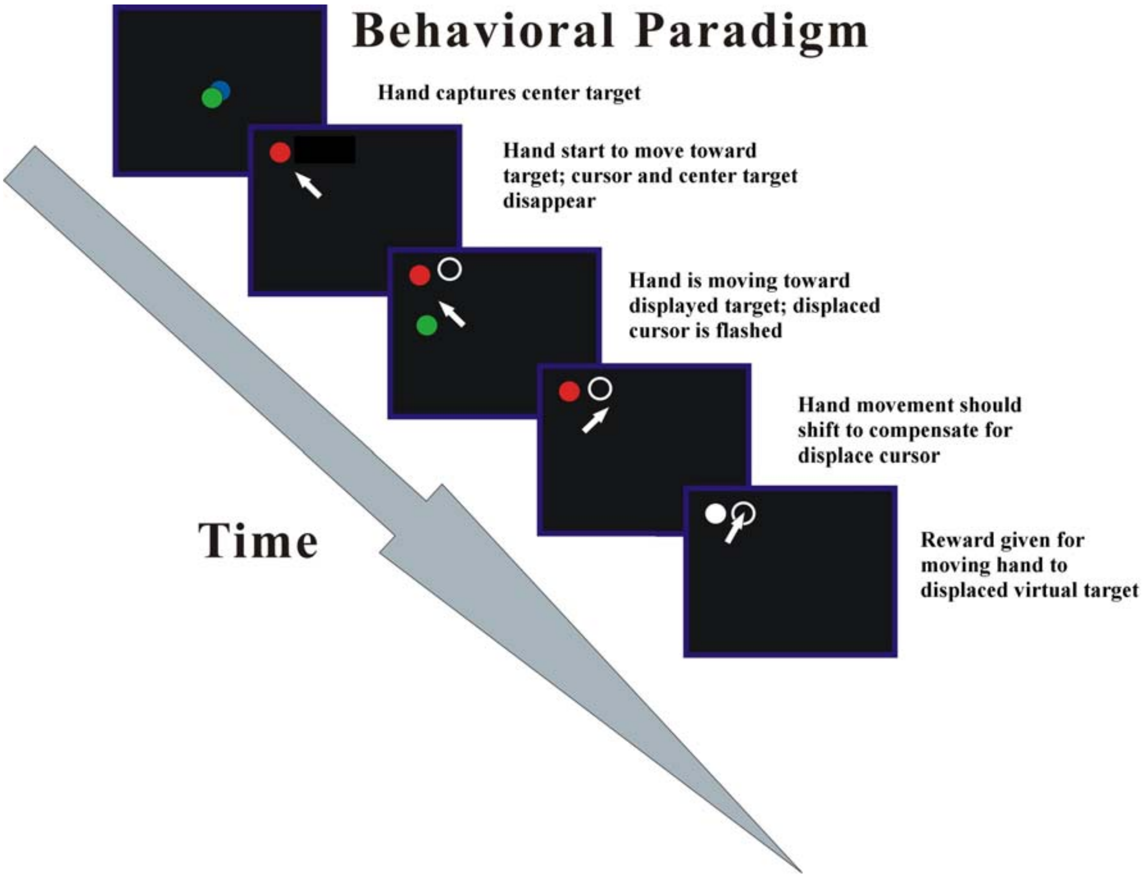


Figure 17. *behavioral paradigm (arrow – the hand movement direction, green circle – the cursor, blue circle – the center target, red circle – peripheral target, white circle – the peripheral target when touch, hollow white circle –physical space target zone)*

The monkey was seated in a primate restraint chair. His hand position was tracked by a 3D space tracking system. The behavior paradigm is shown on Figure 17. Feedback was given in the form of a spherical cursor which was flashed briefly on the computer screen. The 12mm radius peripheral target zones were set on the physical space XY plane *(x, y, 0)* and were 60mm away from the center *(0, 0, 0)*. If this cue was salient, the monkey would move its (invisible) hand toward a target location that was displaced from the displayed on target monitor. If the monkey moved to this virtual target correctly, the color of the displayed target would change and the animal would be rewarded. Moreover, we used a special Reward scaling and failure repeating rules to enhance the monkey attention (See Appendix).

2.3.2 Result

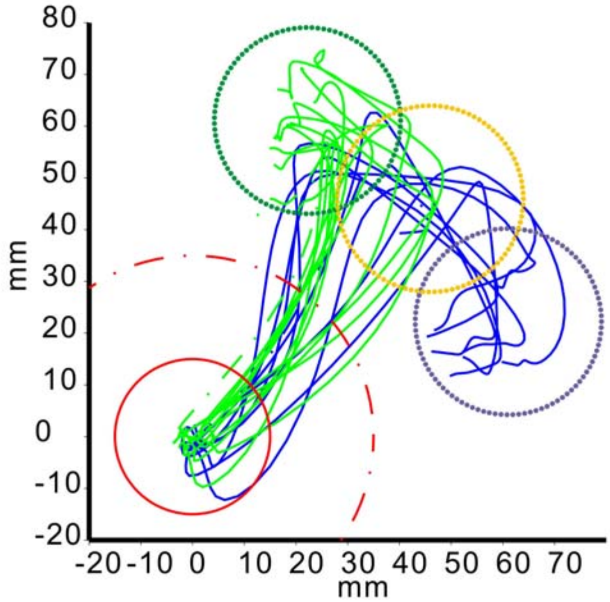


Figure 18. *The monkey movement trajectories in the physical space*

(Solid lines were success trials; dash line were fail trials)

Figure 18 is an example of the animal's performance in one of the four directions. In this illustration, three targets are shown. The middle target is displayed the other two are virtual as signaled by the displaced feedback cursor. This monkey used two different strategies to reach the virtual target. In this example, it can be seen that the monkey sometimes went straight to the virtual target on the left (green). However, most of the time there is a clear hook in the trajectory. We hypothesize that this hook signifies a movement correction resulting from the processing of the displaced feedback that was presented earlier in the movement. This would mean that the straight trajectories were a guess and this is supported by the observation that all of the straight trajectories were to the left (upward) virtual target. Most of the hooks were located in the middle, displayed target. The animal's strategy seems to be to either proceed to the displayed target and make the appropriate correction at that point, or to guess that the correct target is displaced to the left and to either stop there or to make a correction to the rightward target once the feedback was processed.

