Sensorimotor strategy selection under time constraints in the presence of two motor targets with different values

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Article

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Abstract

Goal-directed movements often require choosing an option from multiple potential goals under time constraints. However, there are limited studies on how humans change their time spent on decision-making and their movement patterns in accordance with time constraints. Here, we examined how sensorimotor strategies are selected under time constraints when the value of targets is uncertain. In the double-target condition, the values were uncertain before the start of the task and presented at the start. The behavior in this condition was compared to the single-target condition. The movement kinematics showed beneficial difference of motor patterns between the conditions when the time constraint is long. Moreover, the participants frequently used the choice-reaction even under tight time constraints, and their performance was consistently lower than that in the single-target condition. Our results suggest that there is a consistent cognitive bias to choose a higher value when there are multiple alternatives with different values.

Introduction

In many situations, decision making involves deciding on a single strategy among multiple action possibilities. In many studies of motor decision-making, the focus has been on how to output an action according to a prior gain function in advance^{1–9}. On the other hand, in sports and other decision-making situations, it is necessary to collect information about the value of potential goals in a limited time while planning and executing the movement.

In such situations, to maximize the performance, strategy selection is important for the speed-accuracy trade-off^{9–11}, such as the relationship between movement speed and movement variability^{12,13} or between decision speed and decision accuracy^{10,14,15}. For choice behavior, in particular, the Hick–Hyman law^{16,17} describes the fundamental human property whereby reaction times for making decisions become longer as the number of options increases because having more options requires more time to accumulate information.

In a situation where there are two alternatives, for example, the response strategy can be divided into two categories: a simple reaction, in which an individual quickly responds to the predetermined choice, and a choice reaction, in which an individual responds by choosing the more rewarding of the two choices. The simple reaction strategy, while having temporal effectiveness, is disadvantageous in terms of the amount of information obtained. In contrast, the choice-reaction strategy allows us to choose better alternatives by increasing the amount of information available but at the cost of time. Therefore, in choosing such a strategy, the values of both time and amount of information should be considered.

In our previous study,¹⁰ we used a selective-response task between two alternatives with progressively decreasing gains or probabilities of each option over time to test whether strategy optimization occurs in terms of reward maximization. By varying the rate of decrease in value from trial to trial and examining strategy switching, we found that although participants changed their response strategies according to

the rate, there was a bias toward over-preferring the choice-reaction strategy in situations where the gain decreased over time. This bias may have stemmed from the difficulty of taking into account changes in value over time or from the known possible rewards for each target. Therefore, it is necessary to consider whether a similar bias occurs in situations where there is high uncertainty about value.

In situations in which obtaining information and executing an action exist simultaneously, two control strategies can arise: go-after-you-know and go-before-you-know. The go-after-you-know refers to situations in which the action is carried out after the goal has been determined, and the go-before-you-know refers to situations in which the action is started before the goal is determined¹⁸. These control strategies were studied in separate experimental settings. In particular, motor planning and execution in a go-before-you-know situation have been examined in which the final target is informed after the movement onset (the possible targets are known before the movement onset). However, in some situations, it is possible to either start a movement after determining the final target or to determine the final target while moving and correcting the ongoing movement. Therefore, a new decision-making problem arises as to how to make a decision between the control strategy of starting a movement after determining the target (i.e., go-after-you-know) or before determining the target (i.e., go-before-you-know).

As shown above, various decision-making problems need to be solved to improve performance. First, an individual needs to decide on a strategy (e.g., a simple reaction or a choice reaction) regarding the speed-accuracy tradeoff depending on a given time constraint. It is also necessary to determine the strategy in the time sequence of target determination and movement onset (e.g., go-after-you-know control or go-before-you-know control). Furthermore, the execution strategies in each control phase, such as the input system (how to see), the processing system (how to judge), and the output system (how to move), are also involved. However, it is still unclear how such a wide variety of decisions are made and what their optimality is, given the freedom to choose strategies.

