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Perceived Difficulty in a Fitts Task

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PERCEIVED DIFFICULTY IN A FITTS TASK

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PERCEIVED DIFFICULTY IN A FITTS TASK

SUZANNE M. GRILLI

ABSTRACT

This study provided a detailed investigation of perceived difficulty (PD) in a Fitts task. The Fitts task has been used to study Fitts's law, which shows that movement time (MT) is related to the information constraints of the movement (Fitts's Index of Difficulty, ID) such that there is a positive, linear relationship between MT and ID and MTs are similar when the scale of the movement requirements vary but ID is equal (scale invariance). According to Fitts's law, Fitts's ID provides an index of objective difficulty; does Fitts's ID also provide an index of subjective difficulty? The main goal of this study was to address this question. It was hypothesized that the characteristics of the MT-ID relation described by Fitts's law extend to the PD-ID relation. This hypothesis was addressed in two experiments, both including a variety of ID and scale conditions. In Experiment 1, participants (N = 20) assessed performance difficulty in prospective action; in Experiment 2, participants (N = 40) assessed performance difficulty in imagined and actual action. The results from both experiments supported the hypothesis. The support was limited, however; under certain conditions, there was evidence of a non-linear PD-ID relation and scale variance for PD. Thus, within limits, Fitts's ID provides an index of subjective difficulty in prospective, imagined, and actual action.

In Experiment 2, MTs were collected in addition to the PD judgments. It was hypothesized that MT is superior to ID in predicting PD and that MT mediates the relationship between PD and ID. The results supported these hypotheses for many participants in both action conditions, but particularly in imagined action. An additional

finding was that participants' PD judgments in imagined and actual action were very similar. In conclusion, participants' PD judgments relate more to the outcome of their action experience (i.e., MT) than the information constraints of the action (i.e., ID). Furthermore, actual experience in the task, and the external feedback that accompanies actual experience, does not have much of an effect on participants' PD judgments. It appears that internal feedback influences participants' PD judgments in both imagined and actual action.

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CHAPTER I

INTRODUCTION

Motor behavior research has traditionally focused on objective measures in evaluating performance difficulty. A common objective measure used in this research has been time: For example, a movement is considered more difficult to perform than another movement if it takes longer to perform. Fitts's law, a fundamental principle of motor behavior, is based on this idea. Fitts's law describes the relationship between the time it takes to perform a movement (movement time, MT) and the information constraints of the movement. In the context of a motor task, the information constraints refer to the amount of information that the actor needs to process to resolve the uncertainty among the number of possible movements and generate a successful movement. In the context of Fitts's law, the information constraints are represented by levels of Fitts's Index of Difficulty (ID) and are a function of two features of the movement environment: the amplitude over which the movement must be made and the width of the target within which the movement must end. As the amplitude-to-width ratio increases, ID increases. The predictions of Fitts's law are that MT increases linearly with increases in ID and MT is similar for conditions where the amplitude and/or width requirements vary but ID is equal. Numerous studies have found support for these predictions since the introduction of Fitts's law in Fitts (1954) (for a comprehensive review of studies, see Plamondon & Alimi, 1997).

Given the relationship between MT and ID and because MT is a measure of objective difficulty, ID provides an index of objective difficulty. Does ID also provide an index of subjective difficulty? The main goal of this study was to address this question. Addressing this question will indicate not only the scope of the label the "Index of Difficulty," but also whether objective and subjective assessments of performance difficulty are influenced by similar information from the movement environment, that is, the information constraints as defined by ID. The two experiments conducted in this study addressed this question. In both experiments, subjective difficulty was measured by numerical judgments that reflected participants' perceived difficulty (PD) [1] of task performance, and the PD judgments were compared to levels of ID. Participants judged the difficulty of performance in a Fitts cyclical aiming task (Fitts, 1954), or Fitts task, which has been used in studies on Fitts's law. The main difference between the two experiments was the form of action that participants were judging. In Experiment 1, participants' PD judgments reflected the difficulty of prospective task performance; that is, participants judged the difficulty that someone would experience if they were to perform the task. Participants never actually performed the task, which facilitated the collection of the PD judgments. In Experiment 2, in separate action conditions, participants judged the difficulty they experienced in imagined and actual task performance. In both action conditions, MTs were collected in addition to the PD judgments. MT and ID were compared as predictors of PD, and the role of MT as a mediator of the relationship between PD and ID was examined. Overall, this study provided a detailed investigation of PD in a Fitts task.

In the next section, the research on Fitts’s law is described to provide a background for this study and the previous studies that have investigated PD in the context of Fitts’s law. This previous research on PD is reviewed subsequently. Following the literature review is a more detailed overview of this study that includes the hypotheses addressed.

1.1 The Fitts task, Fitts’s ID, and Fitts’s law

In his landmark 1954 study, Fitts formally described the relationship between MT and ID in an equation that came to be known as Fitts’s law. In the first experiment of his study, the Fitts task was introduced: Participants were presented with various target displays, each consisting of two targets of equal width that were separated by a given amplitude, which was defined as the center-to-center distance between targets. For each target display, participants used a hand-held stylus to generate continuous target-to-target movements for a period of 15 s. Participants were instructed to be as accurate as possible in contacting the targets. Across trials, the two targets were separated by different amplitudes and the target width varied to provide different limitations on the spatial variability of the target contacts. There were sixteen unique target displays: There were four width requirements, which ranged from 0.64 to 5.08 cm, and for each width requirement, there were four amplitude requirements, which ranged from 5.08 to 40.64 cm.

Fitts found that the average time taken to complete a target-to-target movement (i.e., MT) increased as the amplitude between the targets increased and/or the target width decreased in size. Furthermore, Fitts found that MT related to the ratio of the movement amplitude to the target width: MTs were similar for target displays that shared the same amplitude-to-width ratio, but had different combinations of amplitude and width. Accordingly, the amplitude-to-width ratio became the main ingredient in a formula for performance difficulty that Fitts labeled the Index of Difficulty (ID): $\log_2(2A/W)$. (Hereafter, the terms amplitude and width will be abbreviated as A and W, respectively, when referring to the equation $\log_2[2A/W]$). In line with information theory, which was popular at the time, levels of ID were measured in binary digits, or bits, of information; hence, the $\log_2$ element. In terms of information theory, 2A/W represented the number of potential movements that could be made in traveling to the target and $\log_2(2A/W)$ represented the amount of information, in bits, that the actor needed to process to resolve the uncertainty among the potential movements (Schmidt & Lee, 1999, pp. 175-176). According to Fitts, the greater the value of $\log_2(2A/W)$, the more information the actor needed to process to resolve this uncertainty and generate a successful movement. By including the logarithmic transformation, that is, $\log_2$, a doubling of the A/W ratio (or the 2A/W element) resulted in a 1-bit increase in ID. Multiplying the A/W ratio by a value of two was included to avoid an ID level with zero difficulty; according to the formula for ID, if ID was 0 bits, the two targets would completely overlap. When ID was 1 bit, the two targets were adjacent.

Fitts (1954) described the relationship between MT and ID in the equation, $MT = b\log_2(2A/W) + a$, which, due to its robustness, became known as Fitts’s law. Fitts’s law predicts a positive, linear relationship between MT and ID and similar MTs when the scale of the movement requirements vary but ID is equal. This last prediction is described as *scale invariance* for MT. Fitts's law has been demonstrated in a variety of movement environments, such as when movements are performed under water (Kerr, 1973), in a computer environment (Card, English, & Burr, 1978), and in a virtual reality environment (Decety & Jeannerod, 1996). Support for Fitts's law has also been found for different movement conditions, such as when movements are generated to a single target (Fitts & Peterson, 1964) or back and forth between two targets (Fitts, 1954), when movements are performed with different effectors (e.g., forearm, wrist, and finger; Langolf, Chaffin, & Foulke, 1976), or when movements are not actually performed but imagined (Decety & Jeannerod, 1996; Sirigu et al., 1995; Sirigu et al., 1996). Fitts's law has particular significance in motor behavior research because there are few motor principles that can be described mathematically and can extend to a variety of movement environments and conditions (Schmidt & Lee, 1999, p. 177).

1.2 Fitts's ID and PD

As stated, the main goal of this study was to test whether Fitts's ID provides an index of subjective difficulty. In other words, do the characteristics of the MT-ID relation described by Fitts's law extend to the PD-ID relation? An affirmative answer would be provided if there is (a) a positive, (b) linear PD-ID relation and (c) evidence of scale invariance for PD, that is, PD judgments are similar for target displays representing the same ID level but different levels of scale. Previous studies have tested the first two predictions; however, none of these studies has tested the third prediction. A test of scale invariance for PD would involve a single group of participants evaluating performance difficulty for multiple target displays representing the same ID level but different levels of scale. The current study used this method and tested all three predictions for the PD-ID relation derived from Fitts's law. Thus, this study provided a definitive test of whether Fitts's ID provides an index of subjective difficulty. The following section details the results of previous research on PD in a Fitts task.

1.3 Previous research on PD in a Fitts task

Deliginières and Famose (1992) and Deliginières and Brisswalter (1996) investigated the relationship between subjective and objective difficulty in actual action using a Fitts task. The apparatus used in these studies was comparable to that used in Fitts (1954). Participants engaged in actual task performance under five target displays that were characterized by ID levels ranging from 1.32 to 5.32 bits with a 1.00-bit increment between ID levels. Both the amplitude and width requirements varied among the target displays: When ID = 1.32 bits, width = 4.00 cm; when IDs = 2.32-4.32 bits, width = 2.00 cm; when ID = 5.32 bits, width = 1.00 cm; at all ID levels, amplitude varied according to the formula for Fitts's ID, $\log_2(2A/W)$. Each ID level was depicted by a single target display; therefore, the issue of scale invariance was not examined. For each target display, participants performed ten blocks of trials. A trial consisted of five back-and-forth movements. After performing the ten blocks of trials for a target display, participants provided a numerical judgment that reflected the difficulty that they experienced in performing the task under that target display. PD was assessed according to the psychophysical method of magnitude estimation where participants assigned numbers in relation to their PD of task performance. Participants first performed under the target display that represented an ID level of 1.32 bits. That target display served as the standard and had a modulus of 10. Participants referred to the standard in assigning their PD judgments to the remaining target displays. The order of the remaining target displays was counterbalanced among participants.

Deliginières and Famose (1992) tested the forms of three relations: the PD-ID, PD-MT, and MT-ID relations. For each relation, both the individual-participant and group data were fit to linear, power, logarithmic, and exponential functions. The results showed that the three relations were all positive in form for both the individual-participant and group data. For the PD-ID relation, an exponential function most often provided the best fit for the individual-participant data and provided the best fit for the group data. There was also strong support for a linear PD-ID relation for both the individual-participant and group data. The same results were found for the MT-ID relation. For the PD-MT relation, an exponential function most often provided the best fit for individual-participant data, although there was not strong support for any of the four functions, and linear and power functions provided the best fit for the group data. In summary, the PD-ID, MT-ID, and PD-MT relations were found to be positive and curvilinear in form.

The results of Deliginières and Famose (1992) supported the prediction for a positive PD-ID relation. Contrary to the prediction for a linear PD-ID relation, however, even though a linear function provided a good fit to the data, an exponential function provided the best fit. Based on this result, the authors concluded that the true psychophysical function of the PD-ID relation is exponential. It seems, however, the finding of a curvilinear trend could have been attributed to the amplitude and width requirements of the target displays: In particular, the ID level of 5.32 bits was characterized by both a large amplitude requirement (20.00 cm) and a small width requirement (1.00 cm) compared to the requirements of the other ID levels. The deviations from linearity for the PD-ID relation may have reflected a sensitivity that participants have to extreme amplitude and width requirements. Such a sensitivity might have also affected participants' MTs: Similar to the PD-ID relation, an exponential function best fit the MT-ID relation. Indeed, Fitts (1954) and subsequent researchers (e.g., Welford, 1968, chap. 5; Sheridan, 1979) have noted that there are limitations to the Fitts's law predictions for the MT-ID relation when the amplitude and width requirements are extreme.

In a follow-up study, Deliginières and Brisswalter (1996) tested if PD could be considered a general concept, independent of the type of task. The relevant results of that study were those that involved the Fitts task and the PD-ID relation. The results of Deliginières and Brisswalter (1996) were in agreement with those of Deliginières and Famose (1992): There was a positive PD-ID relation and an exponential function best fit both the individual-participant and group data. Again, improvements in the fit of the data to a non-linear function were small. Overall, the research by Deliginières and colleagues showed evidence of a positive, curvilinear PD-ID relation in actual action. The results of these studies suggest that, within limits, Fitts's ID provides an index of subjective difficulty in actual action.

Slifkin and Grilli (2006) reached the same conclusion when studying PD in prospective action using a Fitts task. Prospective action is action that is not performed but could be performed in the future. When participants are instructed to judge prospective action, they do not actually perform the action and are not instructed to imagine performing the action. Yet, research suggests that participants formulate their prospective action judgments by imagining action performance. For example, research shows that the time it takes to judge a prospective action is correlated with the time it takes to imagine performing the action (Parsons, 1994) or to actually perform the action (Johnson, 2000; Parsons, 1994). Furthermore, studies using brain imaging procedures have shown that prospective, imagined, and actual action activate many of the same brain regions: For example, Parsons et al. (1995) used positron emission tomography (PET) to show that prospective action is associated with activity in the premotor cortex and cerebellum, which are brain regions known to be active during imagined and actual action. In fact, prospective action is sometimes referred to as implicit imagined action (e.g., Parsons et al., 1995) because it appears that in judging prospective action participants imagine performing the action even though they are not instructed to do so and sometimes they are not aware they are imagining performance (Parsons, 1994). In this paper, the term prospective action is used to refer to implicit imagined action (i.e., where participants imagine action performance even though they are not instructed to do so) and the term imagined action is used to refer to explicit imagined action (i.e., where participants are instructed to imagine action performance).

