Choosing the Fastest Movement: Perceiving Speed-Accuracy Tradeoffs

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Abstract

Several studies have shown that humans exhibit an intimate knowledge of prospective motor actions when imagining and planning movements. To probe this knowledge, we used a 2-alternative forced-choice task to determine whether people are consistent with Fitts's law when choosing the movement they perceive to require the least movement time. We hypothesized that participants would choose the target with the lower Index of Difficulty with a probability greater than 0.5 in all situations. Participants performed almost perfectly when one of the targets was closer, wider, or both. Contrary to expectations, however, participants showed biases for close targets when one of the targets was closer and narrower. We argue that this pattern of behavior may result from a subjective representation of movement time that is based on both Fitts's law and the distance to the target, suggesting a preference for movements that are less effortful.

Keywords

Humans; Adult; Choice Behavior; Motor Skills; Models, Psychological

Introduction

One factor that allows the nervous system to choose one movement from an almost limitless selection of potential movements is the ability to accurately predict the consequences of motor actions. Research has shown that knowledge of future motor outcomes is the basis of many of the things that underlie humans' smooth and versatile movements, such as anticipatory grip changes, anticipatory posture changes, and eye movements that lead our actions (Davidson and Wolpert 2005). It is widely believed that these anticipatory actions rely on a mental internal model, or emulation system, that predicts the outcome of motor actions on the basis of the generated motor commands (Jeannerod 2001; Wolpert and Ghahramani 2000). In addition to planning motor actions that are currently underway, there is evidence that humans can use an internal model of movement to evaluate potential motor actions and plan movements to be performed in the future. For example, people grasp objects differently depending upon what they plan to do with them (Rosenbaum et al. 2006); people are able to choose an endpoint for movement with apparent knowledge of the errors they are likely to make (Trommershauser et al. 2003); and people can predict movement duration by actively imagining movements (Decety and Lindgren 1991). To further examine humans' ability to compare potential actions, this paper investigates the ability of participants to choose movements that require the least movement time.

To probe the ability of people to make this decision, we focused on one of the most fundamental principles of human movement, the trade-off between speed and accuracy (Schmidt and Lee 2005). This trade-off was first formalized by Fitts (Fitts 1954; Fitts and Peterson 1964), who proposed an equation to relate movement time (MT) with the distance (D) and target width (W) of two-dimensional movements: $MT = a + b * \log_2(2 * D / W)$. In this equation, a and b are empirically derived constants, and the log term is referred to as the Index of Difficulty (ID). In words, Fitts's equation states that (a) MT increases with increasing D, as the hand must travel further to reach the target; (b) MT increases with decreasing W, as the hand must travel at a slower average speed in order to land in the smaller target; and (c) any two movements with the same ID have the same MT. While variations of Fitts's equation have been proposed (For a review, see Plamondon and Alimi 1997), the general relation between D, W, and MT has been verified in such a wide variety of populations, movement tasks, and body parts that it is often referred to as Fitts's law (Schmidt and Lee 2005).

Several studies have shown that Fitts's law arises from the motor system optimizing movement trajectories to minimize MT in the presence of neuromotor noise (Harris and Wolpert 1998; Meyer et al. 1988; Tanaka et al. 2006). These studies suggest that the motor system determines the minimum MT based on the target's ID, before the movement even starts, and then chooses the optimal motor commands to build the required trajectory. In this paper, we investigate whether people are able to choose entire movements in a time-optimal way. In other words, does a person demonstrate the same knowledge of the speed-accuracy trade-off when choosing targets for movement as that exhibited by the person's motor system when choosing motor commands to build a movement?

Research in several different paradigms has shown that people are, indeed, consistent with Fitts's law when imagining, choosing, and perceiving movements. The first evidence comes from studies of motor imagery, in which participants imagine performing actions and report the duration of the imagined movement. Decety and Jeannerod (1995) had participants imagine walking through a gate in virtual reality. The distance to the gate and width of the gate were varied between trials, and the experimenters measured the time between participants' reports of starting and ending walking. They found that imagined MT obeyed Fitts's law, using gate distance and gate width in the ID. Sirigu et al. (1996) demonstrated similar results with hand movements. Participants made real or imagined reciprocal hand movements between a line and a target, and target size was varied between trials. Imagined MT was highly correlated with actual MT, and they found a similar r^2 value when fitting Fitts's law to both imagined and actual MT.