The two types of trajectory can clearly be distinguished in the velocity profiles as well (Figure 19). The hooked trajectories have a large first peak followed by a smaller but prominent second peak. The straight trajectories have a smaller (compared to the large first peak of the hooked movement) and little evidence of a secondary peak. These two categories were separated for the counterclockwise rotation and displayed in Figure 20.

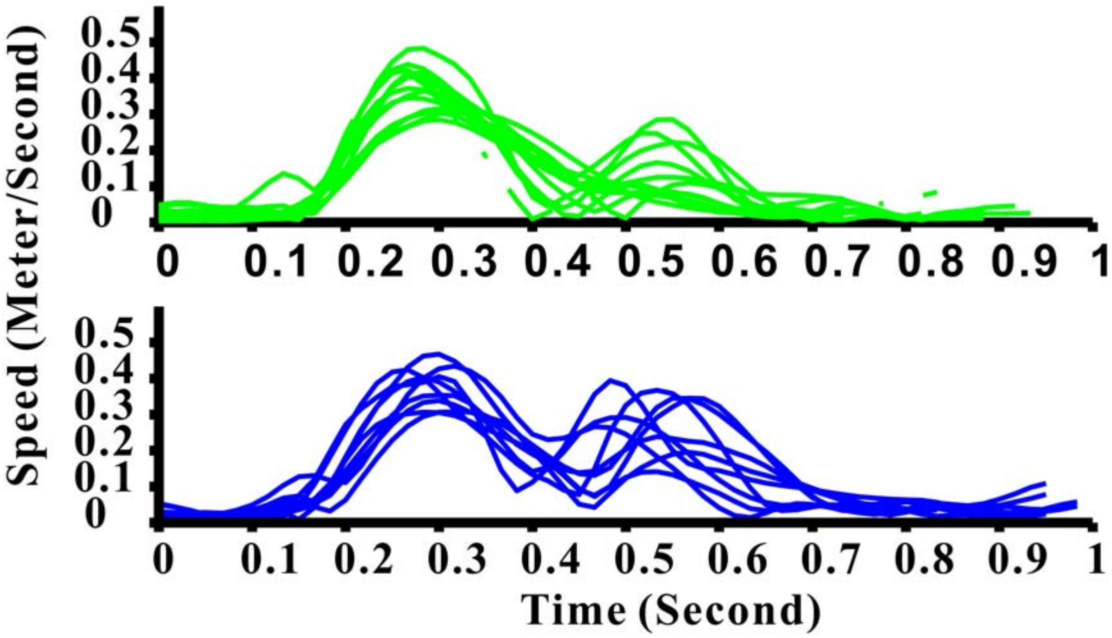


Figure 19. *Movement speed profile*

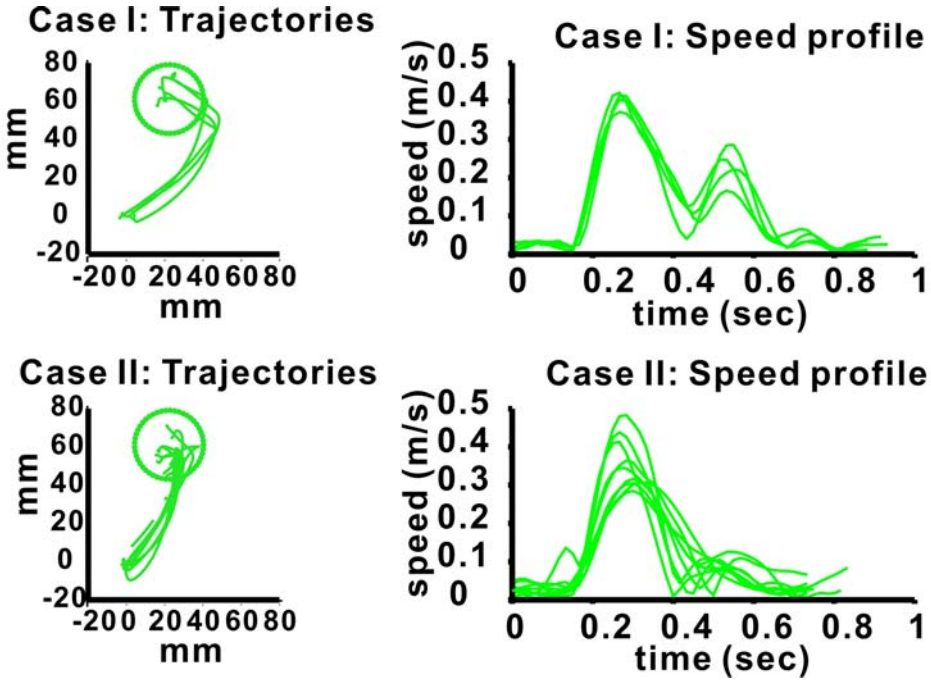


Figure 20. *Trajectories and speed profiles of two different styles of movement behavior*

It might be argued that the monkey uses the hooking strategy to obviate the need for the online feedback given in the middle of the movement. By guessing that the correct target is leftward, it would seem possible that the monkey could enter that target and wait to see if the displayed target changed color to indicate success. This would only be possible if the monkey could react to the change of color and stop the hand with a duration shorter than the time the hand spent in the guessed target. This duration averaged about 150 ms. which is comparable to a fast reaction time. This would leave no time to decelerate the limb. Another consideration is the duration from entering the wrong target to the beginning of the corrective hook. This took about 100 ms (Figure 21) which is significantly faster than a reaction time and too fast to make a decision based on a color change of the displayed target.