There were two main objectives of Slifkin and Grilli (2006): to determine whether a positive PD-ID relation would result despite participants not having experienced task performance and to determine whether the PD-ID relation would generalize to different experimental settings. In contrast to the studies by Deliginières and colleagues, the form of the PD-ID relation was not investigated in detail. The study consisted of two experiments involving different groups of participants. Participants in both experiments were introduced to the Fitts task. In contrast to the usual apparatus used for the Fitts task where target displays are made of paper or some related material and presented on a horizontal surface, the target displays were computer images. The images of the target displays were presented either through personal computer monitors (Experiment 1) or on a projection screen (Experiment 2), and both the computer monitors and the projection screen were in a vertical orientation. Participants in both experiments were presented with twelve target displays that represented ID levels ranging from 1.00 to 6.50 bits. Following exposure to each target display, participants provided magnitude estimates that reflected the difficulty they perceived someone would experience in performing continuous target-to-target movements (with a computer mouse) for 15 s while being as fast and accurate as possible. The judgments were quantified using a magnitude estimation procedure, as in the research by Deliginières and colleagues; here, however, a modulus-free magnitude estimation procedure was used where neither a standard nor a modulus was provided to which participants could refer in making their judgments. Participants were told that there were no restrictions on the range of numbers that could be assigned. The only constraint on the number assignments was that the higher the number the participants provided, the greater their PD of task performance.

The main differences in the methods between the two experiments in Slifkin and Grilli (2006) were the scale of the target displays used and the method of presenting the target displays. In Experiment 1, participants viewed images of target displays presented through personal computer monitors. The target width was set at 0.51 cm for all ID levels, and the amplitude varied according to the formula for ID, $\log_2(2A/W)$. In Experiment 2, participants viewed similar target displays as in Experiment 1, but the size of the displays was scaled up by a factor of 7.5 and the images of the target displays were projected onto a large screen.

The results of the individual-participant and group data from both experiments showed a strong, positive PD-ID relation. In addition, the results of the group data from both experiments showed support for a linear PD-ID relation. (The only test on the form of the PD-ID relation was the fit of the group data to a linear function, however, and the authors noted that the trend actually appeared curvilinear.) Support for a positive, linear PD-ID relation in both experiments in Slifkin and Grilli (2006) suggests that Fitts's ID provides an index of subjective difficulty in prospective action.

Between-experiment analyses showed that participants provided very similar PD judgments. For example, when the average PD values across participants at each of the twelve ID levels were compared between experiments, the results showed no differences in the paired comparisons. The authors interpreted this finding to mean that the PD-ID relation can generalize to different movement environments and to different scaled versions of the target displays. Furthermore, the results suggested scale invariance for PD. The authors noted, however, that the close similarity in results between experiments might have been attributed simply to participants' number preferences. For example, Baird, Lewis, and Romer (1970) found that participants prefer numbers of one to ten in ratio estimation. Furthermore, the question remained whether the PD data would support scale invariance if a single group of participants evaluated performance difficulty for target displays representing the same ID level but different levels of scale. The authors suggested that future research test the scale invariance prediction for PD using a within-subjects design; this was accomplished by the current study.

1.4 Current study: A further investigation of PD in a Fitts task

The main goal of this study was to test whether Fitts's ID provides an index of subjective difficulty. In contrast to previous research on PD in a Fitts task, this study tested all three predictions for the PD-ID relation derived from Fitts's law: The predictions were of (a) a positive, (b) linear PD-ID relation and (c) scale invariance for PD. Although the effect of changes in scale on participants' PD was examined in Slifkin and Grilli (2006), the scale of the target displays was manipulated between experiments. In Deliginières and Famose (1992) and Deliginières and Brisswalter (1996), both the amplitude and width requirements varied among target displays, but each ID level was depicted by a single level of scale. A true test of scale invariance for PD would involve a group of participants evaluating performance difficulty for multiple target displays representing the same ID level but different levels of scale. This method was used in the current study. Testing for scale invariance using a within-subjects design provided a conclusive test of whether Fitts's ID provides an index of subjective difficulty.

In two experiments, participants provided judgments that reflected their PD of performance in a Fitts task. The judgments were in the form of magnitude estimates; the magnitude estimation procedure was the same as that used in Slifkin and Grilli (2006). Participants provided PD judgments for a wide range of target displays: The target displays represented ID levels ranging from 1.00 to 5.00 bits, and for each ID level, there were five target displays representing different scale levels. In Experiment 1, Scales 1 through 5 were represented by target widths of 0.25, 0.76, 1.27, 1.78, and 2.29 cm, respectively; in Experiment 2, Scales 1 through 5 were represented by target widths of

0.13, 0.38, 1.14, 1.91, and 2.16 cm, respectively. The variety of target display conditions allowed for a thorough test of the predictions for the PD-ID relation.

The main difference between the two experiments was the form of action that participants judged. Experiment 1 was designed as a follow-up experiment to Slifkin and Grilli (2006) to test the scale invariance prediction for PD using a within-subjects design. Because Experiment 1 was a follow-up experiment, participants judged the difficulty of prospective task performance as in Slifkin and Grilli (2006). Again, participants never actually performed the task, and so their judgments could not have been affected by feedback associated with actual performance (i.e., visual and kinesthetic feedback). Using prospective action provided an efficient method for collecting the judgments because participants did not actually perform the task and MTs were not collected; participants were simply instructed to view the target displays and to judge how difficult it would be to perform the task if someone were to actually perform it. In Experiment 2, in separate action conditions, participants judged the difficulty of imagined and actual task performance. Both PD judgments and MTs were collected in both action conditions. Collecting the PD judgments and MTs allowed a test of whether MT or ID was superior in predicting PD. In addition, the role of MT as a mediator of the relationship between PD and ID was examined. Overall, this study provided a detailed investigation of PD in a Fitts task.

The following sections describe the hypotheses addressed in this study.

1.4.1 Hypothesis 1: The characteristics of the MT-ID relation described by Fitts's law extend to the PD-ID relation. It was hypothesized that the characteristics of the MT-ID relation described by Fitts's law extend to the PD-ID relation in prospective, imagined, and actual action. There were three conditions to this hypothesis following from the three characteristics of Fitts's law. The three conditions were the same for all action conditions. First, the PD-ID relation should be positive in form: Increases in PD should correspond to increases in ID. Second, there should be support for a linear PD-ID relation. Third, there should be evidence of scale invariance for PD: The PD judgments should be similar for target displays depicting the same ID level but with different amplitude and width requirements. Finding support for all three conditions would indicate that Fitts's ID provides an index of subjective difficulty.

1.4.1.1 Hypothesis 1 and previous research on the PD-ID relation and Fitts's law. Research using a Fitts task to study PD has tested the first two conditions of this hypothesis in prospective (Slifkin & Grilli, 2006) and actual (Deliginières & Brisswalter, 1996; Deliginières & Famose, 1992) action. All of these studies found support for a positive PD-ID relation, which suggests that this result should also be found in the current study. In addition, all of these studies found some support for a linear PD-ID relation. In the studies by Deligniéres and colleagues, the data best fit an exponential function, but the results showed that a linear function provided a very good fit to the data. In Slifkin and Grilli (2006), the PD-ID relation appeared curvilinear, but, again, a linear function provided a very good fit to the data. Similar to this research, research on Fitts's law has found that the MT-ID relation is not always linear (Welford, 1968, chap. 5; Welford, Norris, & Shock, 1969). Researchers have even suggested revisions to the Fitts' law equation to account for the deviations from linearity (e.g., Welford, 1968, chap. 5; see Plamondon & Alimi, 1997, for review). Thus, although a strict application of the predictions for the PD-ID relation derived from Fitts's law would include finding support for a linear PD-ID relation without any evidence of non-linearity, finding at least some support for a linear PD-ID relation will be sufficient in this study.

1.4.1.2 Hypothesis 1 and previous research on the PD-MT relation and Fitts's law. Previous research on the PD-MT relation suggests that this study should find support for all three conditions of the hypothesis (Bratfisch, Dornič, and Borg's study, as cited in Borg, Bratfisch, & Dornič, 1971; Deliginières & Famose, 1992). As described, Deliginières and Famose (1992) found evidence that PD and MT are related in their study on PD in actual action using a Fitts task. A study by Bratfisch, Dornič, and Borg (as cited in Borg et al., 1971) on PD in actual action found a similar result. In that study, participants used sticks to transfer metal rings through a wire labyrinth, and following each of seven trials they provided magnitude estimates corresponding to the difficulty they experienced in task performance. The results showed a positive correlation between the time to complete the task and PD across trials. The results of the studies by Bratfisch, Dornič, and Borg (as cited in Borg et al., 1971) and Deliginières and Famose (1992) suggest that, in this study, participants' PD judgments will relate to MT.

Since research on Fitts's law in actual action shows a positive, linear MT-ID relation and scale invariance for MT (e.g., Fitts, 1954), if participants' PD judgments in actual action relate to their MTs, then the results should show a positive, linear PD-ID relation and scale invariance for PD in actual action. Research on Fitts's law in imagined action has tested and found support for a positive (Decety & Jeannerod, 1996; Sirigu et al., 1995; Sirigu et al., 1996), linear (Decety & Jeannerod, 1996; Sirigu et al., 1995) MT-ID relation. If the Fitts's law prediction of scale invariance for MT holds in imagined action, as it does in actual action, and if participants' PD judgments in imagined action relate to their MTs, then a positive, linear PD-ID relation and scale invariance for PD should also appear in imagined action. Similar findings would be expected in prospective action since prospective action is considered a form of imagined action (Jeannerod, 2003).

1.4.2 Hypotheses 2 and 3: MT is superior to ID in predicting PD and MT mediates the PD-ID relationship. Two additional hypotheses were tested in Experiment 2. First, it was hypothesized that, in both imagined and actual action, MT is superior to ID in predicting PD. Because participants were asked to evaluate the difficulty of task performance, it is assumed that their PD judgments related to their task performance, as did their MTs. Whereas participants' PD judgments and their MTs could have depended on task performance, the ID levels were static and independent of task performance. Because of the characteristics of the three variables, the relationship between PD and MT should be stronger than the relationship between PD and ID, and, therefore, MT should be superior to ID in predicting PD. Additional support for this hypothesis comes from research that shows a correlation between PD and MT in actual action (Bratfisch, Dornič, and Borg's study, as cited in Borg et al., 1971; Deliginières & Famose, 1992). Research also shows that judgments of imagined action correlate with imagined MTs (Parsons, 1994) and judgments of prospective action correlate with prospective judgment times (Johnson, 2000). Some researchers have even speculated that judgments of qualities of action are derived from temporal measures of action performance (Borg et al., 1971; Parsons, 1994). Because of the potential relationship between PD and MT, it was also hypothesized that, in both imagined and actual action, MT mediates the relationship between PD and ID. If the results support MT as a mediator, then this will indicate that MT accounts for the relationship between PD and ID.

CHAPTER II

EXPERIMENT 1

2.1 Method

2.1.1 Participants. Twenty individuals (13 females) with a mean age of 19.65 years (*SD* = 1.63) participated in this experiment. All participants were right-hand dominant and reported no prior history of neurological or psychiatric disorders. They were undergraduates from Cleveland State University and participated in this experiment for course credit. The request for participants was restricted to students enrolled in lower division courses to reduce the potential influence of previous instruction on the principles of psychophysics (viz., magnitude estimation) and/or motor control (viz., the speed-accuracy trade-off and Fitts's law). In addition, to limit age-related performance variability, the request was restricted to individuals in the age range of 17 to 22 years. Participants completed a pre-experiment questionnaire to ensure that they met these requirements. They provided informed consent approved by the local institutional review board.

2.1.2 Apparatus. The target displays were sheets of 27.94 cm × 43.18 cm white card stock. Printed on the target displays were two rectangular targets of equal size. Participants viewed the target displays in landscape orientation on the horizontal surface of a table with a height of 76.20 cm. A sheet of 91.44 cm^2 white poster board fixed to the surface of the tabletop served as a background for the target displays. Two small pieces of white cardboard glued to the upper portion of the poster board provided a reference for the positioning of the target displays. A lamp with a 20 W bulb provided illumination during the experiment.

2.1.3 Design. Each target display represented one of five ID levels: 1.00, 2.00, 3.00, 4.00, or 5.00 bits. For each ID level, there were five scale levels, one for each of the following target widths (Ws): 0.25, 0.76, 1.27, 1.78, and 2.29 cm. In Experiment 1, the scale levels are referred to as Scales 1 through 5 in order of increasing width. Since the target widths and ID levels were specified in advance of the amplitude (A) values, the amplitude between targets for each target display was determined by the formula for Fitts's ID, $\log_2(2A/W)$. Table 1 lists the amplitude and width values for the target displays as a function of ID and scale. This design yielded 25 unique target display conditions. The targets were always 13.97 cm in height.

Each participant viewed four separate series of the target displays, the first of which was practice. Each series consisted of a randomized presentation of the target displays and was approximately 11 min in duration ([15 s trial + 10 s intertrial interval] × 25 target display conditions). Participants were given a short break between series. Each experimental session was approximately 50 min in duration and included one or two participants. When there were two participants in a session, two sets of stimuli were used, one for each participant.