The current study aims to clarify how sensorimotor strategies are selected under time constraints in the presence of uncertainty in the value of the motor targets and to examine the optimality of the selected strategy. The sequence of the experimental tasks is shown in Fig. 1. In our task, targets were assigned value, and participants could obtain that value when they reached it within a time constraint. In the main condition (the double-target condition), the values of the two targets were uncertain before the start of the trial, and the values of the targets were presented randomly for each trial in the range of 20–80 points with a beep to signal the start of the trial. The two targets were set at $\pm 15^\circ$, $\pm 22.5^\circ$, or $\pm 30^\circ$ to the direction straight above the starting point and 20 cm away from the starting point. Participants were instructed to select a sensorimotor strategy to maximize reward rates. Participants received a score for the target if they could reach the target within the time constraint assigned for each trial. To evaluate the optimality and the control strategy, we compared the behaviors in the double-target condition with those in the condition where only one target exists, which was performed as the control condition. From the interpretation of the behavioral patterns and the evaluation of the optimality of the strategies using a descriptive approach, we examined the mechanism of selecting a strategy for executing the behavior under time constraints and its optimality in a situation where there is uncertainty in value.

Results

The cursor trajectories for each condition are shown in Fig. 2. In the single-target condition, the trajectory was straight, which is widely observed in a general reaching movement. In contrast, in the double-target condition, there were trials that started in the direction of movement closer to the center. This difference in trajectories indicates that the decision-making phase affects movement trajectories.

The time constraints were classified into five bins, and the histograms of the initial reach direction (IRD) within each bin are shown in Fig. 3. The IRD indicates the direction from the start position to the cursor 100 ms after the onset of movement. This variable is often used to describe the characteristics of the initial movement in a go-before-you-know situation^{19,20}. In the single-target condition, the histogram of the IRD did not change considerably with the time constraint, whereas in the double-target condition, the IRD was closer to the middle, and this tendency was observed as the time constraint became longer. Figure 4 shows a comparison between the double-target and single-target conditions in terms of $|\Delta\text{IRD}|$ (i.e., the magnitude of deviation of the IRD from the middle) according to the time constraint in each angle condition. A three-way repeated-measures ANOVA (time constraint [5] $\times$ number of targets [2] $\times$ target-separation angle [3]) on the $|\Delta\text{IRD}|$ showed significant main effects of the number of targets ($F_{[1, 11]} = 30.72$, $\eta_p^2 = 0.74$, $P < 0.001$) and target-separation angle ($F_{[2, 22]} = 556.6$, $\eta_p^2 = 0.98$, $P < 0.001$). There was a significant interaction between time constraint and number of targets ($F_{[4, 44]} = 4.22$, $\eta_p^2 = 0.28$, $P = 0.006$). Post-hoc test showed a simple main effect of number of targets in four longer time constraints ($640 < \tau < 880$: $P = 0.02$; $880 < \tau < 1120$: $P = 0.004$; $1120 < \tau < 1360$: $P = 0.004$; $1360 < \tau < 1600$: $P < 0.001$). These results indicate that more centering initiation actions occur in situations with longer time constraints.

To examine the changes in the sensorimotor strategy according to the number of targets and time constraints, the reaction time (RT) was compared among the conditions (Fig. 5). The upper panel of Fig. 5 shows a scatter plot of time constraints and RT, and the middle and lower panels show bivariate histograms of time constraints and RT in the double-target and single-target conditions. From these results, it can be confirmed that the RT was comparable between the double- and single-target conditions when the time constraint is short, while the deviation of the RT between the conditions increased as the time constraint becomes longer.

The top row in Fig. 6 shows the probability of reaching the target with the higher score ($P_{\text{high-value}}$) according to the time constraint, RT according to the time constraint, and $P_{\text{high-value}}$ according to the RT. The middle row shows the comparison of the initial movement velocity (IMV), movement time (MT), and total length until 20 cm displacement from the start position (TOL) according to the time constraint. The bottom row shows the comparison among conditions of the mean score (mean score), temporal accuracy (P_{temporal}), and spatial accuracy (P_{spatial}) according to the time constraint. These figures were constructed by including all target angle conditions.