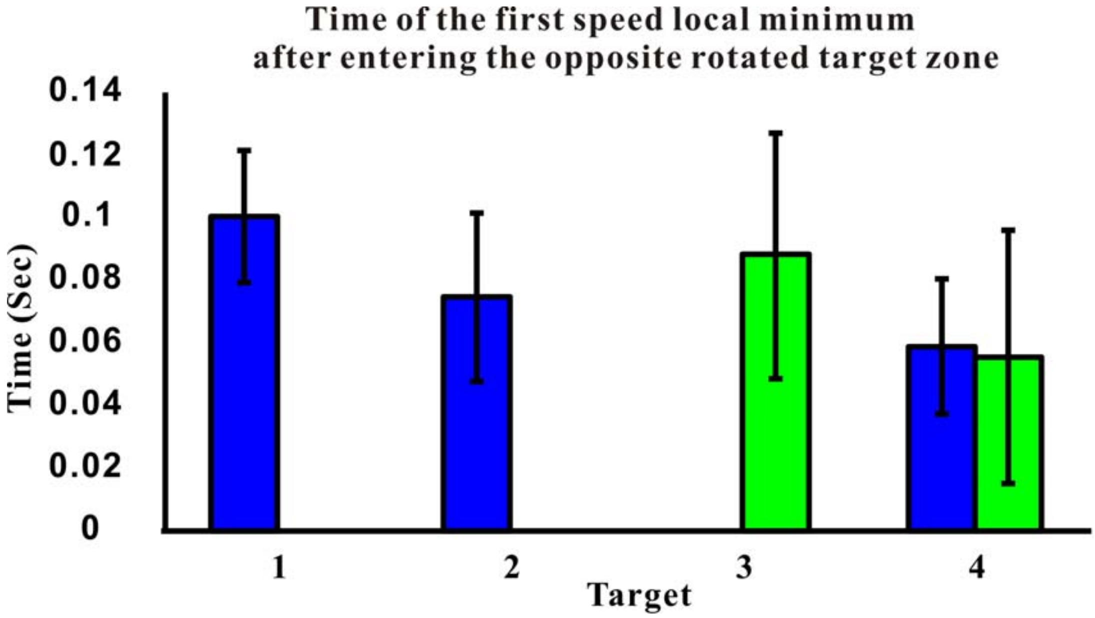


Figure 21. *Time of the first speed local minimum after entered the opposite rotated target zone, Blue (Green) bars represented the time difference in trials that the monkey hand moved to clockwise (counterclockwise) rotated target zone and the trajectories that entered the counterclockwise (clockwise) rotated target zone.*

These arguments and the finding that the hooks rarely occurred in the guessed target show that the correct target indication was not driving the trajectory corrections. Rather, these corrections are related directly to the presentation of the mid-flight cursor that had been presented about 200 ms earlier.

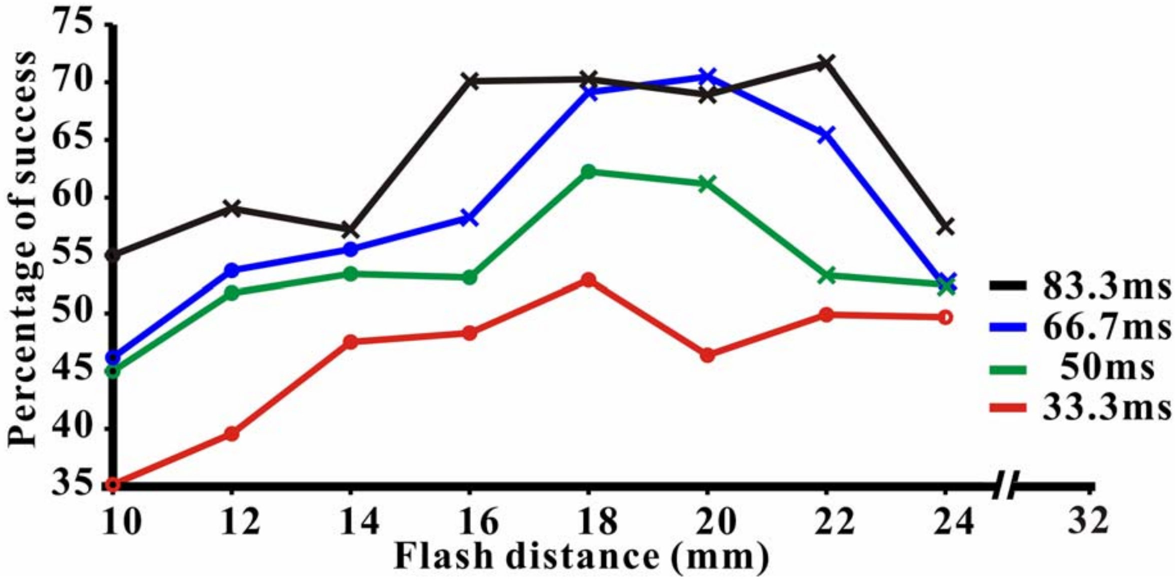


Figure 22. *Overall success rates for different flash distances (mm) and duration. Circles represent the flash end before the maximum speed occurred; crosses represent the flash end after the maximum speed occurred.*

Figure 22 shows the success rates of all trials in relation to the flash distance for four different flash durations. The results show that 1) the success rate increased when the flash duration increased; 2) the global peaks of the success rate for each of the flash occurred between 18-22mm from the center. The average maximum hand speed occurred 32mm from the center, regardless of the flash time length and flash distance conditions. Circles designate data where the flash ended before the monkey's hand movement reached its maximum speed. On the other hand, the crosses show that the flash ended after the monkey's hand movement reached its maximum speed.