2.1.4 Instructions. Prior to experimentation, the experimenter delivered oral instructions. The initial part of the instructions involved introducing participants to the

Fitts task. While being shown a sample target display, participants were told that a common task in the study of motor control requires participants to tap a stylus back and forth between two targets while being as fast and accurate as possible. Accuracy was defined by the termination of a movement within a target region. The experimenter used the sample target display and the stylus to provide an example of both an accurate and an inaccurate target-to-target movement. Participants were told that an individual performing this task would generate the target-to-target movements during the entire time that the target display was in view and without any part of their arm resting on the tabletop.

After describing the Fitts task, the experimenter informed participants that they would view various target displays similar to the sample target display and would judge the difficulty that someone would experience in performing the continuous back-and-forth movements under speed-accuracy conditions. To maximize the implicit nature of the judgment process, participants were instructed to judge performance difficulty from a third-person perspective; that is, they were instructed to judge the difficulty that someone other than him- or herself would experience in performing the task. Participants were told that they would not be performing the task; during a trial, they were to view the target display and form a PD judgment. During the intertrial interval, they wrote their PD judgment for that trial in a memo book provided to them prior to the start of the experiment.

The instructions for the PD judgments were based on instructions for a modulus-free magnitude estimation procedure (Stevens, 1975, p. 30):

> The numerical values you assign to the target displays are up to you. You can assign whole numbers, whole numbers with decimals, just decimals, or even fractions. Choose values and a range of values that you feel comfortable working with; however, you do not want to come into the experiment with a rating scheme in mind. We will begin with a series of practice trials so that you can get a feel for the rating scheme you would like to use. When assigning values, you want to make sure that the higher the number you assign, the more difficult it would be for someone to perform the task, and, likewise, the lower the number you assign, the easier it would be for someone to perform the task.

Following these instructions was a detailed description of the trial events. At this time, participants were seated behind the table with the poster board, and they positioned their chairs so that their heads were aligned with the center of the poster board. Participants were told to place their hands on their laps and to refrain from moving while viewing the target displays; these instructions were intended to ensure that overt movement would not influence participants' PD judgments. During Series 1, the experimenter monitored participants' compliance with the instructions and corrected any observable deviations.

2.1.5 Procedure. Prior to the start of each series, a new stack of randomized target displays was placed face down on the tabletop to the right of the poster board. A tape-recorded sequence of cash register sounds (Microsoft Office Cashreg.wav) provided cues for the trial events. Each trial included two cash register sounds. The first cash register sound marked the start of a 15 s trial. Upon hearing this cue, participants turned over the top target display from the stack to their right and aligned the upper corners of the target display against the cardboard guides. The second cash register sound marked the start of a 10 s inter-trial interval. At this time, participants removed the target display in front of them and placed it face down on the tabletop to the left of the poster board, forming a pile of the target displays that they had viewed for that series. Then, they wrote their PD judgment for that target display on the first blank page in their memo book. They recorded each judgment on a separate page in the memo book. This sequence of events repeated until participants viewed all 25 target displays in the series.

2.1.6 Post-experiment questionnaire. Following the experiment, participants completed a questionnaire in which they responded to a variety of questions regarding their PD judgments and their understanding of the instructions for assigning the PD judgments. A participant was judged to have understood the instructions if their performance during the experiment and their responses in the post-experiment questionnaire agreed with the instructions. For example, if during the experiment, participants assigned higher numbers to target displays with greater distances between the targets, and in the post-experiment questionnaire, they provided responses that reflected such a relation, then it was determined that they followed the instruction to assign higher numbers to target displays that they associated with greater performance difficulty. Based on a review of the questionnaires, all of the participants understood the instructions and no participants were excluded from the analyses.

2.1.7 Assumptions, transformations, and analysis. Analysis of variance (ANOVA) provided the framework for the main analyses. Before conducting these analyses, the data were inspected to ensure that the assumptions of ANOVA were met. There was evidence that the assumptions of ANOVA were not met, and the data were transformed. (See Appendix for a description of the method used for evaluating the assumptions of ANOVA and selecting a data transformation.) The transformation selected for the main analyses, the maximum-value transformation, involved a linear transformation of the data. This transformation reduced the frequency of extreme positive scores and provided the least manipulation of the data from its original form compared to the other transformations considered, that is, logarithmic and reciprocal transformations.

The main analyses were based on a 3 (series) × 5 (ID) × 5 (scale) repeated measures ANOVA. Only the data from Series 2 through 4 were transformed and analyzed (Series 1 was treated as practice). Contrasts and Tukey's HSD post-hoc tests were applied as appropriate; details are provided in the Results and Discussion.

When ANOVA was performed, Mauchly's sphericity tests indicated that the assumption of sphericity was violated in all of the significance tests. The Greenhouse-Geisser correction, which adjusts the degree-of-freedom when there are violations of sphericity, was considered to compensate for the violations; however, since there were no differences in the outcomes of the significance tests with or without the Greenhouse-Geisser correction, the standard sphericity-assumed results are reported.

All statistical tests were evaluated at an alpha level of .05.

2.2 Results and Discussion

2.2.1 Series effects. The omnibus test for series was not significant, $F(2, 38) = 0.25$, $p = .78$, $MSE = 3.45$, which indicates that repeated exposure to the target displays did not have an overall effect on participants' PD. In addition, none of the interactions involving series was significant: ID × Series interaction, $F(8, 152) = 1.49$, $p = .17$, $MSE =$

0.98; Scale × Series interaction, $F(8, 152) = 0.47$, $p = .88$, $MSE = 1.31$; ID × Scale × Series interaction, $F(32, 608) = 1.18$, $p = .23$, $MSE = 0.77$.

2.2.2 The PD-ID relation. Table 2 shows the PD means and standard deviations for the target display conditions in prospective action. Figure 1 shows the mean PD values plotted as a function of ID for each scale level. Regression lines characterize the trends.

As illustrated in Figure 1, PD increased with increases in ID at each scale level. The slopes describing the regression lines supported this observation: All were positive and significantly different from zero (see Figure 1 caption for statistics). Contrasts were used to determine whether the overall PD-ID relation (i.e., when PD was collapsed across scale levels) and the PD-ID relations at the individual scale levels were linear. If the linear contrast but not the residual was significant, then the data were fully characterized by a linear trend. If both the linear contrast and residual were significant, then there was some support for a linear trend. The statistics are reported in Table 3.

Full support for a linear PD-ID relation was found at Scales 1 and 3 as the linear contrasts but not the residuals were significant. The remaining tests showed some support for a linear relation: Both the linear contrasts and residuals were significant for the PD-ID relations at Scales 2, 4, and 5 and for the overall PD-ID relation. The η^2 values associated with the linear contrasts for the overall PD-ID relation and the PD-ID relations at Scales 2 through 5 were large (η^2 ranged from .67 to .77), which indicates that the linear contrasts explained a substantial portion of the variability in PD that was associated with ID at those scale levels.

As seen in Figure 1, there were variations in the rates of change of PD as a function of ID among the scale levels, with the slopes of the regression lines increasing as the target display scale increased. A linear ID × graded Scale interaction contrast was performed to test this observation. The scale means served as the basis for the contrast weights for scale since there was an inverse relationship between the scale means and the slopes of the regression lines: As the target display scale increased, the scale means decreased (Table 2) and the slopes increased (Figure 1). The contrast weights were determined by centering the scale means around the grand mean, and then reversing the signs of the centered values; the contrast weights for Scales 1 through 5 were -3.50, -0.14, 0.90, 1.28, and 1.46, respectively. The contrast was significant, $F(1, 19) = 40.35$, $p < .001$, $MSE = 9.95$, $\eta^2 = .41$, as was the residual, $F(15, 285) = 1.93$, $p = .02$, $MSE = 2.36$. These results indicate that the slopes of the estimated linear PD-ID relations (or, in other words, the size of the linear contrasts) increased as the target display scale increased, but the pattern of means was not represented fully by the contrast weights. The finding of differences in the slopes of the PD-ID relations among scale levels suggested the presence of scale variance for PD.

2.2.3 Scale invariance and scale variance. According to Figure 1, the magnitude of the PD values varied with the scale of the target displays: Overall, PD appeared to be similar for Scales 3 through 5 and to increase with further decreases in scale. The omnibus test for scale confirmed the presence of scale variance for PD, $F(4, 76) = 95.01$, $p < .001$, $MSE = 13.27$, $\eta^2 = .83$. To estimate the source of the scale effect, Tukey's HSD post-hoc tests were applied to the PD data collapsed across ID. The tests revealed a significant increase in PD when scale decreased from Scale 2 to 1 (target width was 0.76 and 0.25 cm, respectively), (M_{Scale5} = 3.68, M_{Scale4} = 3.86, M_{Scale3} = 4.23, M_{Scale2} = 5.28) < M_{Scale1} = 8.63, D_{Tukey} = 3.22, *p*s < .05. Thus, changes in scale affected participants' PD such that when the target display scale became very small, participants' PD increased.

Although PD increased with decreases in scale, changes in scale appeared to have less of an effect on PD as ID increased (see Figure 1). To estimate more precisely where scale variance appeared, and to test whether it depended on ID, Tukey's HSD tests were applied at each ID level to test for differences in PD among the scale levels. The results are summarized in Table 2. In agreement with the tests for scale variance when PD was collapsed across ID, the Scale 1 mean was significantly greater than the means of the other four scale levels at all ID levels. In addition, depending on the ID level, the Scale 2 mean was significantly greater than the Scale 4 and 5 means: When IDs = 1.00 and 2.00 bits, it was greater than the Scale 4 and 5 means; when ID = 3.00 bits, it was greater than the Scale 5 mean; when IDs = 4.00 and 5.00 bits, it was not different from either the Scale 4 or 5 means. There were no differences in PD among Scales 3, 4, and 5 (target width was 1.27, 1.78, and 2.29 cm, respectively) at any ID level. Thus, when target width ranged from 1.27 to 2.29 cm, participants' PD did not vary significantly within an ID level. With further decreases in target width (from 1.27 to 0.76 to 0.25 cm), however, participants' PD increased, particularly at the lower ID levels.

2.2.4 Summary. The results of Experiment 1 showed that repeated exposure to the target displays did not significantly affect participants' PD in prospective action. Thus, even though each series was comprised of a randomized sequence of the 25 target displays, participants maintained a similar response pattern across the three series. This finding is in agreement with the results of Slifkin and Grilli's (2006) study on PD in prospective action. Studies using magnitude estimation procedures with sensory stimuli (e.g., where participants evaluate brightness of light) have also found that participants quickly settle on their judgments (Stevens, 1956, 1957).

As hypothesized, there was evidence of a positive PD-ID relation in prospective action. In addition, depending on the scale level, there was also support for a linear PD-ID relation in prospective action: For two of the five scale levels, the PD-ID relation was linear. Furthermore, as hypothesized, there was evidence of scale invariance for PD in prospective action: For example, performance difficulty was judged to be equal across the three largest scale levels, when target width ranged from 1.27 to 2.29 cm. Taken together, these results showed that the characteristics of Fitts's law extend to the PD-ID relation in prospective action.

The results showed that there are limitations in the extent that the characteristics of Fitts's law extend to the PD-ID relation in prospective action, however. First, although a linear function provided a good fit to the PD-ID relation for three of the five scale levels and the PD-ID relation overall, there was evidence that the trends were non-linear. These findings agree with the studies by Slifkin and Grilli (2006) and Deliginières and colleagues: Those studies found that although there was some support for a linear PD-ID relation, either the PD-ID relation appeared curvilinear (Slifkin & Grilli, 2006) or an exponential function provided a superior fit to the data (Deliginières & Brisswalter, 1996; Deliginières & Famose, 1992). Second, although there was evidence of scale invariance for PD there was also evidence of scale variance for PD: Overall, participants judged that performance difficulty increased when the target display scale became very small.

Furthermore, participants' PD judgments were affected by not only changes in ID and scale alone, but by changes in combinations of the two variables: As the target display scale increased, changes in ID had more of an effect on participants' PD. Furthermore, as ID increased, changes in the target display scale had less of an effect on participants' PD. As a result, the occurrence of scale variance decreased as ID increased. In summary, the results of Experiment 1 revealed that, within limits, Fitts's ID provides an index of subjective difficulty in prospective action.

2.2.5 Can imagined action explain the results? A potential explanation for the results of Experiment 1 is that participants formed their prospective action judgments by imagining task performance and their judgments were related to imagined MT. Three lines of research support this hypothesis. First, research shows that judging prospective action elicits imagined action processes (Johnson, 2000; Parsons, 1994; Parsons et al., 1995). Second, research shows that Fitts's law holds in imagined action: Research has tested and shown support for a positive (Decety & Jeannerod, 1996; Sirigu et al., 1995; Sirigu et al., 1996), linear (Decety & Jeannerod, 1996; Sirigu et al., 1995) MT-ID relation in imagined action. Third, research shows that PD judgments relate to MT (Bratfisch, Dornič, and Borg's study, as cited in Borg et al., 1971; Deliginières & Famose, 1992). The results of Experiment 1 are consistent with this hypothesis: The results showed that, within limits, there is a positive, linear PD-ID relation and scale invariance for PD, which would be expected if participants' PD judgments in prospective action were related to estimates of imagined MT. The finding of limitations to the predictions for the PD-ID relation might also agree with the hypothesis that participants' PD judgments were related to estimates of imagined MT. That is, there might also be evidence of deviations from a linear MT-ID relation and scale variance for MT in imagined action; in other words, there might also be limitations to Fitts's law in imagined action. Indeed, Fitts (1954) and subsequent researchers (e.g., Welford, 1968, chap. 5; Sheridan, 1979) have noted that there are limitations to Fitts's law in actual action when the amplitude and width requirements are extreme. If participants' PD judgments in this study were related to imagined MT, then the results would likely have reflected limitations to Fitts's law in imagined action.

The next experiment examined the PD-ID relation in imagined and actual action and the effect of actual task experience on PD. In addition, in both action conditions, ID and MT were compared as predictors of PD, and the role of MT as a mediator of the relationship between PD and ID was tested.