There is also evidence that a person has knowledge of Fitts's law when preparing for future movements and perceiving the limitations of movements. Augustyn and Rosenbaum (2005) demonstrated that individuals are consistent with Fitts's law when choosing the starting location for future target-directed movements. In this experiment, each participant chose a location at which to place his or her finger on a line between two targets. One of the targets then disappeared, and the participant attempted to move his or her finger to the remaining target within a limited time. By choosing the start location of the movement, the participant controlled the ID of the two potential future movements. The experimenters showed that participants chose a starting location that resulted in the same ID for both potential movements. Finally, Grosjean et al. (2007) showed that a person's perceptions of movement limitations are also consistent with Fitts's law. Participants watched displays of a human or a robot making reciprocal movements between two targets, and they reported whether the movements were possible without missing the targets. Target width, distance between targets, and motion speed were varied between trials. The movement times predicted by participants as the threshold between possible and impossible agreed with the movement time predictions of Fitts's law.

Unlike the aforementioned studies, the question we ask in this study is whether people have sufficient awareness of Fitts's law to select the movement with the shortest MT when given two targets that vary in D and W. To answer this question, we used a two-alternative forced-choice task, as shown in Figure 1. Participants were given a common horizontal start location and two targets for movement. They were asked to determine the target to which they perceived they could move with the shortest MT. We expected participants to make decisions in a way that was consistent with Fitts's law, as found in the previously mentioned studies.

Participants were presented with four types of decisions based on the relative difference in D and W of the targets. In the first two types of decisions, targets varied in only one dimension—D or W. Both of these situations seem intuitive: we expected participants to choose the closer target or wider target with very high probability. The third type of decision—the closer target was wider than the farther target—also seemed intuitive: we expected participants to choose the closer and wider target with high probability. We expected people to find the fourth type of decision—in which the closer target was narrower than the farther target—more difficult. Contrary to the first three types of decisions, there were no obvious visual cues to indicate the movement with shorter MT. People would need to rely on knowledge of their motor abilities in order to choose the target with the lower ID. To determine if people were consistent with Fitts's law for this type of decision, we found pairs of targets for which participants chose each with equal probability, thereby indicating that participants believed each target had the same MT. Similar approaches are used in psychophysics (Gescheider 1997), where the stimuli that participants choose with equal probability are referred to as being subjectively equal (i.e., the participant does not show a consistent preference for either stimulus, so he must believe the stimuli are equal). According to Fitts's law, in order to have the same MT, movements must have the same ID. Therefore, we hypothesized that participants would find targets with equal values of ID to be subjectively equal. In order to ensure that the observed decision-making behaviour was not purely an artifact of the particular targets presented, we replicated the four types of decisions with several target combinations.

Methods

Participants

Eleven healthy, right-handed volunteers (3 females) participated in this study. The mean age was 27.5 years old (range 20 – 39). None of the participants had performed the task previously. The study was conducted in accordance with ethical guidelines established by the ethics review boards of the University of Toronto and Bloorview Research Institute. All participants gave their informed consent prior to participating in the study.

Procedure

Participants sat at a table and used a stylus to interact with an LCD tablet (Cintiq 15X tablet and UP-813E-01A stylus, both from Wacom Company Ltd., Japan). The tablet was placed flat on the table, and the table was adjusted to a comfortable height for each participant. Participants first performed 20 practice target-directed movements and 20 practice trials of the two-alternative forced-choice task to ensure that they understood the decision they were being asked to make. Participants then performed 630 test trials of the two-alternative forced-choice task. The test trials were organized into 10 blocks of 63 trials with one minute of rest between each set.

Each trial of the forced-choice task followed the same protocol. Prior to the trial, a start square appeared on the right side of the screen. When ready, participants touched the start square with the stylus. This action started the trial and displayed the two-alternative forced-choice task shown in Figure 1. Participants then determined the target to which they perceived they could move with the shortest MT. Participants considered movements in which the stylus started from rest at any point on the start line and ended with the stylus at rest at any point within one of the target rectangles. Participants were instructed to make decisions as accurately as possible, and to take as long as they needed to complete each trial. They were also instructed to avoid using the location of the target on the screen (i.e., top or bottom target) as a factor when making decisions. While deliberating their decision, participants were not permitted to make movements to the targets, but they were permitted to imagine movements. Participants indicated their choice by placing the stylus in the appropriate selection rectangle, and not by making a movement to the target rectangle. This action ended the trial, and a new start square appeared.