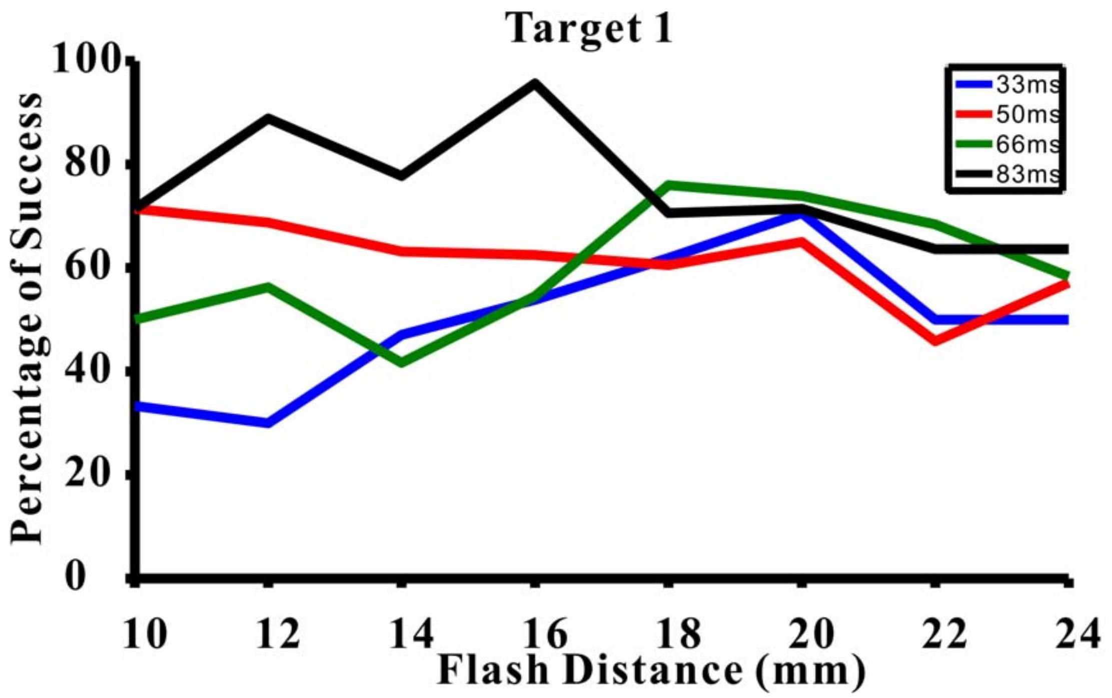


Figure 23. *Success rate target #1 with different flash distances (mm) and duration*

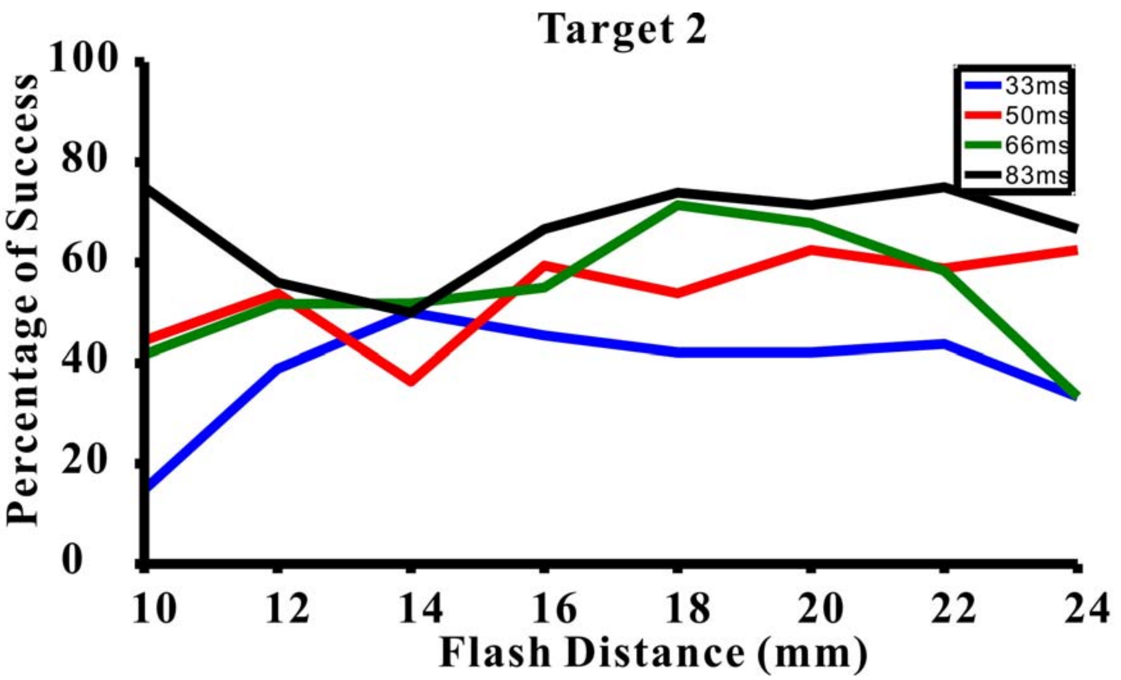


Figure 24. *Success rate target #2 with different flash distances (mm) and duration*