One-sample t-tests for 0.5, with the $P_{\text{high-value}}$ as the dependent variable, confirmed significant differences in the latter three time-constraint levels ($P\text{-values} < 0.001$), suggesting that a choice reaction strategy is used in conditions with long time constraints. Two-way repeated-measures ANOVA (time constraint [5] $\times$ number of targets [2]) on the RT revealed significant main effects for both factors (number of targets: $F_{[1, 11]} = 77.13$, $\eta_p^2 = 0.86$, $P < 0.001$; time constraint: $F_{[4, 44]} = 42.79$, $\eta_p^2 = 0.80$, $P < 0.001$). A significant interaction ($F_{[4, 44]} = 25.63$, $\eta_p^2 = 0.70$, $P < 0.001$) was also identified. Post-hoc tests revealed the simple main effects of the number of targets ($P\text{-values} < 0.001$) in all time-constraint levels and time constraint levels ($P\text{-values} < 0.001$) in both target conditions. The RT and $P_{\text{high-value}}$ had a relationship similar to that of a sigmoid curve. Because the RT had a sigmoidal function according to the $P_{\text{high-value}}$, the RT increased linearly with the time constraint, while the $P_{\text{high-value}}$ had an increasing pattern similar to a sigmoidal curve with the time constraint.

A two-way repeated-measures ANOVA (time constraint [5] $\times$ number of targets [2]) on the IMV showed a significant main effect of time constraint ($F_{[4, 44]} = 41.53$, $\eta_p^2 = 0.80$, $P < 0.001$), no significant main effect of the number of targets ($F_{[1, 11]} = 0.12$, $\eta_p^2 = 0.011$, $P = 0.74$), and no significant interaction ($F_{[4, 44]} = 1.30$, $\eta_p^2 = 0.11$, $P = 0.29$). A two-way repeated-measures ANOVA (time constraint [5] $\times$ number of targets [2]) on the MT showed a significant main effect for time constraint ($F_{[4, 44]} = 2.63$, $\eta_p^2 = 0.19$, $P = 0.047$), no main effect of the number of targets ($F_{[1, 11]} = 0.70$, $\eta_p^2 = 0.057$, $P = 0.43$), and a significant interaction ($F_{[4, 44]} = 2.63$, $\eta_p^2 = 0.19$, $P = 0.047$). Post-hoc tests revealed simple main effects of time constraints in both the double-targets condition and single-target condition ($P\text{-values} < 0.001$) and no simple main effects of the number of targets conditions at all time constraint levels. These results indicate that the number of alternatives did not significantly affect IMV and MT.

Two-way repeated-measures ANOVA (time constraint [5] $\times$ number of targets [2]) on the TOL showed a significant main effect for both time constraints ($F_{[4, 44]} = 7.02$, $\eta_p^2 = 0.057$, $P < 0.001$) and number of targets ($F_{[1, 11]} = 11.90$, $\eta_p^2 = 0.52$, $P = 0.005$). A significant interaction ($F_{[4, 44]} = 6.49$, $\eta_p^2 = 0.37$, $P < 0.001$) was also found. Post-hoc tests revealed simple main effects of time constraint in the single-target condition ($P < 0.001$). There were simple main effects of the number of targets conditions only in the longer three time-constraint ranges ($880 < \tau < 1120$: $P = 0.042$; $1120 < \tau < 1360$: $P = 0.001$; $1360 < \tau < 1600$: $P = 0.005$). These results suggest that different movement patterns were used between the double-target and single-target conditions as the time constraint increased, similar to the difference in $|\Delta\text{IRD}|$ (Fig. 4).