Stimuli

Each trial presented a pair of targets, and all subjects were tested with the same 63 pairs. Each pair was presented 10 times, for a total of 630 trials. Trials were organized into 10 randomized blocks of 63 trials, and the location of each target within each trial (i.e., top or bottom target) was counterbalanced. The 63 pairs of targets were determined by defining 7 target groups (not to be confused with a group of subjects), each containing 9 pairs of targets (i.e., 7 * 9 = 63). The 9 pairs in each target group were used to measure participants' behaviour in four types of decisions, based on the relative difference in D and W of the targets in the pair (as explained in the introduction and below). The 7 target groups were chosen to replicate those four types of decisions with targets of various D and W.

Each target group consisted of a single reference target and nine comparison targets. Nine pairs of targets were created by comparing the reference target to each of the comparison targets. Each group was defined by three parameters: the ID of the reference target (ID_{ref}); the D of the reference target (D_{ref}); and the separation (S), a parameter used to define the D and W of the comparison targets relative to the reference target, as outlined below. For each group, the same approach was used to determine its respective comparison targets. First, three comparison targets were chosen to create the three types of decisions that we expected participants to find intuitive. One target had a greater D than the reference target: $D = D_{ref} + S$. Another had a greater W than the W of the reference target (W_{ref}): $W = W_{ref} + S$. The third target had lesser D and greater W than the reference target: $D = D_{ref} – S/3$ and $W = W_{ref} + S/3$. We expected participants to choose the reference target with probability of (a) 1.0 for trials involving the comparison target with greater D; (b) 0.0 for trials involving the comparison target with greater W; and (c) 0.0 for trials involving the comparison target with lesser D and greater W.

Additionally, within each group, six comparison targets were chosen to create the type of decision that we expected participants to find more difficult. All of these targets had a greater D and greater W than the reference target. Each target was chosen so that the total of differences between its D and W and those of the reference target was equal to S: $(D – D_{ref}) + (W – W_{ref}) = S$. One target was chosen to have the same ID as the reference target, and the other 5 were distributed evenly at values of ID higher and lower than ID_{ref}. As shown by the dashed line in Figure 2, we expected participants to display a type of psychometric function for decisions involving these targets: the probability of choosing the reference target was expected to increase monotonically with increasing ID, from 0 for the target with greater W than the reference, to 1 for the target with greater D than the reference. To be consistent with Fitts's law, we expected the probability of choosing the reference target to be 0.5 for trials involving the comparison target with the same ID as the reference target.

We created seven target groups by using different values of the parameters D_{ref}, ID_{ref}, and S. One target group was defined using a base set of these parameters (i.e., D_{ref} = 120mm, ID_{ref} = 4, and S = 38 mm) and six additional groups were created by modifying one of D_{ref}, ID_{ref}, or S, while keeping the other two parameters constant. Table 1 shows the parameter values for each group. Changes in D_{ref} changed the D of all the targets in the group, and changes in ID_{ref} changed the W of all the targets in the group. Changes in S, meanwhile, had no effect on the reference target but changed the similarity of the comparison targets to the reference target.

Results

For the three types of decisions that we expected participants to find relatively easy, results were as expected. We counted the number of times participants chose the reference target for each type of decision, creating a total of 770 trials across target groups and participants (i.e., 10 trials * 7 target groups * 11 subjects) for each of the three types of decisions. Participants chose the reference target 763 times for trials involving the targets with greater D, 7 times for trials involving targets with greater W, and 2 times for trials involving targets with less D and greater W.

For the type of decision that we expected people to find more difficult, there were some differences from our expectations. For an example that is representative of most target groups, the solid line in Figure 2 shows the probability of choosing the reference target for Target Group 1 (calculated across all participants). As expected, the probability of choosing the reference target increased monotonically from the target with greater W to the target with greater D. Contrary to expectations, however, the probability of choosing the reference target was greater than 0.5 for the comparison target with the same ID as the reference target. As a result, the ID value at which the psychometric function was equal to 0.5 was less than ID_{ref}. This indicates that the subjectively equal comparison target had a lower ID than the reference target.