CHAPTER III

EXPERIMENT 2

3.1 Method

3.1.1 Participants. Forty-two individuals (26 females) with a mean age of 20.43 years (*SD* = 2.41) participated in this experiment. All participants were right-hand dominant, reported no prior history of neurological or psychiatric disorders, and met the age requirement of 18 to 26 years. (The age requirement was expanded from Experiment 1 to increase the possible pool of participants.) They were undergraduate students from Cleveland State University and participated in this experiment for course credit. Prior to experimentation, each participant provided informed consent approved by the local institutional review board. They also completed the pre-experiment questionnaire administered in Experiment 1.

3.1.2 Apparatus. The target displays were sheets of 27.94 cm × 43.18 cm white card stock. Printed on the target displays were two rectangular targets of equal size. Participants viewed the target displays in landscape orientation on the horizontal surface of a graphics tablet (Wacom Intuos2 30.48 cm × 45.72 cm Model) that rested on a table with a height of 90.81 cm. A lamp with a 13 W bulb provided illumination during the experiment.

In the actual action condition, the MTs were recorded through the graphics tablet, which was interfaced with a computer. Participants simply contacted the graphics tablet with a stylus (Wacom Grip Pen) when completing each movement. In the imagined action condition, the MTs were recorded through an external touchpad (Cirque Easy Cat 6.86 cm × 8.34 cm Model), which was also interfaced with the computer. The touchpad resembled one commonly found on laptop computers and consisted of two buttons and a touchpad surface. Only the left button was used for response recording. Each time participants imagined making a target contact, they pressed the left button with their right index finger. The touchpad rested on a 19.36 cm × 18.42 cm platform attached to the underside of the table supporting the graphics tablet. The platform was large enough that participants could rest their wrist during imagined performance.

3.1.3 Design. Each target display represented one of four ID levels: 1.00, 2.33, 3.67, or 5.00 bits. For each ID level, there were five scale levels, one for each of the following target widths (Ws): 0.13, 0.38, 1.14, 1.91, and 2.16 cm. As in Experiment 1, in this experiment, the scale levels are referred to as Scales 1 through 5 in order of increasing target width. Since the target widths and ID levels were specified in advance of the amplitude (A) values, the amplitude between targets for each target display was determined by the formula for Fitts's ID, $\log_2(2A/W)$. Table 1 lists the amplitude and width values for the target displays as a function of ID and scale. This design yielded 20 unique target display conditions. The targets were always 13.97 cm in height.

All participants participated in both the imagined and actual action conditions. They judged performance difficulty in both conditions. The order of action conditions was counterbalanced across participants: Half of the participants performed the imagined trials first. There were three series of target displays in both action conditions. Each series consisted of a randomized presentation of the target displays and was 10 min in duration ([15 s trial + 15 s intertrial interval] × 20 target display conditions). Participants were given a 2-min break between series and a 10-min break between action conditions. Each experimental session was approximately 120 min in duration and involved a single participant.

3.1.4 Instructions. Prior to the start of an action condition, the experimenter provided oral instructions specific to that condition. There were two sets of instructions, one for each action condition. The first set of instructions began with a description of the Fitts task and a brief demonstration of the Fitts task using a sample target display and the stylus. Then, the instructions for the respective action task were delivered, followed by the instructions for the PD judgments, and then a description of the trial events. Instructions for the PD judgments were included in both sets of instructions. Participants were informed of a second action condition only after they performed in the first action condition.

3.1.4.1 Imagined action. In the imagined action condition, participants were told that they would be viewing target displays and would imagine task performance rather than actually perform the task. They were told to imagine generating back-and-forth movements with the stylus during the entire time a target display was in view. They were to imagine performing the movements under speed-accuracy conditions (i.e., to generate target contacts while being as fast and as accurate as possible) and without any part of their arm resting on the graphics tablet. The experimenter emphasized that participants' imagined performance should be as close as possible to how they would actually perform.

Participants were told to have their right index finger resting on the left button of the touchpad at the start of each trial. They were to begin each trial by imagining moving the stylus to the left target. As soon as they imagined making a target contact, they were to press the left button on the touchpad. Participants pressed the button when completing each imagined movement. They were instructed to press their finger directly down on the button, as opposed to moving their finger from side-to-side. The experimenter demonstrated this procedure using the space bar on the computer keyboard. During the trial and intertrial interval, participants were permitted to rest their hand on the platform with the touchpad.

3.1.4.2 Actual action. In the actual action condition, participants were told that they would be actually performing the task. During each trial, they would generate the back-and-forth movements with the stylus under speed-accuracy conditions and without any part of their arm resting on the graphics tablet. They were to begin each trial by moving the stylus to the left target. They were to complete each movement by contacting the graphics tablet with the stylus. During the intertrial interval, participants rested with the stylus in hand and their arm by their side or in their lap.

3.1.4.3 PD judgments. As in Experiment 1, the instructions for the PD judgments were adapted from Stevens (1975, p. 30). There were three main distinctions in the instructions between Experiments 1 and 2. First, participants in this experiment were asked to engage in either imagined or actual task performance. In contrast, in Experiment 1, instructions for movement were not provided. Second, participants in this experiment were asked to evaluate the difficulty that they experienced in task performance (first-person perspective) rather than the difficulty that someone else would experience if actually performing the task (third-person perspective; Experiment 1). Third, participants in this experiment orally reported their PD judgments and the experimenter recorded their judgments on paper. Participants in Experiment 2 were not tasked with recording their judgments so that they had extra time to prepare for the upcoming trials. In contrast, participants in Experiment 1 recorded their judgments in a memo book.

3.1.5 Procedure. Prior to experimentation, the experimenter placed six stacks of target displays (one per action condition and series) face down on a desk behind the participant. A sequence of cash register sounds (Microsoft Office Cashreg.wav) that emitted from the computer speakers provided cues for the trial events. Each trial included two cash register sounds. The first cash register sound marked the start of a 15 s trial; the second marked the start of a 15 s intertrial interval. At the start of the intertrial interval, participants reported their PD judgment for the target display in view. The experimenter recorded the PD judgment on paper, and then removed the target display from the graphics tablet and replaced it with a new target display. This sequence of events repeated until all 20 target displays were presented for the series. Following the experiment, participants completed a post-experiment questionnaire similar to that used in Experiment 1.

Two participants were excluded from the data analyses. One participant was excluded due to a lack of understanding of the task instructions: In the post-experiment questionnaire, this participant indicated that she ignored the instructions for accuracy in the actual action condition. A second participant was excluded due to technical problems with the MT collection. As a result of these exclusions, 20 participants (12 females) remained in each group.

3.1.6 Assumptions, transformations, and analysis. To minimize the likelihood that the data would violate the assumptions of parametric tests, and to be consistent with the method of data handling used in Experiment 1, the PD and MT^2 data were submitted to the maximum-value transformation used in Experiment 1 (see Appendix for details). The measure of central tendency used to define the common upper limit for the MT data was different from measure of central tendency used for the PD data because the maximum values of MT were unique among participants; for MT, the common upper limit was the mean, rather than the mode, of the maximum values from the participants' distributions. Again, Series 1 was treated as practice; only the PD and MT data from Series 2 and 3 were transformed and analyzed.

ANOVA provided the basis for examining the effect of the independent variables on PD. The PD data were analyzed in a 2 × 2 × 4 × 5 mixed design ANOVA in which order (imagined-actual, actual-imagined) served as a between-subjects factor and action condition (imagined, actual), ID (1.00, 2.33, 3.67, and 5.00 bits), and scale (1, 2, 3, 4, and 5) served as within-subjects factors. Series was not included in the ANOVA design; prior to submitting the data to ANOVA, but following transformation of the data, each participant's data were averaged across Series 2 and 3. Contrasts and Tukey's HSD post-hoc tests were applied as appropriate; details are provided in the Results and Discussion.

When ANOVA was performed, Mauchly's sphericity tests indicated that the assumption of sphericity was violated in all of the significance tests. As in Experiment 1, the Greenhouse-Geisser correction was considered to compensate for these violations. There were no differences in the outcomes of the significance tests with or without applying the Greenhouse-Geisser correction; thus, the standard sphericity-assumed results are reported.

In addition to ANOVA, multiple regression analyses were performed. For each participant and each action condition, regression was used to determine (a) whether MT or ID was the superior predictor of PD and (b) whether MT mediated the relationship between PD and ID. Each participant's transformed, unaveraged PD and MT data from Series 2 and 3 were submitted to regression. The data from imagined and actual action were analyzed separately. In the main regression model (Model 3), PD was regressed on ID and MT for each participant using standard regression. The number of participant regressions where MT was the superior predictor was compared to the number of participant regressions where ID was the superior predictor. A predictor was considered superior if it was the only significant predictor in regression or if both predictors were significant but the one predictor carried a greater β weight. In addition, paired *t* tests were used to determine whether there was a significant difference between predictors in the average magnitude of the squared semi-partial correlations (sr^2s). A significant difference favoring a predictor would indicate that, on average among participants, that predictor accounted for more unique variance in PD than did the other predictor.

The mediation analyses followed Baron and Kenny's (1986) procedure for assessing mediation. Two additional regression models were run on each participant's data: In one model, MT was regressed on ID (Model 1); in the other model, PD was regressed on ID (Model 2). In Model 3, the model described in the previous paragraph, PD was regressed on ID and MT. According to Baron and Kenny (1986), four criteria determined partial mediation: (a) if ID had a significant effect on MT in Model 1; (b) if

ID had a significant effect on PD in Model 2; (c) if MT had a significant effect on PD in Model 3; and (d) if the effect of ID on PD was less in Model 3 than in Model 2. Complete mediation occurred if ID had a significant effect on PD in Model 2 but not in Model 3.

All statistical tests were evaluated at an alpha level of .05.

3.2 Results and Discussion

3.2.1 Order effects. The omnibus test for order was not significant, $F(1, 38) = 0.02$, $p = .90$, $MSE = 42.50$, which indicates that the order in which participants performed the action conditions did not have an overall effect on participants' PD. In addition, none of the interactions involving order was significant: Order × Action Condition interaction, $F(1, 38) = 0.12$, $p = .73$, $MSE = 15.91$, Order × ID interaction, $F(3, 114) = 0.44$, $p = .73$, $MSE = 3.91$, Order × Scale interaction, $F(4, 152) = 0.32$, $p = .86$, $MSE = 5.62$, Order × Action Condition × ID interaction $F(3, 114) = 1.03$, $p = .38$, $MSE = 1.33$, Order × Action Condition × Scale interaction $F(4, 152) = 2.33$, $p = .06$, $MSE = 1.60$, Order × ID × Scale interaction $F(12, 456) = 1.09$, $p = .36$, $MSE = 0.63$, Order × Action Condition × ID × Scale interaction $F(12, 456) = 1.01$, $p = .44$, $MSE = 0.50$.

3.2.2 Action condition effects. Table 4 shows the PD means and standard deviations for the target display conditions in imagined and actual action. Figures 2 and 3 show the mean PD values plotted as a function of ID for each scale level in imagined and actual action, respectively. Regression lines characterize the trends.

At the broadest level, there was not a difference in PD between imagined and actual action, $F(1, 38) = 0.002$, $p = .97$, $MSE = 15.91$. Conversely, all of the interactions involving action condition were significant: Action condition influenced changes in PD as a function of ID, $F(3, 114) = 4.77$, $p = .004$, $MSE = 1.33$, and changes in PD as a function of scale, $F(4, 152) = 5.39$, $p < .001$, $MSE = 1.60$, and there were between-condition differences in the PD-ID relations as a function of scale, $F(12, 456) = 2.70$, $p = .002$, $MSE = 0.50$. Although all of the interactions involving action condition were significant, the overall pattern of results appeared very similar between imagined and actual action (cf. Figures 2 and 3). Furthermore, when PD was compared between action conditions at each of the 20 target display conditions, differences between action conditions were only observed for four target display conditions: At Scale 2 when ID = 1.00 bit and at Scales 3, 4, and 5 when ID = 2.33 bits (see Table 5). Because there was evidence of differences in PD between action conditions, however, PD was examined separately for imagined and actual action in the remaining analyses.

3.2.3 The PD-ID relation. As illustrated in Figures 2 and 3, PD increased with increases in ID at each scale level in both action conditions. The slopes describing the regression lines supported this observation: All were positive and all but the slope associated with Scale 1 were significantly different from zero (see Figures 2 and 3 captions for statistics). Contrasts were performed to determine whether the overall PD-ID relation (i.e., when PD was collapsed across scale levels) and the PD-ID relations at the individual scale levels were linear. If the linear contrast but not the residual was significant, then the data were fully characterized by a linear trend. If both the linear contrast and residual were significant, then there was some support for a linear trend. The statistics are reported in Table 6 for both action conditions.

For imagined action, there was strong support for a linear PD-ID relation: At Scales 2 through 5, the data were fully characterized by a linear trend, and for the overall PD-ID relation, there was some support for a linear trend. For the overall PD-ID relation and the PD-ID relations at Scales 3 through 5, the η^2 values associated with the linear contrasts were large (η^2 ranged from .60 to .68), which indicates that the linear contrasts accounted for a substantial proportion of the variability in PD at these scale levels. For actual action, only the data at Scale 2 were fully characterized by a linear trend. For the overall PD-ID relation and the PD-ID relations at Scales 3 through 5, there was some support for a linear trend. Except at Scale 1, all of the η^2 values associated with the linear contrasts were large (η^2 ranged from .50 to.72). For both imagined and actual action, the linear contrast at Scale 1 was not significant. This finding agrees with the results when the group PD data were regressed on ID; in both action conditions, the slopes for Scale 1 were not significantly different from zero (see Figures 2 and 3 captions).