Two-way repeated-measures ANOVA (time constraint [5] $\times$ number of targets [2]) on the mean score showed a significant main effect for time constraint ($F_{[4, 44]} = 62.68$, $\eta_p^2 = 0.85$, $P < 0.001$) and no significant main effect for the number of targets ($F_{[1, 11]} = 0.004$, $\eta_p^2 = 3.59 \times 10^{-4}$, $P = 0.952$). A significant interaction ($F_{[4, 44]} = 7.27$, $\eta_p^2 = 0.40$, $P < 0.001$) was found. Additionally, there were simple main effects of time constraint in both types of target conditions ($P\text{-values} < 0.001$). There were simple main effects of the number of targets conditions only in the second and third time-constraint ranges ($640 < \tau < 880$: $P =$

0.002; $880 < \tau < 1120$: $P = 0.016$). Two-way repeated-measures ANOVA (time constraint [5] $\times$ number of targets [2]) on the P_{temporal} probability showed significant main effects for both factors (number of targets: $F_{[1, 11]} = 17.25$, $\eta_p^2 = 0.61$, $P = 0.002$; time constraint: $F_{[4, 44]} = 51.71$, $\eta_p^2 = 0.83$, $P < 0.001$). A significant interaction ($F_{[4, 44]} = 6.28$, $\eta_p^2 = 0.36$, $P < 0.01$) was also found. There were simple main effects of time constraints in both types of target conditions ($P\text{-values} < 0.001$). There were simple main effects of the number of targets conditions only in the second and third time-constraint ranges ($640 < \tau < 880$: $P = 0.001$; $880 < \tau < 1120$: $P = 0.017$). Two-way repeated-measures ANOVAs (time constraint [5] $\times$ number of targets [2]) on the P_{spatial} showed significant main effects for both factors (number of targets: $F_{[1, 11]} = 6.47$, $\eta_p^2 = 0.37$, $P = 0.027$; time constraint: $F_{[4, 44]} = 8.77$, $\eta_p^2 = 0.44$, $P < 0.001$). There was no significant interaction ($F_{[4, 44]} = 0.50$, $\eta_p^2 = 0.043$, $P = 0.74$). These results suggest that having more choices has a negative effect on temporal (especially in moderately tight time constraints) and spatial (in a wide range of time constraints) performance.

Discussion

The current study examined a sensorimotor strategy under time constraints in a situation where there was uncertainty about the value of the target. In the main task, there were two alternative targets, and target values were presented along with an auditory stimulus that signaled the start of the trial, followed by a value if the cursor passes the target within a time constraint. When the time constraint is short, it is desirable to adopt a simple-reaction strategy because the attempt to obtain information about the target's values will not result in reaching the target in time. In contrast, if there is enough time to recognize the value of the target, it is preferable to accurately recognize the target information and choose the target that has a higher value (i.e., a choice-reaction strategy). Thus, time constraint is a key factor that determines the desired strategies for the participants. Moreover, in the current task, the participants were free to initiate actions at any time after the auditory go-signal, so they could start movements after identifying the target values or before identifying them. This setup allows us to evaluate the optimality of the strategy and examine the characteristics of the selected movement patterns.

By analyzing the modulations in spatiotemporal movement patterns according to time constraints, we obtained two main findings. First, the modulation of the initial reach direction and the total length of trajectories under the time constraint revealed that different motor patterns were selected between the double-target and single-target conditions when the time constraint became relatively long. Second, participants used the choice-reaction strategy even in the tightly time-constrained condition and their performance was lower than that in the condition with a single goal. The fact that the temporal performance (i.e., whether or not reached in time) was significantly lower suggests that this negative effect of multiple alternatives was caused by the choice reaction of not being able to meet the time constraint.

Comparing the cursor trajectories between the double-target and single-target conditions, we found that the initial reach direction was more centered in the double-target condition than in the single-target

condition. It is generally known that in a reaching movement, the trajectory is almost straight to the target^{21,22}. In fact, a trajectory of straight movement was often observed in the single-target condition, and if the movement was initiated after the determination of the target, it was likely that the movement would also follow a straight trajectory in the double-target condition. However, we found that the initial reach direction was closer to the middle direction of the two targets under a relatively long time constraint, suggesting that the valuation process between the targets may have interfered with the movement trajectory.