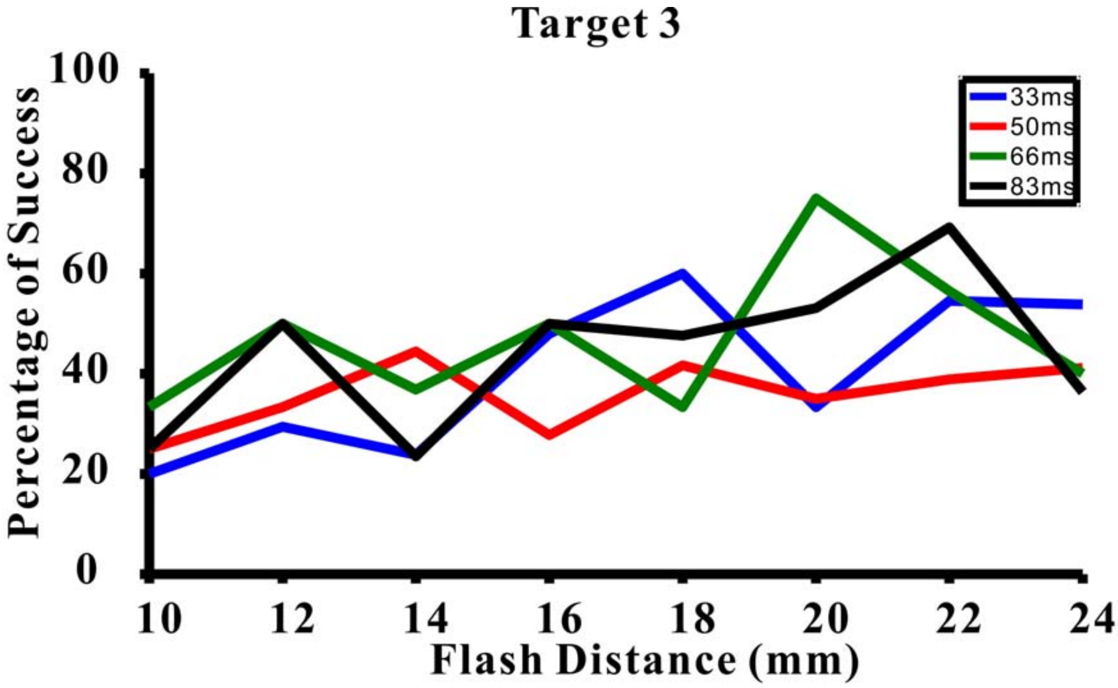


Figure 25. *Success rate target #3 with different flash distances (mm) and duration*

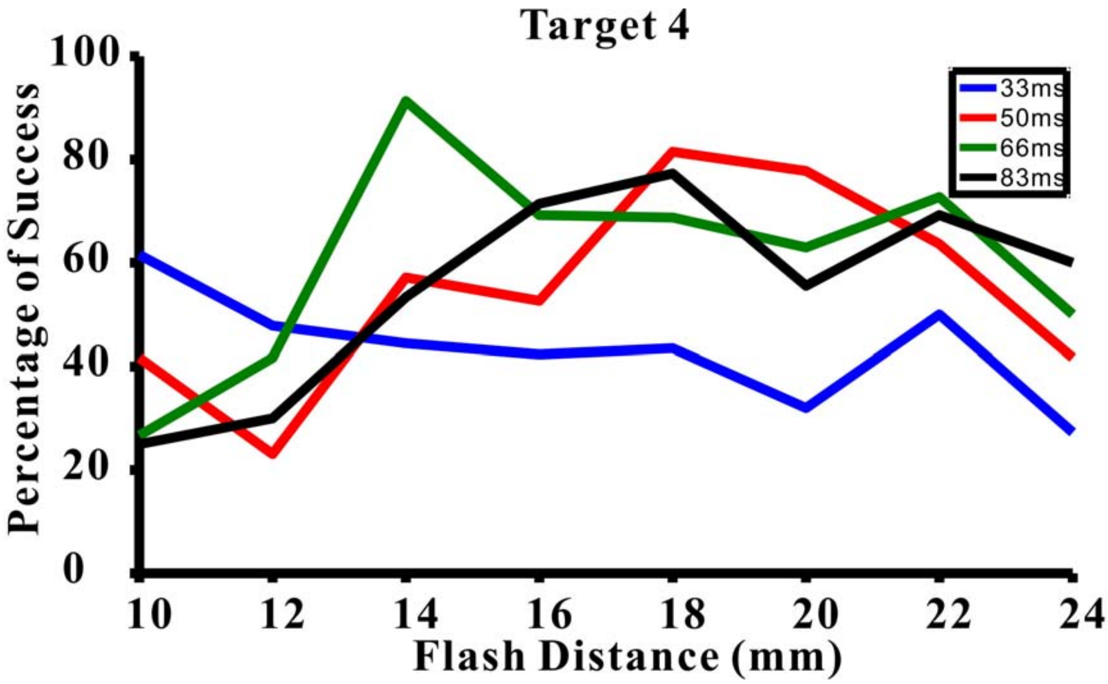


Figure 26. *Success rate target #4 with different flash distances (mm) and duration*