To analyze the differences between expected and measured behaviour, we first tested the hypothesis that participants chose the reference target with p = 0.5 for pairs in which the reference and test targets had the same ID. For each target pair in which both targets had the same ID (i.e., one pair in each group), we determined the frequency of choosing the reference target across participants, as shown in Table 1. The total possible frequency for each pair was 110 (i.e., 10 trials * 11 participants), and we expected participants to have a frequency of 55 (i.e., 0.5 * 110). We used a chi-square test to determine whether the measured frequency for each pair was significantly different than 55. As shown in Table 1, participants chose the reference target with a significantly greater frequency than expected in all target groups except the group with the smallest D_{ref}.

Next, we estimated the IDs of subjectively equal comparison targets by finding the ID values resulting in p = 0.5 for each measured psychometric function. We followed a non-parametric psychophysical approach called the Spearman-Karber method (Miller and Ulrich 2001). First, we used the frequency with which each participant chose the reference target to estimate that participant's probability of choosing the reference target for each pair of targets. To get a maximum-likelihood estimate of each participant's psychometric function for each target group, we used a non-parametric approach from Ayer et al. (1955) to monotonize any psychometric functions that were not completely monotonic. This resulted in adjustments to 35 of the 616 probability values. We then estimated the ID value that resulted in a probability of 0.5 for each psychometric function by interpolating between targets with probability values nearest to 0.5. For each target group, we calculated the mean ID value across participants and compared it to the expected ID (i.e., the ID of the reference target) using a t-test. As shown in Table 1, the mean IDs of the subjectively equal targets were significantly lower than the IDs of the reference targets for all target groups except the group with the smallest D_{ref}.

Discussion

The present study used a two-alternative forced-choice task to determine whether individuals are consistent with Fitts's law when choosing target-directed movements to minimize MT. We found that participants chose the movement with the shortest MT almost perfectly in situations in which visual cues provided clear indications of the correct choice—when one target was closer, larger, or both closer and larger. In situations for which there were no obvious visual cues—when one target was closer and smaller—we observed some differences from the hypothesized behavior. When faced with two targets that had the same ID but a different D, participants chose the closer target with probability significantly greater than chance, indicating that they believed that the closer movement had a shorter MT. This was seen for all target groups we measured, except the group with the shortest D_{ref}. As a result, participants' subjectively equal targets were consistently at a lower ID than what was predicted, except for movements of the shortest studied D_{ref}. Therefore, it appears that people do choose movements with knowledge of Fitts's law, but they also show systematic deviations from Fitts's law in some situations.

To visualize the differences between expected and measured subjectively equal targets, Figure 3 plots our results in width-distance space along with lines of constant ID. In this view, targets are represented as points in two dimensions: the x-axis indicates the target's W, the y-axis indicates the target's D. We had predicted that all of the subjectively equal targets—the targets that participants believed to have the same MT as the reference targets—would fall on the curves of constant ID. This is the case for the target group with the shortest D_{ref}, but the subjectively equal targets from all other groups are at a lower ID than their respective reference target. As a result, lines connecting the reference targets to the subjectively equal targets have a lower slope than the curves of constant ID.

To better represent the observed behavior, we searched for a function that could approximate the pattern of subjective MT (MT_{subj}) we observed. We tried several functions of the parameters D and W, looking for a function that had constant values for each reference target and its respective subjectively equal targets. We found the greatest r^2 values for a group of functions with the form $MT_{subj} = f(D/W) + g(D)$, where f(D/W) is a log or power function of D/W (as seen in almost all expressions of Fitts's law) and g(D) is a linear, square, or polynomial function of D. The above equation suggests that participants were considering a subjective measure of MT that was based on both Fitts's law and D. These functions duplicate several aspects of the results shown in Figure 3. First, the curves connecting reference targets to subjectively equal targets are generally at a lower slope than the curves of constant ID, as seen for six of the seven target groups. Second, the differences in slope between these two sets of curves increase with increasing D, as seen for the three target groups that differed in D_{ref}. Finally, the functions create curves of MT_{subj} that are non-linear, with slopes decreasing with increasing D and W. This agrees with our observations: a small change in slope is apparent in Figure 3 for the curve connecting the subjectively equal targets of the target groups that differed in S, and larger changes in slope were prominent in the same curve from 5 of the 11 participants.