The question that arises here is whether this interference is due to unintentional or intentional control, but a view that supports each is possible. Many previous studies have reported that when initiating a movement in the presence of multiple potential targets, the initial movements are directed toward the weighted average of the given targets^{19,23–28}. An unintentional averaging output of discrete motor plans corresponding to each potential target has been proposed as one of the causes of such motor patterns. This is supported by neurological evidence that motor plans for each target are represented simultaneously when there are multiple competing movement targets in the reaching-related areas^{29–33}.

Most of the studies that provided this evidence used go-before-you-know situations, in which participants were forced to initiate a movement for multiple competing targets and then reach a final goal presented after the movement had begun^{19,23,25–27,34–38}. However, the present study was different from the go-before-you-know situation in that the participants were able to initiate the movement at their own timing. Therefore, it was also possible to start a movement after the movement target had been specified by the participants. Even in such a situation, we observed the centering (albeit imperfect) of the initial movement, which may be attributed to the existence of some advantage of online control^{39–45}.

One of the possible reasons for the centering of the initial movement is that the participants may have intended to shorten the reaction time since the participants were required to reach the target within a given time constraint and thus, there is an advantage of starting earlier. As shown in a previous study, an overlap between motor planning and execution reduces the reaction time when there are multiple motor goals⁴⁶. In addition, reaction time and movement time can be reduced if participants pre-plan the kinematic components of the movements commonly required for both targets before determining the targets⁴⁷. Thus, it is possible that the centralized initial movement is a goal-oriented action generation that increases the time available to determine the movement target⁴².

Another possibility of the centering tendency of the initial movement is to maintain the capability to respond to target changes during movement execution. Accounting for possible movement corrections that may occur later is an important aspect of motor planning⁴³, and the state of the movement affects whether or not the goal is changed^{44,45}. Because the current task requires instantaneous decisions, errors in value processing may occur, and changing the target during movement execution may be necessary. A centering tendency in movement trajectory is advantageous when dealing with a changing target.

Therefore, the centered initial movement could reduce the cost of possible later movement corrections, including temporal performance, reach accuracy, and biomechanical costs.

When the time constraint became longer, the reaction time was longer in the double-target condition than in the single-target condition, while the reaction times were close to an intermediate value between the conditions under severe time constraints. Accompanying this change, the probability of reaching the target with the highest score ($P_{\text{high-value}}$) increased as the time constraint increased. Therefore, when the reaction time was short, the participant started to move in the predetermined direction as a simple reaction, but when the reaction time was long, the participant started to move after acquiring the value information as a choice reaction. These results showed that the participants varied their strategy to obtain information about the target depending on the given time constraint.

The question then is whether such a strategy switch is optimal or biased in terms of objective reward maximization. When we compared the mean scores according to the level of time constraint between the single-target and double-target conditions, interestingly, we found that participants performing the single-target condition scored higher under the relatively severe time constraint, and this tendency was consistent across participants. This can be attributed to two factors. The first is the difference in temporal performance. In the double-target condition, the probability of reaching the target in time was lower than that in the single-target condition under the relatively more severe time constraint. This reflects, in the double-target condition, the longer reaction time due to the time spent obtaining information about the target, and the lack of a corresponding reduction in the movement time. Second, the difference in the expected value between simple and choice reactions is theoretically less than 10 points. In the case of a simple reaction, the expected value of the target that the participant aims at is 50 points. If the participant performs a choice reaction and selects and heads for the higher scoring of the two targets with perfect accuracy, the expected value of the target is 60 points. Therefore, if the success probability of the double-target condition is less than 5/6 against the success probability of the single-target condition, rather than benefiting from making a choice, a loss is incurred.