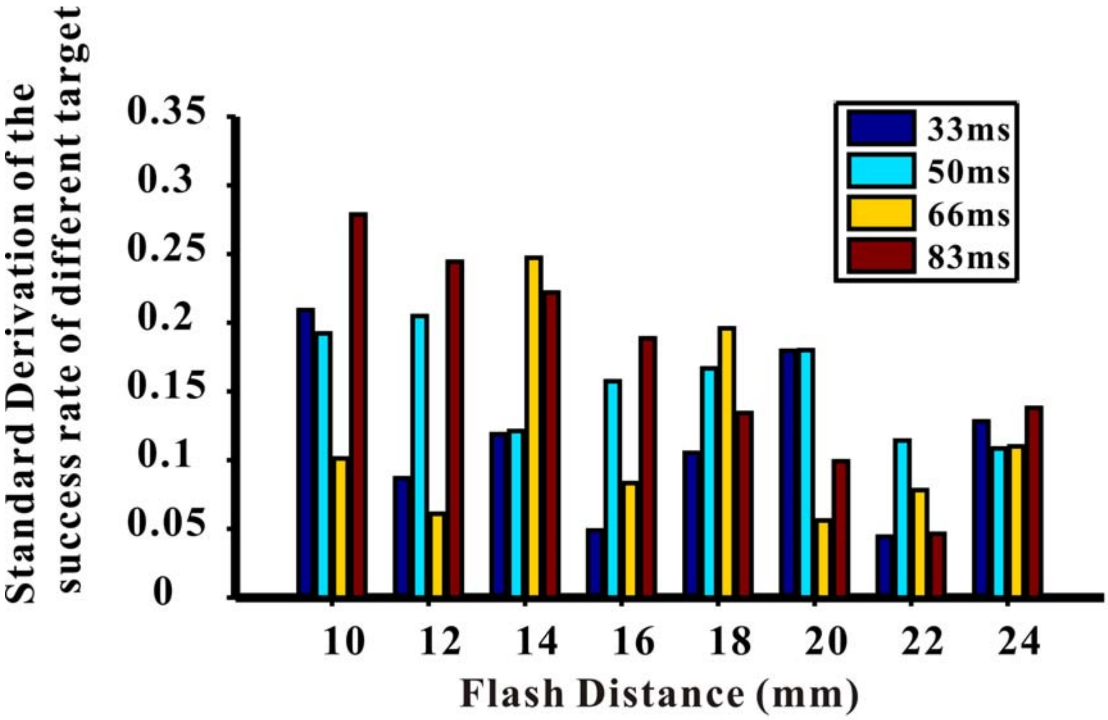


Figure 27. *standard derivation of success rate across targets*

Figure 23 to Figure 26 show the success rates for trials in which the monkey moved his hand toward each individual target in relation to the distance at which the flash began. The four curves on each graph represent different flash durations. Different target numbers have significantly different success rates; and the variation in success rates is significant across targets. Figure 27 shows the standard derivation of the success rates across targets. The 83 ms flash duration shows a concave pattern with a minimum variation for a flash distance of 22 mm. This was also the highest average success rate for this duration.

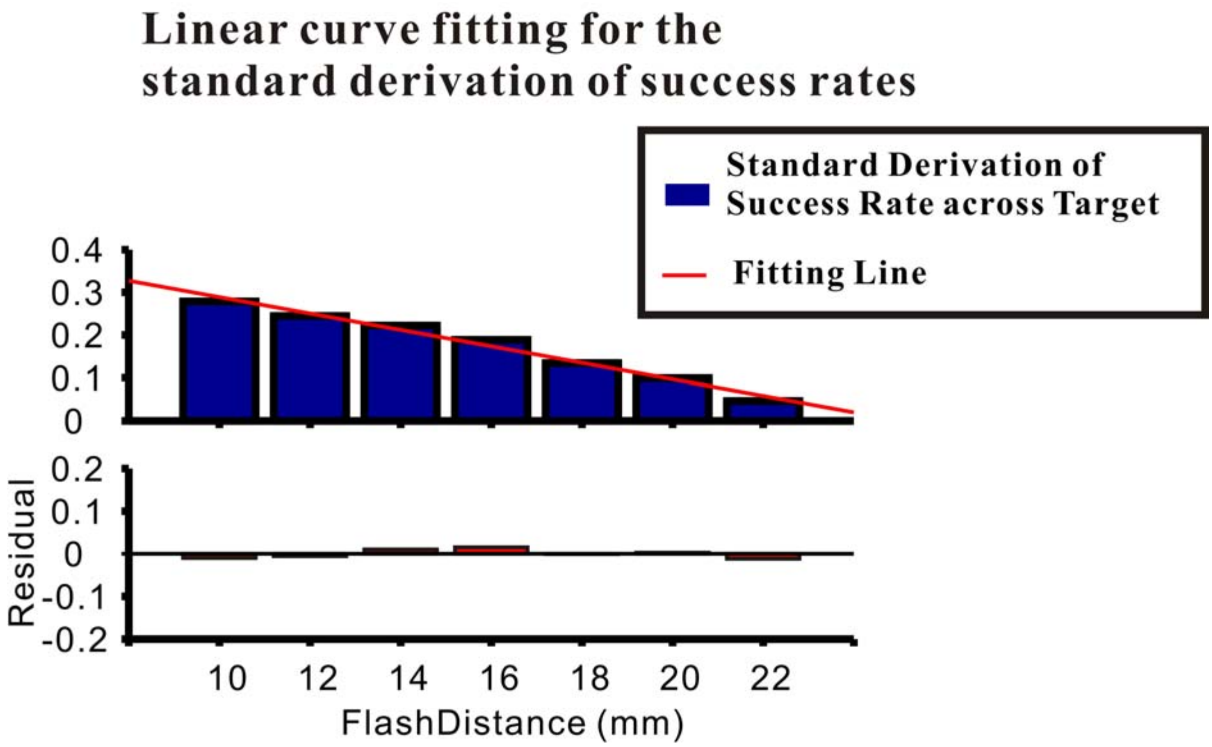


Figure 28. *A linear fitting for the standard derivation of success rates for target position for which the flash time length was 83ms and the flash distance was between 10 and 22mm*

A linear curve fitting (the average residual is 0.025) for the standard derivation of success rates for target position for one specific condition is shown (See Figure 28). The relation between flash and performance is less affected by targets when the distance increases.