The observed dependence on D is consistent with the results of one other study. As indicated in the introduction, Decety and Jeannerod (1995) showed that motor imagery of a virtual reality task was consistent with Fitts's law. One point on which they did not elaborate, however, was the variation in imagined MT for movements of the same ID but different D. Their experiment contained three data points with the same ID but different D, and imagined MT increased with D. We analyzed the data shown in the paper and found that each increase in D with constant ID resulted in a significant increase in the imagined MT. Therefore, Decety and Jeannerod's study provides additional evidence that people can perceive movement durations that are systematically different than the predictions of Fitts's law. The same analysis cannot be duplicated for other motor imagery studies, as Decety and Jeannerod (1995) was the only motor imagery study that included more than one target with the same ID.

Why would people consider D in addition to Fitts's law when predicting MT? Perhaps, when estimating MT, people also consider the energy required to make the movement. The energy expended in a target-directed movement increases with the distance moved and the peak velocity of the movement. Since both mean distance moved and peak velocity increase with D in target-directed movements (Mackenzie 1987), energy expenditure should also increase with D. Optimal control models that can explain arm trajectories and whole body movements often include a measure of energy, so there is reason to believe that participants consider energy when planning movements (Pandy 2001; Todorov and Jordan 2002). Motor imagery experiments also provide support for this possibility. It has been shown that people will estimate longer movement durations for movements that require more energy but equal MT, such as moving heavier objects (Cerritelli et al. 2000; Decety and Lindgren 1991).

While we have assumed that our participants' MTs would have followed Fitts's law, it is also possible that our participants might have produced MTs inconsistent with Fitts's Law. Therefore, their decisions might reflect these non-conforming MTs. While we cannot fully rule this possibility out, as we did not measure MT for our participants' movements, we do believe that it is unlikely. As we mentioned in the introduction, Fitts's law has been shown to be robust in a wide variety of tasks and populations over many years of research. Almost every variation of Fitts's law (For a review, see Plamondon and Alimi 1997) relates MT to a function of D/W, the hypothesis used in this paper. Further, the movement targets we used—rectangular targets that differ in W and D—and the population that we used—young, able-bodied adults—have been commonly used in past research on Fitts's law. With this background, we feel that it is unlikely that the MT of our participants' movements would deviate from past research on Fitts's law by the same magnitude as the decisions they made. Instead, we believe that it is more likely that our participants (and others) simply have a disparity between their actual MT and their subjective belief of MT, as demonstrated in the decisions of this task.

It is also possible that our participants' preferences reflect a consideration of more complex trajectories than we expected. Because participants were free to consider movements that started from any point along the start line, they might have considered curved movements as a strategy to reduce MT. A curved trajectory would allow a participant to end their movement with velocity in the vertical direction (i.e. aligned with the longest dimension of the target). This strategy might allow greater movement speed, as endpoint variance tends to be greatest in the direction of final movement velocity (van Beers et al. 2004). While it has been shown that movements with straight trajectories, even at an angle to the target, follow Fitts's law (Mackenzie and Buxton 1992), it has not been shown that Fitts's law represents the MT for movements with curved trajectories. We doubt that participants were considering curved movements, as all participants made straight movements during the practice session. At the same time, we cannot rule the curved movements out because we didn't require participants to make actual movements to the targets. Future work with a version of this task that requires overt movement to the targets can resolve this question.

It is worth noting that our results differ from the agreement with Fitts's law seen in similar studies, particularly that of Augustyn and Rosenbaum (2005). In some ways, the task used by Augustyn and Rosenbaum could be considered an analog to the task in the present paper, using a different psychophysical method (Gescheider 1997). Their task used a method of adjustment to determine the IDs for given movements, while our task used a method of constant stimuli to determine the preferred movement for given IDs. Differences in both motor actions and task presentation might have caused the disparate results. First, participants in Augustyn and Rosenbaum's study had much more practice making target-directed movements than the participants in our study. As a result, the participants in Augustyn and Rosenbaum's study likely had a greater knowledge of their actual expected MT. Additionally, our participants did not plan movements to the targets as part of making a choice, whereas the participants in Augustyn and Rosenbaum's study were required to prepare for future target-directed movements as part of choosing a start location. As a result, it is possible that the participants in Augustyn and Rosenbaum's study benefited from the motor system's knowledge when they chose a start location.