Interestingly, the preference of the choice-reaction strategy over the simple-reaction strategy, even when the benefit of the strategy is small, is a cognitive bias similar to the tendency of our previous study to have longer reaction times than the optimal strategy¹⁰. In the present study, avoiding the uncertainty of the outcome possibly caused the preference for the choice-reaction strategy. In the presence of two different values, it is undesirable to start a movement with uncertainty about which value target to go for, and this may lead to a cognitive bias in choosing the better alternative.

Many previous studies have found that risk-seeking decision-making is more likely to occur in motor tasks^{6,7,48-50}, which can be interpreted from two perspectives: distortion of subjective and objective values (i.e., preference for higher scores) and overestimation of one's own ability. The distortion of subjective and objective values has been widely confirmed in economic decision-making⁵¹ and suggested to be present in motor tasks as well, although it was shown to be approximated by different functions⁵. There is a tendency to choose the highest value that exists in the place. In such cases, it is

acceptable to use a choice strategy by selecting the option with the higher reward. In particular, motor tasks may be prone to such preferences, because daily movement decisions require instantaneous decisions.

Another possibility, as mentioned above, is the existence of a bias in the estimation of ability. In the current task, it is necessary to correctly estimate the relationship between reaction time and choice accuracy, but it is not clear whether humans are able to represent the relationship accurately. In the current task, it is necessary to correctly estimate the relationship between reaction time and accuracy of choice, as well as the relationship between the movement time and the reach accuracy; however, it is not clear whether humans can represent them correctly. Given the representation that it is possible to make accurate choices even with a shorter reaction time than actual, it is understandable that the choice-reaction strategy is used frequently in a suboptimal manner.

Presently, the major challenge is the difficulty in separating the effects of distortion of subjective and objective values and misestimation of one's own abilities. It is possible that only one influence is strongly at work, or that both are at work, or that different factors are at work depending on the decision-maker. In our previous study ¹⁰, we found that different strategies were selected between conditions in which the scores changed and conditions in which the probabilities changed, even when the expected values were equal. Thus, in future studies, manipulating value from various factors and examining the modulation of the strategy accordingly may contribute to the separation of the two possibilities.

The current study investigated a sensorimotor strategy according to a time constraint in a situation where there was uncertainty about the value of the target. We obtained two main findings. First, the modulation of the movement kinematic patterns under on time constraints revealed that different motor patterns were selected between the double-target condition and single-target conditions when the time constraint became relatively long. This modulation could be due to both unintentional and intentional control, but more importantly, it can be interpreted as a beneficial and adaptive action. Second, we found that participants frequently used the choice-reaction strategy even in the tightly time-constrained condition, and that performance was consistently lower than that in the single-goal condition across participants. The results suggest that there is a consistent cognitive bias among individuals to choose a higher value in situations where there are multiple alternatives with different values. Future studies are required to clarify the causes of this bias.

Methods

Participants

Twelve right-handed participants (age: 21.3 ± 2.3 years, ten male) were recruited. All participants had normal or corrected-to-normal vision. All participants were naive to the purposes of this study and provided written informed consent. This study was approved by the Ethics Committee of the Graduate

School of Arts and Sciences, University of Tokyo. All experimental procedures adhered to approved guidelines. Written informed consent was obtained from each participant.

Experimental setup

The participants sat in a quiet, dim room. A pen tablet with sufficient workspace to measure the participant's arm reach movement (Wacom, Intuos 4 Extra Large; workspace: 488 × 305 mm) was set on the table. A monitor (I-O DATA, KH2500V-ZX2, 24.5 inches, 1920 × 1080 pixels, vertical refresh rate 240 Hz) that was used to present stimuli was set with an approximately 30° gradient angle over the pen-tablet. The participants manipulated a cursor on a screen whose position was transformed from the position of the pen. The elapsed time from the movement onset and the location of the cursor on the monitor were sampled at 240 Hz. All stimuli were controlled using the Psychophysics Toolbox of MATLAB (MathWorks, Natick, MA, USA).