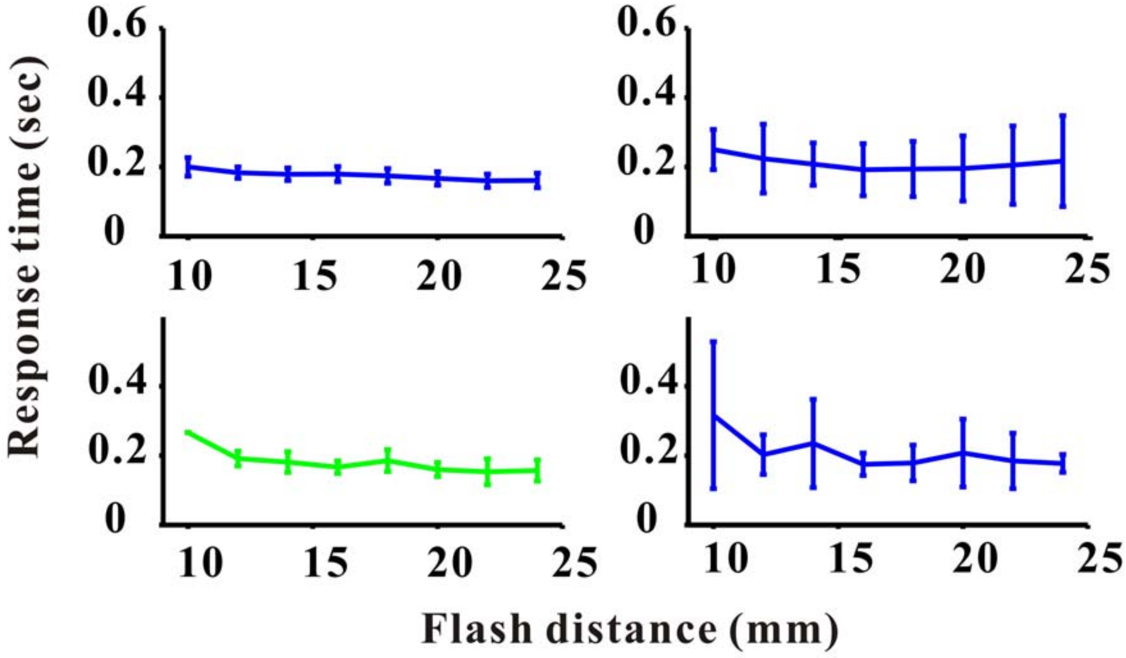


Figure 29. *The visuomotor behavior response time to different targets*

Figure 29 shows the time difference between the flash and when the hook began for each target. The time difference took around 200ms regardless of the target direction and flash distance. This is consistent with the literature [7].

3.0 CONCLUSION

The amount of visual feedback and the point at which the visual feedback appeared affected the success rate of the task. The best place to give the visual feedback was 18 to 22 mm away from the center (if the target was located 60mm away the center). In this case, the monkey may have found that it was easier to identify the true movement direction, because the visual feedback deviation was higher at a longer distance with enough time to make use of the feedback signal. However, the amount of movement correction time decreased significantly if the flash distance was long and the monkey did not have enough time to correct the movement. Therefore, the global maximum success rates peaked when the flash distance was 18 to 22mm. When the duration was long (83ms), there was a more consistent relation between success and flash location. However, we didn't see the same result for each individual target, which indicated that the effect was target-dependent. The monkey may have relied more on the visual feedback, when the flash duration was relatively long. On the other hand, the average success rate increased with flash distance. Visual feedback information contributed to the movement, even though it ended before the start of the approach phase. Visual feedback presented during the transport phase of the task was registered but not acted upon immediately.

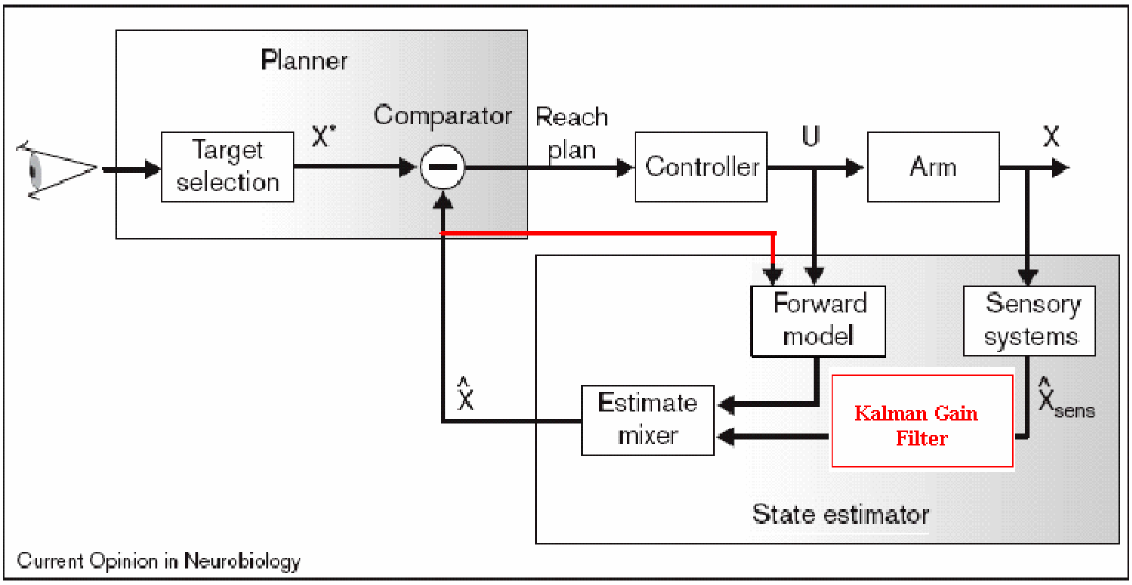
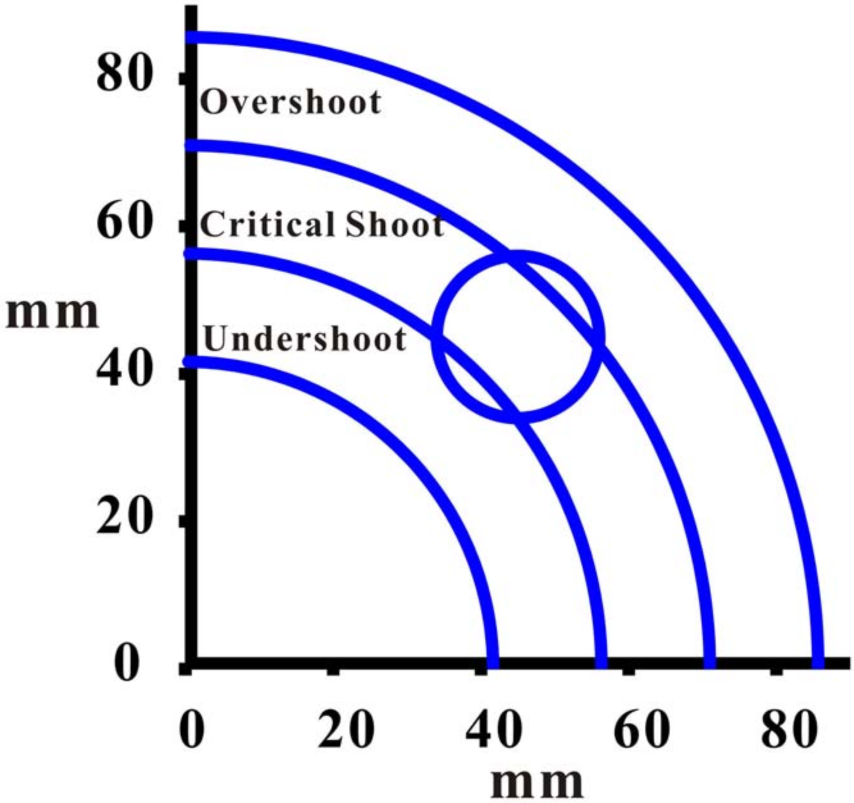