In addition to differences in motor practice and planning, factors of the task presentation might have affected the way that participants made decisions. There are many ways to ask participants to compare two different movements; our paper and that of Augustyn and Rosenbaum present only two of these variations. As is known from the decision-making literature, the way a decision is framed can have a substantial effect on the choices that participants make (Tversky and Kahneman 1981). The difference in results between our study and that of Augustyn and Rosenbaum is very interesting, as it might present a situation in which a framing effect is also seen for decisions on motor tasks. There appear to be at least two possible ways that the task presentation might have affected the decisions. First, we used two movements in the same direction but with a different start point, whereas Augustyn and Rosenbaum used two movements with the same start point but different directions. As a result, our task might have encouraged people to emphasize the differences between movements (i.e., the differences in D and the W of the targets), whereas Augustyn and Rosenbaum's task might have encouraged people to find some type of middle point that balanced the two possible movements. Second, the participants' choice behaviour might have been interpreted differently based on differences in how target area was related to target ID. Whereas the both groups of authors calculated ID using W, our targets increased in area linearly with W, whereas Augustyn and Rosenbaum's targets (circles) increased in area by the square of W. This could lead to a different interpretation of behaviour if people consider target area more than target width when making choices.

In this experiment, we asked whether people exhibit the same consistency with Fitts's law when choosing movements as they have in previous studies of movement perception, motor imagery, and preparation for future movements. While participants followed Fitts's law almost perfectly when provided with visual cues indicating the correct choice, they showed a bias for closer movements when there were no visual cues. This disparity between Fitts's law and our participants' preferences suggests two things. First, the existence of a disparity provides evidence that people choose movements in a way that is inconsistent with their actual movements, indicating that people can behave sub-optimally in at least one aspect of motor planning. Several studies have shown that people perform optimally in motor-planning tasks

(Augustyn and Rosenbaum 2005; Trommershauser et al. 2005), leading some to suggest that motor planning does not suffer from the sub-optimalities seen in some classical decision-making tasks (Trommershauser et al. 2006). The present study, however, suggests that optimal performance is not universal in all motor planning tasks, and that research should focus on understanding the factors that lead people to perform optimally. Second, the pattern of disparity observed in this study suggests a need for better understanding of the internal measurements that humans use when planning movements. Although our participants deviated from our definition of optimal, this deviation was consistent across several groups of targets. This pattern indicates that the participants were making choices in a systematic fashion, but that we, as experimenters, don't fully understand the factors involved. Only by measuring the factors that cause people to prefer one movement over another will we get a full understanding of the way in which the central nervous system plans movements (Kording et al. 2004). This knowledge is needed if we hope to understand why people choose particular movements over the myriad possibilities with which they are faced every time they try to accomplish a goal.

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Table 1 Target group parameters and results.

Target Group	Target group parameters			Frequency at same ID[1]			ID of subjectively equal target		
	D_{ref} (mm)	ID_{ref}	S (mm)	Frequency (across participants)	χ^2 (df = 2)	p	Mean	t (df=10)	p
1	120	4	38	90	24.7	<0.001	3.29	-5.46	0.002
2	49	4	38	50	0.455	0.500	3.81	-0.724	0.485
3	227	4	38	109	69.9	<0.001	3.22	-6.76	<0.001
4	120	1	38	103	51.7	<0.001	0.94	-5.62	<0.001
5	120	2	38	101	46.6	<0.001	1.64	-15.4	<0.001
6	120	4	10	100	44.2	<0.001	3.68	-4.14	<0.001
7	120	4	152	92	28.1	<0.001	2.47	-4.77	<0.001

[1] Frequency with which participants chose the reference target when the comparison target had same ID