Experimental task

The participants performed the double-target trials as the main condition and the single-target trials as the control condition. The trial sequences for both conditions are shown in Fig. 1. In the double-target trials, the two targets were set at $\pm 15^\circ$, $\pm 22.5^\circ$, and $\pm 30^\circ$ to the direction directly above the starting point (target separation angle $\theta = 30^\circ$, 45° , and 60° , respectively) and 20 cm away from the starting point. Before starting the trial, the time constraint (the bar on the target) and the location of the target were shown on the screen. The time constraint for each target was randomly assigned for each trial in the range of 400–1600 ms, and participants were able to recognize the time constraint by the size of the yellow area. The values of the two targets were uncertain until the start of the trial, and the values were presented at the start. The target scores were randomly assigned in the range of 20 to 80 points for each trial and were presented as numbers on the target after trial onset. The bar indicates the time remaining after onset, the yellow area gradually shrank and finally disappeared. Participants were instructed to maximize reward rates. If the participant was able to cross the target while the yellow area remained, they were scored, and feedback was obtained after the trial. In single-target trials, only one target on either side was presented. The basic sequence of the task was the same as that for the main condition.

The participants performed 324 trials (54 trials × 6 sets) of the task. Each set contained 36 trials in the double-target trials and 18 trials in the single-target trials. The directions of the targets were assigned evenly. Between sets, participants receive sufficient rest to avoid fatigue.

Data analysis

Four sets of the second half of the double-target trials (224 trials) and all trials of the single-target trials (112 trials) were included in the analysis. The cursor position (horizontal position: $X_c(t)$, vertical position:

$Y_c(t)$ at each time (t) was smoothed using a second-order low-pass Butterworth filter with a cutoff frequency of 14 Hz.

Reaction time (RT) was defined as the time at which the cursor moved 1 cm away from the start position. The arrival time (AT) was defined as the time when the cursor was more than 20 cm away from the starting point. The difference between AT and RT was defined as the movement time (MT). The cursor direction at each time (t) was defined as the angle formed by the vector from the start position to the cursor and the horizontal vector. The initial reach direction (IRD) was defined as the cursor direction 100 ms after movement onset. $|\Delta\text{IRD}|$ is defined as the unsigned angle between the intermediate direction and IRD. The initial movement velocity (IMV) was defined as the movement velocity of the cursor (IMV: cm/s) 100 ms after movement onset. Temporal success or failure was judged based on whether the arrival time was smaller than the given time constraint. Spatial success or failure was judged based on whether the shortest distance between the target and cursor was smaller than the target radius. The temporal success probability is denoted as P_{temporal} , and the spatial success probability is denoted as P_{spatial} . In the double-targets condition, the $P_{\text{high-value}}$ was defined as the probability of reaching the target with the higher score of the two alternatives. The time constraints (minimum: 400 ms, maximum: 1600 ms) were classified into five equal time intervals, and within each bin, the mean values of the above variables were calculated for each participant.

Statistical analysis

A three-way repeated-measures ANOVA (time constraint [5] $\times$ number of targets [2] $\times$ target-separation angle [3]) on the $|\Delta\text{IRD}|$ was conducted. We also performed two-way repeated-measures ANOVAs (time constraint [5] $\times$ number of targets [2]) on the mean values of the initial movement parameters (RT, IRD, IMV) and performance variables (MT, $P_{\text{high-value}}$, P_{temporal} , P_{spatial} , score), including all angle conditions. In each target-angle condition, two-way repeated-measures ANOVAs (time constraint [5] $\times$ number of targets [2]) on the mean values of $|\Delta\text{IRD}|$ were conducted. Multiple comparison tests using the Bonferroni method were conducted between the double-target condition and the single-target condition at each time constraint level. Partial η^2 for ANOVA and Cohen's d for post-hoc t -tests were used to report effect sizes.