As seen in Figures 2 and 3, in both action conditions, the slopes of the regression lines increased as the target display scale increased. Linear ID $\times$ graded Scale interaction contrasts were performed to test this observation. As in Experiment 1, the slope values had an inverse relationship with the scale means: As the target display scale increased, the scale means decreased (Table 4) and the slopes of the PD-ID relations increased (Figures 2 and 3). The contrast weights representing scale were derived the same way as in Experiment 1: the scale means were centered around the grand mean and then the signs of the centered values were reversed. For imagined action, the contrast weights for Scales 1 through 5 were -2.95, -0.61, 0.90, 1.34, and 1.31, respectively; for actual action, they were -3.53, -0.45, 1.04, 1.47, and 1.48, respectively. For imagined action, there was evidence that the slopes of the estimated linear PD-ID relations increased as the target display scale increased, $F(1, 38) = 116.75$, $p < .001$, $MSE = 1.23$, although the pattern of means was not represented fully by the contrast weights, residual, $F(11, 418) = 2.30$, $p <$

.01, *MSE* = 0.45. For actual action, there was also evidence that the slopes of the estimated linear PD-ID relations increased as the target display scale increased, $F(1, 38) = 176.04$, $p < .001$, *MSE* = 1.17, but, here, the contrast weights fully supported the data, residual, $F(11, 418) = 0.45$, $p = .66$, *MSE* = 0.57. The results of the linear ID $\times$ graded Scale interaction contrasts suggested the presence of scale variance for PD in both action conditions.

3.2.4 Scale invariance and scale variance. According to Figures 2 and 3, in both action conditions, the magnitude of the PD values varied with the scale of the target displays: Overall, PD appeared to be similar for Scales 3 through 5 and to increase with further decreases in scale. The omnibus tests for scale confirmed the presence of scale variance for PD in imagined and actual action, $F(4, 152) = 137.76$, $p < .001$, *MSE* = 3.88 and $F(4, 152) = 216.78$, $p < .001$, *MSE* = 3.34, respectively. To estimate the source of the scale effects, Tukey's HSD post-hoc tests were applied to the PD data collapsed across ID for each action condition. For imagined action, the tests revealed a significant increase in PD with each incremental decrease in scale from Scales 3 to 1 (target width was 1.14, 0.38, and 0.13 cm, respectively), ($M_{scale5} = 3.17$, $M_{scale4} = 3.14$, $M_{scale3} = 3.58$) < $M_{scale2} = 5.09 < M_{scale1} = 7.43$, $D_{Tukey} = 1.20$, *p*s < .05. The same pattern of differences among means was revealed for actual action, ($M_{scale5} = 3.00$, $M_{scale4} = 3.01$, $M_{scale3} = 3.44$) < $M_{scale2} = 4.93 < M_{scale1} = 8.01$, $D_{Tukey} = 1.12$, *p*s < .05.

In imagined and actual action, although PD decreased with increases in scale, changes in scale appeared to have less of an effect on PD as ID increased (see Figures 2 and 3). In both action conditions, to estimate more precisely where scale variance occurred, and to test whether it depended on ID, Tukey's HSD post-hoc tests were applied at each ID level to test for differences in PD among the scale levels. The results are summarized in Table 4. The results of these tests were in complete agreement with the tests when the PD data were collapsed across ID: At each ID level, differences among means were found at Scale 1 versus the other scale levels and at Scale 2 versus the other scale levels. This pattern of results appeared in both action conditions. In addition, in both action conditions, there were no differences in PD at any ID level among Scales 3, 4, and 5 (target width was 1.14, 1.91, and 2.16 cm, respectively). Given that in both action conditions the same pattern of scale variance was found at all ID levels, the post-hoc tests were not sensitive to the ID $\times$ Scale interactions revealed by the interaction contrasts.

3.2.5 Summary of ANOVA results. As hypothesized, there was evidence of a positive PD-ID relation in imagined and actual action. In addition, depending on the scale level, there was also support for a linear PD-ID relation in imagined and actual action: For four of the five scale levels in imagined action and one of the five scale levels in actual action, the PD-ID relation was linear. Furthermore, as hypothesized, there was evidence of scale invariance for PD in imagined and actual action: Performance difficulty was judged to be equal across the three largest scale levels when target width ranged from 1.14 to 2.16 cm. Taken together, these results show that the characteristics of Fitts's law extend to the PD-ID relation in imagined and actual action.

The results of Experiment 2 showed that there are limitations in the extent that the characteristics of Fitts's law extend to the PD-ID relation in imagined and actual action, however. First, there was evidence in both action conditions that some of the PD-ID relations were non-linear. In actual action, although a linear function provided a good fit to the PD-ID relation for three of the five scale levels, there was evidence that the trends were non-linear. In both action conditions, there was evidence that the trends for the overall PD-ID relation were non-linear although a linear function provided a good fit to the data. In addition, in both action conditions, there was no evidence that a linear function fit the data for the smallest scale level. These findings agree with the research by Slifkin and Grilli (2006) and Deliginières and colleagues: These studies found that although there was some support for a linear PD-ID relation, either the PD-ID relation appeared curvilinear (Slifkin & Grilli, 2006) or an exponential function provided a superior fit to the data (Deliginières & Brisswalter, 1996; Deliginières & Famose, 1992). Second, although there was evidence of scale invariance for PD there was also evidence of scale variance: Overall, participants judged that performance difficulty increased when the target display scale became very small. Furthermore, participants' PD judgments were affected by not only changes in ID and scale alone, but by changes in the combinations of the two variables: As the target display scale decreased, changes in ID had less of an effect on participants' PD. In addition, as ID increased, changes in scale appeared to have less of an effect on participants' PD. Indeed, there was a significant interaction between ID and scale; however, post-hoc tests did not reveal evidence differences in the occurrence of scale variance among the ID levels. In summary, the results of Experiment 2 revealed that, within limits, Fitts's ID provides an index of subjective difficulty in imagined and actual action.

There was evidence of differences in PD between imagined and actual action; yet, participants' PD judgments were very similar between action conditions. First, the same pattern of results for PD was found in imagined and actual action: There was evidence of a positive, linear or non-linear PD-ID relation and scale invariance and scale variance for PD in both action conditions. Second, the boundaries of scale invariance and scale variance were the same between action conditions. Third, there were differences in PD between imagined and actual action for only four of the 20 target displays. Thus, it appears that participants use similar information in evaluating performance difficulty when the judgments are of imagined or actual performance. An additional finding was that the order of action conditions did not significantly affect PD. Thus, differences in PD between action conditions were not due to the order in which participants performed in the action conditions.

3.2.6 Regression analyses. The statistics from the regression analyses are provided in Tables 7 and 8 for imagined and actual action, respectively.

In the main regression model (Model 3), for both action conditions, PD was regressed on ID and MT and these variables were compared as predictors of PD. In imagined action, MT was the superior predictor for three-quarters of participants (30 of 40 participants): For 23 participants, MT was the only significant predictor of PD, and for seven participants, both MT and ID were both significant predictors of PD, but MT carried the greater β weight. For the remaining participants, the results did not support MT as the superior predictor: For three participants, ID was the only significant predictor of PD; for one participant, MT and ID were both significant predictors of PD, but ID carried the greater β weight; and for six participants, neither MT nor ID was a significant predictor of PD. Although MT was not always the superior predictor of PD, it was a significant predictor of PD for most participants (31 of 40 participants). In other words, for those 31 participants, MT accounted for a significant amount of variance in PD beyond the variance accounted for by ID. The comparison of the magnitudes of the sr^2 values between predictors reinforced the superior effect of MT on PD: On average, among participants, MT uniquely accounted for 29% of the variance in PD (*SD* = .25) whereas ID uniquely accounted for 5% of the variance in PD (*SD* = .06), $t(39) = 5.91$, $p < .001$, $d = 1.29$.

In actual action, MT was the superior predictor for just over half of participants (21 of 40 participants): For nine participants, MT was the only significant predictor of PD, and for 12 participants, both MT and ID were significant predictors of PD, but MT carried the greater β weight. For the remaining participants, the results did not support MT as the superior predictor: For three participants, ID was the only significant predictor of PD; for three participants, MT and ID were both significant predictors of PD, but ID carried the greater β weight; and for 13 participants, neither MT nor ID were significant predictors of PD. As in imagined action, although MT was not always the superior predictor of PD, it was a significant predictor of PD for most participants (24 of 40 participants). Again, the comparison of the magnitudes of the sr^2 values between predictors reinforced the superior effect of MT on PD: On average, among participants, MT uniquely accounted for 21% of the variance in PD (*SD* = .22) whereas ID uniquely accounted for 10% of the variance in PD (*SD* = .12), $t(39) = 3.67$, $p = .001$, $d = 0.53$.

A final regression analysis tested whether MT mediated the relationship between ID and PD. For this analysis, two additional regression models were run: In one model, MT was regressed on ID (Model 1); in the other model, PD was regressed on ID (Model 2). According to the guidelines for determining mediation described in the Method, the criteria for complete mediation was met by 37.5% of participants in imagined action and

22.5% of participants in actual action. Including participants whose data supported partial mediation, there was evidence that MT mediated the relationship between ID and PD for 45.0% of participants in imagined action and 30.0% of participants in actual action.

3.2.7 Summary of regression results. For most participants in imagined and actual action, the results supported the hypothesis that MT is superior to ID in predicting PD: For three-quarters of participants in imagined action and just over half of participants in actual action, MT was the superior predictor of PD. For these participants, either MT was the only significant predictor of PD or both MT and ID were significant predictors, but MT was determined to be the superior predictor when comparing the sizes of the β weights between predictors. For the remaining participants, the results fell into one of three categories: (a) ID was the only significant predictor; (b) both MT and ID were significant predictors, but ID was determined to be the superior predictor when comparing the sizes β weights between predictors; or (c) neither MT nor ID were significant predictors. Further support for MT as the superior predictor was found in both action conditions when the sr^2 values from the participants' regressions were compared between predictors: In both action conditions, MT, on average, accounted for more unique variance in PD than did ID.

For many, but not most, participants in imagined and actual action, the results supported the hypothesis that MT mediates the relationship between PD and ID: The data for nearly half of participants in imagined action and nearly a third of participants in actual action supported MT as a mediator. Thus, for the participants whose data supported MT as a mediator, when PD was regressed on ID, changes in ID had an effect on participants' PD, but when MT was added to the regression model, the effect of ID on

PD was either reduced (partial mediation) or eliminated (complete mediation). In other words, where there was evidence for MT as a mediator, the relationship between PD and ID was at least partly attributed to the influence of MT.

There were differences between action conditions in the results of the regression analyses. For one, there was greater support for MT as the superior predictor of PD in imagined as compared to actual action. For example, MT was more frequently the superior predictor of PD among participants in imagined as compared to actual action: The data supported MT as the superior predictor for three-quarters of participants in imagined action versus about half of participants in actual action. In addition, when the sr^2 values were compared between MT and ID, the effect size was over twice as large in imagined than actual action. Support for MT as a mediator was also greater in imagined action: The data supported MT as a mediator for almost half of participants in imagined action versus almost a third of participants in actual action.

The implications of the regression results are discussed in the General Discussion.

CHAPTER IV

GENERAL DISCUSSION

4.1 The characteristics of the Fitts's law relation extend to the PD-ID relation

Research on Fitts's law has established that Fitts's Index of Difficulty (ID) provides an index of objective difficulty: Within limits, there is a positive, linear relationship between MT and ID, and for conditions where the ID is constant but scale varies, MTs are similar (i.e., scale invariance for MT). The main goal of this study was to test whether Fitts's ID provides an index of subjective difficulty. It was hypothesized that the characteristics of the MT-ID relation described by Fitts's law extend to the PD-ID relation. There were three conditions to this hypothesis following from the three characteristics of Fitts's law: It was predicted that the results would show evidence of (a) a positive, (b) linear PD-ID relation and (c) scale invariance for PD. These predictions were tested in prospective (Experiment 1), imagined (Experiment 2), and actual (Experiment 2) action using a Fitts task. There were 25 and 20 unique target display conditions in Experiments 1 and 2, respectively. In Experiment 1, there were five ID levels ranging from 1.00 to 5.00 bits and five scale levels, Scales 1 to 5, represented by target widths of 0.25, 0.76, 1.27, 1.78, and 2.29 cm, respectively; in Experiment 2, there were four ID levels ranging from 1.00 to 5.00 bits and five scale levels, Scales 1 to 5, represented by target widths of 0.13, 0.38, 1.14, 1.91, and 2.16 cm, respectively. Using a variety of action conditions and target display conditions allowed for a thorough test of the predictions.

The results of this study showed support for the hypothesis that the characteristics of the MT-ID relation described by Fitts's law extend to the PD-ID relation in prospective, imagined, and actual action. First, there was evidence of a positive PD-ID relation at all scale levels in all action conditions: Participants perceived increases in performance difficulty as ID increased at all scale levels in prospective, imagined, and actual action. Second, there was evidence of a linear PD-ID relation in all action conditions: A linear function completely described the form of the PD-ID relation for two of five scale levels in prospective action, four of five scale levels in imagined action, and one scale level in actual action. For many of the remaining scale levels in each action condition, a linear function provided a very good although not complete fit to the data. Third, there was evidence of scale invariance for PD in all action conditions: For example, within each ID level, participants judged that performance difficulty was equal across the three largest scale levels in prospective, imagined, and actual action. Thus, there was scale invariance for PD in prospective action when the target width ranged from 1.27 to 2.29 cm and in imagined and actual action when the target width ranged from 1.14 to 2.16 cm. This was the case across the range of IDs used in this study (1.00 to 5.00 bits).