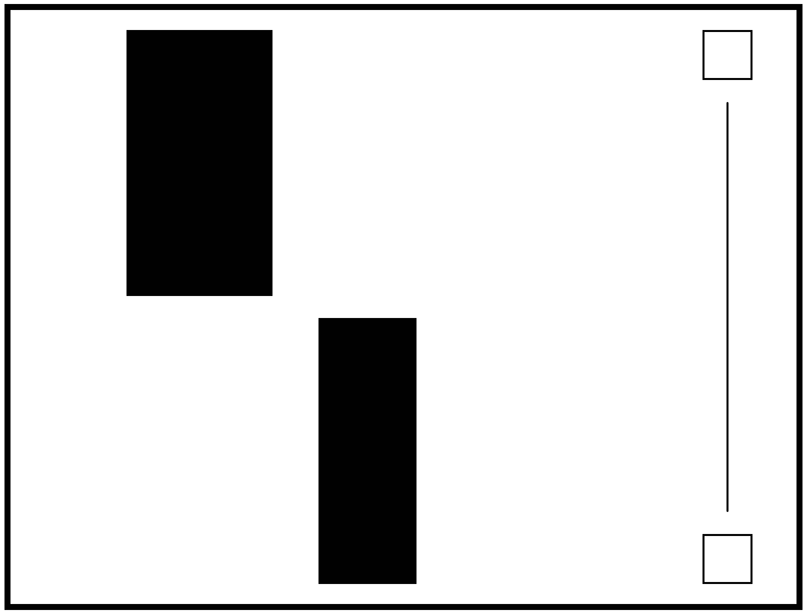

Fig. 1 Two-alternative forced-choice task. Participants considered movements starting from any point on the vertical start line (right side) and ending at any point within one of the target rectangles (left side). Two parameters of the targets were varied between trials: distance from the start line to the center of the target (D), and target width (W). Target height was constant at 100mm. Participants chose the target that they perceived to require the shortest movement duration. They indicated their choice by placing the stylus into the selection rectangle above or below the start line.

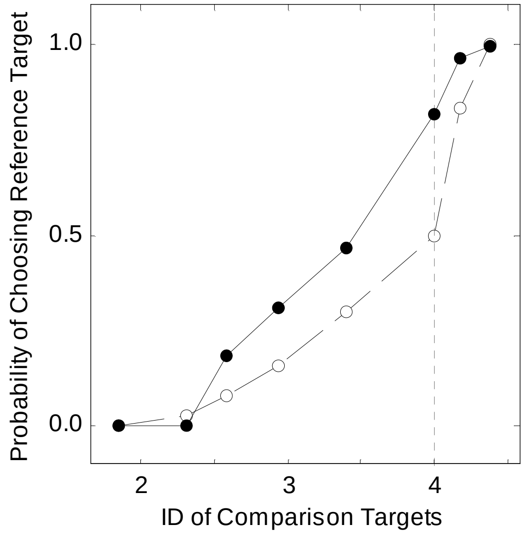

Fig. 2 Expected and measured psychometric functions from Target Group 1. We expected the probability of participants choosing the reference target (open circles and dashed line) to be 0.0 for the target with greater W than the reference (point with lowest ID); to increase monotonically with ID for the targets with greater W and greater D than the reference (6 points with intermediate values of ID); and to be 1.0 for the target with greater D than the reference (point with highest ID). Further, we expected the probability to be 0.5 for trials involving the comparison target with the same ID as the reference target (for this target group, $ID_{ref} = 4$). The measured probability across participants (closed circles and solid line) increased monotonically as expected, but the probability of choosing the reference was greater than 0.5 for the target with ID = 4. As a result, the ID value at which the psychometric function was equal to 0.5 was lower than ID_{ref}.

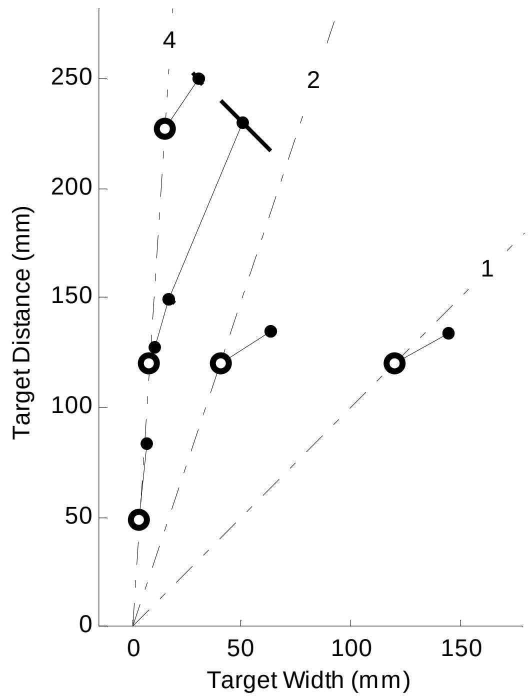

Fig. 3 Mean subjectively equal targets in width-distance space. In this view, targets are represented as points in two-dimensional width-distance space: the x-axis indicates the target's W, and the y-axis indicates the target's D. The reference targets (open circles) are connected to their respective mean subjectively equal targets (closed circles) with light solid lines. Error bars, where visible, indicate the standard error of the means over the participants. We had expected all of the subjectively equal targets to lie on the curves of constant ID (dash-dot lines labeled with their respective ID value), but this is the case only for the replication with the smallest D_{ref}.