Declarations

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Author contributions

R.O. and K.K. designed the experiments. R.O. performed the experiments. R.O. programmed and analyzed the results. R.O. and K.K. interpreted the results. R.O. wrote the paper under the supervision of K.K.

Competing interests

The authors declare no competing interests.

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Figures

Figure 1

Trial sequences. The upper row shows the double-targets condition, and the lower row show the single-target condition. In all conditions, (a) at the beginning of a trial, the cursor is moved to the starting position. (b) After a 1-second foreperiod, (c) two targets or one target and an indicator showing time constraint are presented. After 1800-2200 ms of the target appearance, (d-e) the score is presented on each target with the sound stimulus, and the yellow range of the indicator starts to decrease. After the sound stimulus, the participant can perform the reaching movement freely. If participants could pass the target within the time constraint, they receive the score assigned to that target. (f) After the completion of the movement, participants were given feedback on their success, failure, and score.

Figure 2

Trajectories in each target configuration. The cursor trajectories including all participants' all trials for each target configuration are shown. The upper row shows the double-target condition, and the lower row shows the single-target condition. In the single-target condition, participants made a linear trajectory, which is widely observed in general reaching movements. In contrast, in the double-target condition, although participants made many linear trajectories, there are trials in which participants selected a movement direction closer to the middle and trials in which the target is modified after the movement onset.

Figure 3

Histogram and cumulative distribution function of initial movement direction according to time constraints. The time constraints are classified into five bins, and the histogram and cumulative distribution function (cdf) in the initial reach direction (i.e., the direction of the cursor after 100 ms) within each bin are shown. The color of the cumulative distribution function (rightmost column) corresponds to the color of the histogram for each time constraint. In the single-target condition, the histogram of the initial reach direction did not show any considerable change in response to the time constraint. In

contrast, in the double-target condition, the distribution kurtosis corresponding to each target direction decreased and the frequency of the initial movement being directed toward the center increased in the long time-constraint condition compared to the short time-constraint condition. Similarly, from the cdf, it can be confirmed that the frequency with which the initial movement is directed between targets varies with the time constraint.

Figure 4

Comparison of ΔIRD between the double-targets condition and the single-target condition. Between-participant means and standard deviations of $|\Delta\text{IRD}|$ (i.e., magnitude of deviation from the middle direction of the starting movement direction) according to time constraint are shown for each target-angle condition. Two-way repeated-measures ANOVAs (time constraint [5] $\times$ number of targets [2]) on the $|\Delta\text{IRD}|$ in each target-angle condition showed a significant main effect of target condition in all angle conditions. The results of the multiple comparison tests showed that there was a significant difference when the time constraint was long. These results suggest that more centering initial movements occurred in the long time constraint condition. *: $P < .05$, **: $P < .01$

Figure 5

Comparison of reaction time according to time constraint between the double-target condition and the single-target condition. The upper panel shows a scatter plot of reaction times (of all participants) at a given time constraint. The middle and bottom rows show bivariate histograms (color maps) of time constraints and reaction times for the double-target and single-target conditions. These figures confirm that the reaction times were comparable among the conditions when the time constraint is short, while the discrepancy in reaction times between the conditions increased as the time constraint becomes longer. Although the reaction times were similar between conditions under short time-constraints, the deviation of reaction times becomes larger as the time-constraint becomes longer.

Figure 6

Comparison of execution strategy and performance according to time constraint between the double-target condition and the single-target condition. The top row shows the probability of reaching a target with a higher score according to the time constraint ($P_{\text{high value}}$), the reaction time according to the time constraint (RT), and the $P_{\text{high value}}$ according to the reaction time. The middle row shows the initial movement velocity (IMV), the movement time (MT), and the total length until 20 cm displacement from the start position (TOL) according to the time constraint. The bottom panel shows the mean score, the temporal accuracy (P_{temporal}), and the spatial accuracy (P_{spatial}) according to the time constraint. *: $P < .05$, **: $P < .01$