4.2 Limitations in the extent that the characteristics of the Fitts's law relation extend to the PD-ID relation

There were limitations in the extent that the results of this study supported the predictions for the PD-ID relation. One limitation was mixed support for a linear PD-ID relation in all action conditions. For example, in prospective action, although a linear function provided a good fit to the data for three of the five scale levels and for the overall PD-ID relation (when PD was collapsed across scale levels), there was evidence that these trends were non-linear. Likewise, in actual action, although a linear function provided a good fit to the data for three of the five scale levels, there was evidence that these trends were non-linear. Furthermore, in both imagined and actual action, there was evidence that the trends for the overall PD-ID relation were non-linear even though a linear function provided a good fit to the data, and there was no evidence that a linear function fit the data for the smallest scale level.

A second limitation was evidence of scale variance for PD in all action conditions: In prospective, imagined, and actual action, participants perceived an increase in performance difficulty when the target display scale became small. The effect of changes in scale on participants' PD was not consistent across the ID range, however. Participants perceived the greatest differences in PD among scale levels at the lower ID levels, and as ID increased, the effect of changes in scale on participants' PD appeared to reduce. This pattern of results was observed in all action conditions, but was only significant in prospective action. In addition, the effect of changes in ID on PD was not consistent across scale levels: Changes in ID had less of an effect on participants' PD as scale decreased. That is, the slopes of the PD-ID relations decreased as the target display scale decreased. Because the target width was static within a scale level, the results imply that increases in the amplitude between targets had less of an effect on participants' PD as the target display scale decreased. This was the case in all action conditions.

The limitations in the extent that the results supported the predictions for the PD-ID relation are consistent with the limitations of Fitts's law. Fitts (1954) pointed out that performance might decline when the amplitude and width requirements fall outside a central range. That is, MT may increase when the target width and/or amplitude requirements are very small or very large. This could result in a non-linear MT-ID relation or scale variance for MT. For example, when the data from Experiment 1 of Fitts (1954) were fit to a linear function (Schmidt & Lee, 1999, p. 174), MTs were greater than predicted at the lower end of the ID range where the amplitude and width requirements were very small, and, as a result, the MT-ID relation appeared non-linear. Deviations from linearity have been observed in other studies on Fitts's law (Welford, 1968, chap. 5; Welford, Norris, & Shock, 1969). Researchers have suggested revisions to the Fitts's law equation, in part, to better account for the non-linearity in the MT-ID relation (e.g., Welford, 1968, chap. 5; see Plamondon & Alimi, 1997, for review). With regard to the potential for scale variance for MT, Sheridan (1979) found in analyzing the data from Experiment 1 of Fitts (1954) that there was a trend for MTs to increase within an ID level as the target width became very narrow or the amplitude became very large. The trend was slight in magnitude; however, it suggests that scale variance may appear when the target display conditions are extreme.

In summary, similar to the research on Fitts's law that shows limitations to the predictions for the MT-ID relation, this study revealed that there are limitations to the predictions for the PD-ID relation. Both lines of research have found evidence of non-linearity and scale variance. The similar findings between the two lines of research suggest that there is a relationship between PD and MT; this was confirmed in Experiment 2 for imagined and actual action.

4.3 Previous research on the PD-ID relation and the current results

The findings of a positive, linear PD-ID relation in prospective, imagined, and actual action are consistent with the findings from previous research that has used a Fitts task to examine PD in actual (Deliginières & Brisswalter, 1996; Deliginières & Famose, 1992) and prospective (Slifkin & Grilli, 2006) action. Evidence of a non-linear PD-ID relation for some of the scale levels used in this study agrees with the research by Deliginières and colleagues: In both studies by Deliginières and colleagues, for both the individual-participant and group data, although there was some support for a linear PD-ID relation, an exponential function provided the best fit to the data. Similarly, Slifkin and Grilli (2006) noted that although the PD-ID relation representing the group data was well described by a linear function, the trend appeared curvilinear.

4.4 Interpreting the results of the PD-ID relation

Fitts's law research shows that Fitts's ID provides an index of objective difficulty: There is a positive, linear MT-ID relation and scale invariance for MT. Similarly, the results of this study showed evidence of a positive, linear PD-ID relation and scale invariance for PD. Thus, Fitts's ID also provides an index of subjective difficulty. This means that the scope of the label the "Index of Difficulty" includes both objective and subjective assessments of performance. Furthermore, both objective and subjective assessments of performance are influenced by similar information from the movement environment, that is, the information constraints as defined by ID.

There are limitations in the extent that Fitts's ID provides an index of subjective difficulty, however. As with the limitations to Fitts's law (e.g., Fitts, 1954), these limitations appear when the amplitude and/or width requirements of the target displays are extreme. For example, in all action conditions, participants judged that performance difficulty was greater for target displays characterized by narrow as compared to wide target widths. Thus, participants judged that performance difficulty was greater for target displays characterized by smaller scale levels as compared to larger scale levels. This was the case at all ID levels, but particularly at the lower ID levels. At the lower ID levels, the smaller scale levels would have been characterized by not only high accuracy constraints because the target width was very narrow, but also high spatial constraints because the amplitude between targets was very small. Thus, changes in scale had the greatest effect on participants' PD when both the accuracy and spatial constraints were high.

Examining the effect of changes in scale on PD allowed a test of whether changes in the combinations of the amplitude and width requirements characterizing an ID level, not just the amplitude or width requirements alone, influenced PD. The results of this study showed that participants considered neither the amplitude nor the width requirements alone in their judgment process. For example, each of the 25 or 20 target displays in Experiments 1 and 2, respectively, had a unique amplitude requirement. Had participants scaled their PD judgments to just the magnitude of the amplitudes, with, for example, PD increasing with increases in the amplitude between targets, then scale variance would have likely emerged across all scale levels at each ID level and scale variance would have increased rather than decreased with increases in ID. If participants had only considered target width in determining their PD judgments, with, for example, PD increasing with decreases in the size of the target width, then changes in ID would not have affected participants' PD and there would not have been a positive PD-ID relation at any of the scale levels. Finding evidence of scale invariance at any of the ID levels would have also been unlikely. Thus, changes in amplitude and width requirements together influenced participants' PD.

Still, the finding of scale variance under the smaller scale levels discounts the possibility that participants associated performance difficulty with simply the amplitude-to-width ratios of the target displays. That is, the amplitude-to-width ratios increased exponentially with increases in ID and changes in the amplitude-to-width ratios were constant among scale levels. Thus, if this had been the case, then scale invariance would have appeared across all scale levels and the PD-ID relations for all of the scale levels would have clearly appeared exponential rather than linear in form. The finding of scale variance under the smaller scale levels also discounts the possibility that participants based their PD judgments on knowledge of Fitts's law. That is, if participants had knowledge of Fitts's law, then they would have known that increasing the amplitude-to-width ratios would result in an increase in MT and equal amplitude-to-width ratios would correspond to equal MTs. If participants had then equated performance difficulty with the magnitude of the amplitude-to-width ratios or with values of ID, then there would have been no evidence of scale variance for PD or deviations from a linear PD-ID relation. In conclusion, participants' PD judgments were influenced by, but were not based on, the information constraints of the action as defined by ID.

4.5 MT is superior to ID in predicting PD and mediates the PD-ID relationship

In Experiment 2, in both imagined and actual action, MTs were collected in addition to the PD judgments. Two additional hypotheses were addressed. First, it was hypothesized that, in both imagined and actual action, MT is superior to ID in predicting PD. To test this hypothesis, MT and ID were compared as predictors of PD in both action conditions for each participant. For most participants, in both action conditions, the results supported the hypothesis: MT was the superior predictor for three-quarters of participants in imagined action and just over half of participants in actual action. Furthermore, MT, on average, explained more unique variance in PD than did ID. Second, it was hypothesized that, in both imagined and actual action, MT mediates the relationship between PD and ID. In both action conditions, the results provided some support for this hypothesis: MT mediated the PD-ID relationship for nearly half of participants in imagined action and nearly a third of participants in actual action. Between action conditions, there was clearly more support in imagined than actual action for MT as the superior predictor of PD as well as a mediator of the PD-ID relationship.

4.6 Interpreting the effect of MT on PD

The finding that, in both imagined and actual action, there was greater support for MT as the superior predictor of ID among participants implies that participants' PD judgments were related to MT and more often to MT than ID. In other words, in both action conditions, participants' PD judgments were related more often to the outcome of the action experience (i.e., MT) than the information constraints that characterized the action (i.e., ID). The finding of a relationship between PD and MT in imagined and actual action concurs with research that has demonstrated this relationship in actual action using a Fitts task (Deliginières & Famose, 1992) and a wire transfer task (Bratfisch, Dornič, & Borg's study, as cited in Borg et al., 1971).

For the majority of participants in both imagined and actual action, MT was a significant predictor of PD, if not the superior predictor of PD. In the cases where MT was a significant predictor of PD, there are several implications. First, MT accounted for at least some of the variance in PD not accounted for by ID. In other words, MT accounted for at least some of the limitations to the predictions for the PD-ID relation, that is, deviations from a linear PD-ID relation and scale variance for PD. Second, there were also limitations to the Fitts's law predictions for the MT-ID relation. Third, the limitations to the predictions for the PD-ID relation and the MT-ID relation were similar: The pattern of deviations from a linear PD-ID relation resembled the pattern of deviations from a linear MT-ID relation and the pattern of scale variance for PD resembled the pattern of scale variance for MT. Hence, there was a relationship between participants' PD judgments and their MTs.

The evidence that MT mediated the relationship between PD and ID in both imagined and actual action means that, in those cases, the relationship between PD and ID was attributed to MT. In both action conditions, there was evidence of MT as a mediator for many, but not most, participants. Thus, in imagined and actual action, for the majority of participants, the relationship between PD and ID was independent of MT.

Between action conditions, there was more evidence in imagined than actual action that MT was the superior predictor of PD and that MT mediated the PD-ID relationship. These findings imply that more often in imagined than actual action, MT was related to PD. Furthermore, more often in imagined than actual action, there were limitations to the Fitts's law predictions for the MT-ID relation. That is, the pattern of results for PD was similar between action conditions, and in both action conditions, there were deviations from linearity for the PD-ID relation and scale variance for PD. Because there was more evidence that PD was related to MT in imagined action, this implies that the patterns of results for MT and PD were more similar in imagined than actual action. Thus, particularly in imagined action, the appearance of non-linearity for the MT-ID relation and the pattern of scale variance for MT resembled the corresponding patterns for PD. Furthermore, any limitations to the Fitts's law predictions were more pronounced in imagined than actual action, and, therefore, Fitts's law is less robust in imagined than actual action. Fitts's law was not tested in this study, however, because the purpose of this study was to examine PD in a Fitts task.

If Fitts's law had been tested and these expected results for the MT-ID relation were confirmed, a potential explanation could involve the lack of external feedback in imagined action. It seems that external feedback would be particularly useful when participants are performing movements that they have had less experience performing in everyday life. Participants in this study performed movements that they likely did not have much experience performing in everyday life, for example, arm movements performed under small scales. Perhaps for these less familiar movements, participants could not accurately predict the consequences of their imagined movements, and as a result, their imagined MTs were longer than their actual MTs and limitations to the Fitts's law predictions were pronounced in imagined action. This potential explanation is supported by research that shows a dissociation between imagined and actual MTs for movements that are less familiar to participants in everyday life (Parsons, 1994; Slifkin, 2008).

4.7 PD judgments of imagined and actual action are very similar

An additional finding in Experiment 2 was that participants' PD judgments were very similar between imagined and actual action despite the judgments reflecting different action experiences. Not only were the boundaries of scale invariance and scale variance the same between action conditions, but there were differences in PD between imagined and actual action for only four of 20 target displays. Thus, it appears that participants use similar information in evaluating performance difficulty when judging imagined or actual task performance. Since a similar pattern of results emerged in prospective action, and prospective action is considered a form of imagined action, this statement applies to prospective action as well.

Research shows that similar information and neural processes operate during imagined and actual action. For example, numerous studies have used chronometric measures to study the relationship between imagined and actual MTs, and the consensus is that they are correlated (for review, see Jeannerod, 1997, chap. 4). This relationship has been demonstrated in activities such as writing (Decety & Michel, 1989), walking (Decety, Jeannerod, & Prablanc, 1989), and aiming (Sirigu et al., 1995; Sirigu et al., 1996). Imagined action even supports motor principles established in actual action, such as Fitts's law (Decety & Jeannerod, 1996; Sirigu et al., 1995; Sirigu et al., 1996). There is also evidence from brain imaging studies that shows the pattern of neural activity associated with imagined action overlaps largely with that of actual action (Gérardin et al., 2000; Lotze et al., 1999; for review, see Jeannerod, 2003). Given that similar information and neural processes operate during imagined and actual action, it seems likely that participants' judgments of performance difficulty in imagined and actual action would be similar, as was found in the current study.

The finding of similarities in PD between imagined and actual action suggests that participants' PD judgments in both action conditions were influenced by similar information from their action experience. Perhaps participants' judgments in both action conditions were influenced by internal feedback of performance since this is a feature common to imagined and actual action (Desmurget & Grafton, 2000). Prior to movement onset, a motor plan is assembled, and during movement (imagined or actual), the motor plan is updated continuously by internal feedback loops. Internal feedback loops are essentially mental simulations of action. In both imagined and actual action, these feedback loops provide predictions about the outcome of the motor plan.

In imagined action, participants' movements and their PD judgments could only be influenced by internal feedback of performance since external feedback (e.g., visual feedback) would be unavailable. In contrast, in actual action, participants' movements and their PD judgments could be influenced by both internal and external feedback. Yet, this study showed that participants' PD judgments of imagined and actual action are very similar. Thus, performance in the task and the external feedback that accompanies performance does not have much of an effect on participants' PD judgments in actual action. It appears participants' PD judgments in both action conditions are influenced by internal feedback.