Figure 30: modified version of information processing model

Visual feedback presented during the transport phase of the task was registered but not acted upon immediately. After an obligatory delay of approximately 200ms, the animal makes corrections based on the earlier visual cursor cue. This cue-dependent information was held across the transport and into the approach phase of the task. This suggests that visual cues can be acted on asynchronously during movement. Moreover, the monkey ignored misleading information during the reaching movement in experiment#2, this supports the idea that filters in our brains control the contribution of the feedback. Only the reliable feedback information will be used by the information processing systems.

APPENDIX A

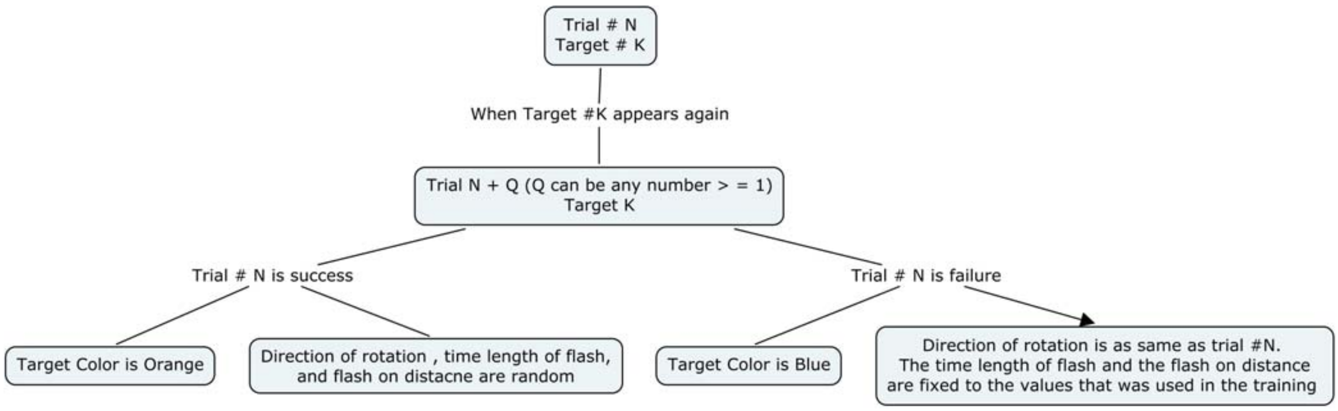
OVERSHOOT, CRITICAL SHOOT, UNDERSHOOT



The stop position (15% of Vmax) has been categorized into 3 different shooting conditions. Critical shoot is that the stop position is 56.3mm to 70.97mm away from the center. Overshoot is that the stop position is 70.98mm to 85.64mm away from the center. Undershoot is that the stop position is 41.64mm to 56.3mm away from the center.

APPENDIX B

REWARDING RULE



Appendix 2: Reward scaling and failure trial repeating

Reward scaling and failure repeating rules: If the previous trials was successful, the monkey saw an orange *(a blue)* target in the current trial, the direction of the physical rotation was randomly selected *(the same as the previous trial that had the same target)*; the values of the flash distance and the time flash length of the current trial were also randomly selected *(as same as the training parameter)*. If the current trial was also successful, the computer gave the monkey 2.5 *(1)* units of water. In general, recording the data using reward scaling and failure trial repeating had a few advantages: 1) making the monkey pay extra attention to the orange target condition, so the analysis result would be more reliable; 2) giving a reward to the monkey under a relatively easy condition if the monkey was successfully hitting the target - blue target condition, so he won't give up easily in the whole difficult task; 3) encouraging him to do better by giving him less of a reward in his successful hit because of his previous failure; 4) gaining extra training (the blue target condition) during the recording because he has more chances to practice the task.

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