Although participants' PD judgments were similar between imagined and actual action, there was more evidence that MT was related to PD in imagined than actual action. This finding implies that although similar information influenced participants' PD judgments in imagined and actual action, different information influenced participants' PD judgments and their MTs in actual action. That is, both internal and external feedback were available in actual action, but it was not apparent from the results that external feedback had much of an influence on participants' PD judgments given the similarities in PD between action conditions. In contrast, it is apparent that external feedback had an influence on participants' MTs in actual action because there was less evidence in actual than imagined action that PD and MT were related. The differences in the influence of internal and external feedback on PD and MT in actual action could explain why there was greater evidence of MT as being the superior predictor of PD and mediator of the PD-ID relationship in imagined action. That is, whereas similar information from the action experience affected participants' PDs and MTs in imagined action (i.e., internal feedback), different information influenced participants' PDs and their MTs in actual action (i.e., internal versus external feedback), or at least to varying degrees, and, consequently, there was more evidence that PD and MT were related in imagined than actual action.

4.8 Summary of results and conclusions

The results of this study showed that, within limits, Fitts's ID provides an index of subjective difficulty in prospective, imagined, and actual action. In all action conditions, the results supported the hypothesis that the characteristics of the MT-ID relation described by Fitts's law extend to the PD-ID relation: There was evidence of a positive, linear PD-ID relation and scale invariance for PD in prospective, imagined, and actual action. There were limitations in the extent that these predictions held, however: There was some evidence that the PD-ID trends were non-linear and scale variance for PD emerged as the target display scale decreased in size in all action conditions. Taken together, the results of this study showed that participants' PD judgments are influenced by but are not based on the ID levels of the target displays.

Experiment 2 revealed that in both imagined and actual action, but particularly in imagined action, MT was superior to ID in predicting participants' PD judgments. In addition, for many participants, but, again, particularly in imagined action, MT mediated the relationship between PD and ID. These findings imply that participants' PD judgments relate more to the outcome of task performance (i.e., MT) than the information constraints of the action (i.e., ID). Furthermore, in the cases where MT was determined to be a mediator, the relationship between PD and ID was attributed to the influence of MT on participants' PD.

The results of Experiment 2 also revealed that participants' PD judgments in imagined and actual action were very similar. It appears that participants use similar information in evaluating performance difficulty when the judgments are of imagined or actual performance. Because a similar pattern of results appeared in prospective action as in imagined and actual action and because prospective action is considered a form of imagined action, the same inference can be made for prospective action. Since internal feedback of performance is available in both imagined and actual action, it appears that participants' PD judgments of actual action are influenced by internal feedback, as in imagined (and prospective) action. Furthermore, given the similarities in participants' PD judgments between action conditions, it appears that actual experience in the task, and the external feedback that accompanies actual experience, does not have much of an effect on participants' PD judgments in actual action. In contrast, it is apparent that external feedback had an effect on participants' MTs in actual action. This could explain why there was greater evidence that PD and MT were related in imagined than actual action; that is, it appears that participants' PD judgments and their MTs in imagined action were based on similar information from the action experience, but that this was not the case in actual action.

4.9 Directions for future research on PD in action

In this study, a common finding in prospective, imagined, and actual action was scale variance for PD. More specifically, in all three action conditions, as the target display scale decreased, participants' PD increased, particularly at lower ID levels. What could account for the finding of scale variance for PD? ID could not have accounted for this finding since, by definition, Fitts's law predicts scale invariance for MT and, therefore, the ID levels are unaffected by changes in scale. MT could have accounted for this finding, and the results of this study suggest that, indeed, for the majority of participants in both action conditions, MT did account for at least some of the scale variance for PD. For some participants, however, MT was not a significant predictor of PD and, thus, did not account for the scale variance for PD. To understand better PD in action, a recommendation for future research is to examine variables in addition to ID and MT that might relate to and predict participants' PD.

Research suggests that a good predictor of PD in action is perceived MT: Borg et al. (1971) speculated that in the study by Bratfisch, Dornič, and Borg, the PD judgments were based on perceived MT. It seems likely that in the current study, participants' PD judgments were also related to perceived MT. Perhaps in this study, perceived MT would have explained the variance in PD not accounted for by ID or MT and perceived MT would have been superior to MT in predicting participants' PD. If this had been the case, then participants' PD judgments would have been related more to their perception of the outcome of their action performance, that is, perceived MT, than the actual outcome of their action performance, that is, MT. Furthermore, future research may find that, like PD, perceived MT is unaffected by the external feedback that accompanies actual performance and, thus, is consistent across prospective, imagined, and actual action. A recommendation for future research is to collect PD judgments and MTs, similar to the current study, as well as judgments of perceived MT. Both participants' PD judgments and their perceived MT judgments could be in the form of magnitude estimates. Action performance could involve imagined or actual action. As in the current study, regression could be used to compare PD, MT, and perceived MT as predictors of PD. Such a study would be aimed at more precisely identifying what variables relate to PD in action.

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FOOTNOTES

[1] In this study, the concept of subjective difficulty is also referred to as perceived difficulty (PD). PD is a type of subjective measure typically referred to in tasks characterized by information constraints (Deliginières, 1998).

[2] In both imagined and actual action, the duration of each target-to-target movement constituted a MT. The median MT of the MTs collected during a trial provided an estimate of the average MT for the trial. Only the median MTs were transformed and analyzed. In this paper, the MTs actually refer to the median MTs for the trials.

Table 1

Amplitude as a Function of Scale and ID for Experiments 1 and 2

		ID				
Scale	W	1.00	2.00	3.00	4.00	5.00
				Experiment 1		
1	0.25	0.25	0.51	1.02	2.03	4.06
2	0.76	0.76	1.52	3.05	6.10	12.19
3	1.27	1.27	2.54	5.08	10.16	20.32
4	1.78	1.78	3.56	7.11	14.22	28.45
5	2.29	2.29	4.57	9.14	18.29	36.58
		ID				
Scale	W	1.00	2.33	3.67	5.00	
				Experiment 2		
1	0.13	0.13	0.32	0.81	2.03	
2	0.38	0.38	0.96	2.42	6.10	
3	1.14	1.14	2.87	7.27	18.29	
4	1.91	1.91	4.79	12.12	30.48	
5	2.16	2.16	5.43	13.74	34.54	

Note . Changes in scale correspond to changes in the size of the amplitude and width requirements characterizing a target display. Within a scale level, target width (W) was static and the (center-to-center) amplitude (A) between targets varied according to the formula for Fitts's Index of Difficulty (ID), $\log_2(2A/W)$, which is measured in bits of information.

Table 2

Perceived Difficulty (PD) Means and Standard Deviations as a Function of Scale and ID in Experiment 1

	ID											
	1.00		2.00		3.00		4.00		5.00		Overall	
Scale	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
1	8.15 $_c$	(2.18)	8.33 $_c$	(1.94)	8.38 $_c$	(2.02)	8.85 $_b$	(1.22)	9.46 $_b$	(0.60)	8.63 $_b$	(5.76)
2	3.44 $_b$	(1.93)	4.57 $_b$	(1.52)	4.89 $_b$	(1.56)	6.24 $_a$	(1.65)	7.24 $_a$	(1.72)	5.28 $_a$	(5.48)
3	2.21 $_{ab}$	(1.24)	3.09 $_{ab}$	(1.12)	4.11 $_{ab}$	(1.27)	5.28 $_a$	(1.61)	6.48 $_a$	(2.16)	4.23 $_a$	(4.57)
4	1.58 $_a$	(1.02)	2.39 $_a$	(0.89)	3.67 $_{ab}$	(1.20)	4.84 $_a$	(1.72)	6.83 $_a$	(2.58)	3.86 $_a$	(4.65)
5	1.38 $_a$	(0.77)	2.13 $_a$	(0.77)	3.24 $_a$	(1.23)	4.93 $_a$	(1.97)	6.71 $_a$	(2.78)	3.68 $_a$	(4.98)
Overall	3.35	(4.42)	4.10	(3.41)	4.86	(4.44)	6.03	(4.98)	7.34	(6.76)		

Note. *N* = 20. Changes in scale correspond to changes in the size of the amplitude and width requirements characterizing a target display. Within a scale level, target width (W) was static and the amplitude (A) between targets varied according to the formula for Fitts's Index of Difficulty (ID), $\log_2(2A/W)$, which is measured in bits of information. Table values were calculated from the transformed values of participants' magnitude estimates. Means in the same column that share a subscript are not statistically different at $\alpha = .05$ according to Tukey's HSD tests (D_{Tukey} = 1.74, 1.69, 1.63, 1.78, 2.05, 3.22 for ID levels 1-5 and across ID levels [Overall], respectively).

Table 3

Linear Contrasts and Residual Tests for Perceived Difficulty (PD) as a Function of Scale in Experiment 1

		df	*F*	*p*	*MSE*	η^2
				Imagined		
Overall	Lin	(1, 19)	78.09	< .001	37.68	.77
	Res	(3, 57)	8.68	< .001	2.06	
Scale 1	Lin	(1, 19)	8.63	.008	6.83	.23
	Res	(3, 57)	2.42	.08	1.13	
Scale 2	Lin	(1, 19)	59.74	< .001	8.62	.67
	Res	(3, 57)	3.31	.03	1.27	
Scale 3	Lin	(1, 19)	58.73	< .001	11.77	.72
	Res	(3, 57)	1.18	.33	0.79	
Scale 4	Lin	(1, 19)	78.79	< .001	12.77	.74
	Res	(3, 57)	5.57	.002	1.46	
Scale 5	Lin	(1, 19)	76.89	< .001	14.09	.74
	Res	(3, 57)	7.41	< .001	1.38	

Note. Changes in scale correspond to changes in the size of the amplitude and width requirements characterizing a target display. Within a scale level, target width (W) was static and the amplitude (A) between targets varied according to the formula for Fitts's Index of Difficulty (ID), $\log_2(2A/W)$, which is measured in bits of information.

Table 4

Perceived Difficulty (PD) Means and Standard Deviations as a Function of Scale, ID, and Action Condition in Experiment 2

	ID				
	1.00	2.33	3.67	5.00	Overall
Scale	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)
			Imagined[a]		
1	7.31 $_c$ (1.98)	7.36 $_c$ (1.83)	7.28 $_c$ (1.77)	7.76 $_c$ (1.92)	7.43 $_c$ (3.39)
2	4.50 $_b$ (1.60)	4.89 $_b$ (1.52)	5.22 $_b$ (1.57)	5.76 $_b$ (1.65)	5.09 $_b$ (2.81)
3	2.18 $_a$ (1.69)	3.14 $_a$ (1.76)	3.98 $_a$ (1.70)	5.00 $_a$ (1.77)	3.58 $_a$ (3.05)
4	1.56 $_a$ (1.45)	2.63 $_a$ (1.62)	3.60 $_a$ (1.86)	4.78 $_a$ (2.19)	3.14 $_a$ (3.23)
5	1.53 $_a$ (1.60)	2.63 $_a$ (1.82)	3.56 $_a$ (1.87)	4.96 $_a$ (2.11)	3.17 $_a$ (3.25)
Overall	3.42 (2.85)	4.13 (3.15)	4.73 (3.31)	5.65 (3.64)	4.48 (5.85)
			Actual[b]		
1	8.10 $_c$ (1.94)	7.95 $_c$ (1.70)	7.73 $_c$ (1.63)	8.25 $_c$ (1.48)	8.01 $_c$ (2.97)
2	3.88 $_b$ (1.75)	4.30 $_b$ (1.80)	5.27 $_b$ (1.45)	6.25 $_b$ (1.49)	4.93 $_b$ (2.70)
3	1.87 $_a$ (1.62)	2.64 $_a$ (1.28)	3.87 $_a$ (1.49)	5.36 $_a$ (1.70)	3.44 $_a$ (2.60)
4	1.43 $_a$ (1.26)	2.12 $_a$ (1.19)	3.63 $_a$ (1.63)	4.86 $_a$ (2.07)	3.01 $_a$ (2.64)
5	1.38 $_a$ (1.25)	2.10 $_a$ (1.24)	3.55 $_a$ (1.66)	4.96 $_a$ (2.13)	3.00 $_a$ (2.79)
Overall	3.33 (2.79)	3.82 (2.53)	4.81 (2.73)	5.94 (3.20)	4.47 (4.92)

Note. N = 40. Changes in scale correspond to changes in the size of the amplitude and width requirements characterizing a target display. Within a scale level, target width (W) was static and the amplitude (A) between targets varied according to the formula for Fitts's Index of Difficulty (ID), $\log_2(2A/W)$, which is measured in bits of information. Table values were calculated from the transformed values of participants' magnitude estimates. Means in the same column that share a subscript are not statistically different at $\alpha = .05$ according to Tukey's HSD tests.

[a]In Imagined action, D_{Tukey} = 0.75, 0.68, 0.66, 0.74, and 1.20, for ID levels 1-5 and and across ID levels (Overall), respectively.

[a]In Actual action, D_{Tukey} = 0.69, 0.65, 0.69, 0.75, and 1.12, for ID levels 1-5 and across ID levels (Overall), respectively.

Table 5

Summary of t *Tests Comparing Perceived Difficulty (PD) Between Imagined and Actual Action in Experiment 2*

Scale	ID	M_{diff}	SD_{diff}	*t*	*p*	*d*
1	1.00	0.79	2.67	1.88	0.07	0.40
	2.33	0.59	2.20	1.69	0.10	0.33
	3.67	0.45	2.28	1.25	0.22	0.26
	5.00	0.49	2.15	1.43	0.16	0.28
2	1.00	-0.62	1.85	-2.13	0.04	-0.37
	2.33	-0.59	2.10	-1.78	0.08	-0.35
	3.67	0.05	1.80	0.18	0.86	0.03
	5.00	0.50	1.84	1.70	0.10	0.31
3	1.00	-0.31	1.49	-1.32	0.19	-0.19
	2.33	-0.50	1.47	-2.16	0.04	-0.32
	3.67	-0.11	1.38	-0.52	0.61	-0.07
	5.00	0.36	1.59	1.43	0.16	0.21
4	1.00	-0.14	1.12	-0.78	0.44	-0.10
	2.33	-0.51	1.18	-2.71	0.01	-0.34
	3.67	0.03	1.78	0.09	0.93	0.01
	5.00	0.08	1.99	0.24	0.81	0.04
5	1.00	-0.15	1.29	-0.75	0.46	-0.10
	2.33	-0.53	1.38	-2.44	0.02	-0.32
	3.67	0.00	1.60	-0.02	0.99	0.00
	5.00	0.00	1.80	-0.01	0.99	0.00

Note. $df = 39$. Changes in scale correspond to changes in the size of the amplitude and width requirements characterizing a target display. Within a scale level, target width (W) was static and the amplitude (A) between targets varied according to the formula for Fitts's Index of Difficulty (ID), $\log_2(2A/W)$, which is measured in bits of information. The formula used in computing the effect size was $d = t\,[2(1-r)/n]^{1/2}$, which is applicable to repeated measure designs (Dunlap, Cortina, Vaslow, & Burke, 1996). M_{diff} = difference of the means for actual and imagined action (means were calculated from the transformed values of participants' magnitude estimates); SD_{diff} = difference of standard deviations for actual and imagined action (standard deviations were calculated from the transformed values of participants' magnitude estimates).

Table 6

Linear Contrasts and Residual Tests for Perceived Difficulty (PD) as a Function of Scale in Imagined and Actual Action in Experiment 2

		df	*F*	*p*	*MSE*	η^2
				Imagined		
Overall	Lin	(1, 38)	78.10	< .001	6.82	.63
	Res	(2, 76)	3.49	.035	0.62	
Scale 1	Lin	(1, 38)	1.86	.18	1.73	.03
	Res	(2, 76)	3.72	.03	0.39	
Scale 2	Lin	(1, 38)	25.76	< .001	1.30	.27
	Res	(2, 76)	0.38	.69	0.51	
Scale 3	Lin	(1, 38)	90.93	< .001	1.90	.60
	Res	(2, 76)	0.20	.82	0.54	
Scale 4	Lin	(1, 38)	106.71	< .001	2.12	.68
	Res	(2, 76)	0.48	.62	0.35	
Scale 5	Lin	(1, 38)	93.38	< .001	2.69	.65
	Res	(2, 76)	2.04	.14	0.43	
				Actual		
Overall	Lin	(1, 38)	136.22	< .001	5.69	.71
	Res	(2, 76)	11.01	< .001	0.98	
Scale 1	Lin	(1, 38)	0.07	.79	1.28	.00
	Res	(2, 76)	3.54	.03	0.83	
Scale 2	Lin	(1, 38)	87.78	< .001	1.49	.50
	Res	(2, 76)	2.04	.14	0.92	
Scale 3	Lin	(1, 38)	190.35	< .001	1.44	.71
	Res	(2, 76)	3.87	.025	0.69	
Scale 4	Lin	(1, 38)	124.17	< .001	2.25	.69
	Res	(2, 76)	5.61	.005	0.46	
Scale 5	Lin	(1, 38)	134.93	< .001	2.20	.72
	Res	(2, 76)	9.29	< .001	0.32	

Note. Changes in scale correspond to changes in the size of the amplitude and width requirements characterizing a target display. Within a scale level, target width (W) was static and the amplitude (A) between targets varied according to the formula for Fitts's Index of Difficulty (ID), $\log_2(2A/W)$, which is measured in bits of information.

Table 7

Summary of Correlation and Regression Analyses by Participant for Imagined Action (Experiment 2)

	r			PD regressed on ID and MT				
Participant	PD-ID	PD-MT	MT-ID	R^2	sr^2_{ID}	β_{ID}	sr^2_{MT}	β_{MT}
1	0.15	0.68 ***	0.58 ***	0.56 ***	0.09	-0.37 **	0.54	0.90 ***
2	0.27	0.82 ***	0.51 ***	0.69 ***	0.03	-0.19	0.62	0.91 ***
3	0.43 **	0.60 ***	0.80 ***	0.37 **	0.01	-0.14	0.19	0.72 **
4	0.74 ***	0.87 ***	0.84 ***	0.76 ***	0.00	0.02	0.22	0.86 ***
5	0.15	0.70 ***	0.36 *	0.51 ***	0.01	-0.11	0.48	0.74 ***
6	0.50 **	0.79 ***	0.58 ***	0.62 ***	0.00	0.06	0.38	0.76 ***
7	0.58 ***	0.90 ***	0.73 ***	0.83 ***	0.02	-0.18	0.50	1.04 ***
8	0.20	0.52 ***	0.73 ***	0.33 ***	0.06	-0.37	0.29	0.78 ***
9	0.46 **	0.89 ***	0.41 **	0.81 ***	0.01	0.12	0.59	0.84 ***
10	0.11	0.30	0.79 ***	0.14 *	0.05	-0.35	0.13	0.58 *
11	0.25	0.81 ***	0.65 ***	0.79 ***	0.13	-0.48 ***	0.73	1.12 ***
12	0.56 ***	0.68 ***	0.65 ***	0.49 ***	0.02	0.20	0.18	0.55 ***
13	0.35 *	0.40 *	0.86 ***	0.16	0.00	0.02	0.04	0.38
14	0.03	0.68 ***	0.49 **	0.59 ***	0.12	-0.40 **	0.59	0.88 ***
15	0.63 ***	0.66 ***	0.78 ***	0.47 *	0.04	0.30	0.07	0.42 *
16	-0.37 *	-0.02	0.05	0.14	0.14	-0.37 *	0.00	0.00
17	0.37 *	0.66 ***	0.25	0.48 ***	0.04	0.22	0.34	0.61 ***
18	0.17	0.29	0.58 ***	0.09	0.00	-0.01	0.06	0.30
19	0.16	0.94 ***	0.09	0.89 ***	0.01	0.08	0.86	0.93 ***
20	0.33 *	0.55 ***	0.52 ***	0.30 **	0.00	0.06	0.19	0.52 **
21	0.15	0.08	0.88 ***	0.03	0.03	0.35	0.01	-0.23
22	0.18	0.85 ***	0.28	0.72 ***	0.00	-0.06	0.69	0.86 ***
23	0.67 ***	0.83 ***	0.51 ***	0.78 ***	0.08	0.34 ***	0.33	0.66 ***
24	0.66 ***	0.51 ***	0.62 ***	0.45	0.20	0.56 ***	0.02	0.16
25	0.29	0.86 ***	0.67 ***	0.87 ***	0.14	-0.50 ***	0.78	1.19 ***
26	0.84 ***	0.74 ***	0.73 ***	0.74 *	0.18	0.62 ***	0.04	0.29 *
27	0.17	0.70 ***	0.57 ***	0.56 ***	0.08	-0.33 *	0.53	0.89 ***
28	0.54 ***	0.72 ***	0.89 ***	0.58 ***	0.05	-0.51 *	0.29	1.17 ***
29	0.39 *	0.18	0.75 ***	0.18	0.15	0.59 *	0.03	-0.26
30	0.46 **	0.42 **	0.83 ***	0.22	0.04	0.36	0.00	0.12
31	0.90 ***	0.92 ***	0.94 ***	0.86 **	0.01	0.31	0.05	0.63 **
32	0.48 **	0.53 ***	0.66 ***	0.31 *	0.03	0.23	0.08	0.38 *
33	0.35 *	0.68 ***	0.18	0.51 ***	0.05	0.23	0.39	0.64 ***
34	0.39 *	0.58 ***	0.60 ***	0.34 **	0.00	0.07	0.18	0.53 **
35	0.61 ***	0.63 ***	0.71 ***	0.45 *	0.06	0.34	0.07	0.39 *
36	0.42 **	0.85 ***	0.53 ***	0.72 ***	0.00	-0.04	0.55	0.87 ***
37	0.33 *	0.26	0.62 ***	0.11	0.05	0.28	0.00	0.09
38	0.12	0.13	0.86 ***	0.02	0.00	0.04	0.00	0.09
39	0.52 ***	0.83 ***	0.70 ***	0.70 ***	0.01	-0.12	0.42	0.92 ***
40	0.68 ***	0.87 ***	0.84 ***	0.76 ***	0.01	-0.17	0.30	1.01 ***

Note. $N = 40$.

* $p < .05$; ** $p < .01$; *** $p < .001$.

Table 8

Summary of Correlation and Regression Analyses by Participant for Actual Action (Experiment 2)

	r			PD regressed on ID and MT				
Participant	PD-ID	PD-MT	MT-ID	R^2	sr^2_{ID}	β_{ID}	sr^2_{MT}	β_{MT}
1	0.26	0.47 **	0.93 ***	0.48 ***	0.26	-1.42 ***	0.42	1.79 ***
2	0.24	0.86 ***	0.64 ***	0.90 ***	0.16	-0.51 ***	0.84	1.19 ***
3	0.38 *	0.42 **	0.92 ***	0.17	0.00	-0.02	0.03	0.43
4	0.45 **	0.67 ***	0.92 ***	0.62 ***	0.17	-1.03 ***	0.41	1.61 ***
5	0.44 **	0.47 **	0.94 ***	0.23	0.00	-0.03	0.03	0.50
6	0.88 ***	0.85 ***	0.87 ***	0.80 *	0.08	0.57 ***	0.03	0.35 *
7	0.54 ***	0.78 ***	0.89 ***	0.72 ***	0.12	-0.77 ***	0.43	1.46 ***
8	0.02	0.32 *	0.91 ***	0.53 ***	0.43	-1.57 ***	0.52	1.74 ***
9	0.52 ***	0.86 ***	0.67 ***	0.75 ***	0.01	-0.11	0.48	0.93 ***
10	0.17	0.21	0.95 ***	0.06	0.02	-0.41	0.03	0.61
11	0.53 ***	0.81 ***	0.83 ***	0.72 ***	0.07	-0.46 **	0.44	1.19 ***
12	0.55 ***	0.60 ***	0.92 ***	0.36	0.00	0.01	0.05	0.59
13	0.64 ***	0.62 ***	0.91 ***	0.42	0.04	0.47	0.01	0.20
14	0.01	0.23	0.95 ***	0.53 ***	0.47	-2.21 ***	0.53	2.33 ***
15	0.47 **	0.75 ***	0.80 ***	0.60 ***	0.04	-0.34	0.38	1.02 ***
16	0.43 **	0.36 *	0.89 ***	0.18	0.06	0.53	0.00	-0.12
17	0.22	0.52 ***	0.87 ***	0.50 ***	0.23	-0.99 ***	0.45	1.39 ***
18	0.30	0.58 ***	0.87 ***	0.52 ***	0.18	-0.87 ***	0.42	1.34 ***
19	0.17	0.64 ***	0.77 ***	0.68 ***	0.27	-0.82 ***	0.65	1.27 ***
20	0.15	0.08	0.91 ***	0.05	0.04	0.50	0.02	-0.38
21	0.06	0.06	0.93 ***	0.00	0.00	0.02	0.00	0.04
22	0.25	0.61 ***	0.80 ***	0.52 ***	0.15	-0.64 **	0.45	1.12 ***
23	0.77 ***	0.83 ***	0.92 ***	0.69 **	0.00	0.06	0.09	0.78 **
24	0.50 **	0.74 ***	0.70 ***	0.55 ***	0.00	-0.04	0.30	0.76 ***
25	0.75 ***	0.78 ***	0.89 ***	0.63 *	0.01	0.26	0.07	0.56 *
26	0.21	0.31 *	0.83 ***	0.11	0.01	-0.15	0.06	0.44
27	0.29	0.04	0.74 ***	0.15	0.15	0.57 *	0.07	-0.38
28	0.34 *	0.48 **	0.91 ***	0.28 **	0.05	-0.54	0.16	0.97 **
29	0.34 *	0.06	0.78 ***	0.23 *	0.22	0.75 **	0.11	-0.53 *
30	0.34 *	0.18	0.92 ***	0.22 *	0.19	1.10 **	0.11	-0.83 *
31	0.73 ***	0.58 ***	0.76 ***	0.54	0.20	0.69 ***	0.00	0.05
32	0.35 *	0.26	0.88 ***	0.13	0.06	0.51	0.01	-0.19
33	0.45 **	0.57 ***	0.36 *	0.40 **	0.07	0.29 *	0.19	0.47 **
34	0.38 *	0.27	0.79 ***	0.15	0.08	0.45	0.00	-0.09
35	0.42 **	0.57 ***	0.90 ***	0.37 **	0.04	-0.47	0.19	0.99 **
36	0.56 ***	0.49 **	0.95 ***	0.32	0.09	0.94 *	0.02	-0.40
37	0.18	0.15	0.78 ***	0.03	0.01	0.17	0.00	0.01
38	0.24	0.24	0.93 ***	0.06	0.00	0.14	0.00	0.11
39	0.59 ***	0.65 ***	0.87 ***	0.42 *	0.00	0.10	0.08	0.56 *
40	0.56 ***	0.65 ***	0.92 ***	0.44 **	0.01	-0.29	0.13	0.92 **

Note. $N = 40$.

* $p < .05$; ** $p < .01$; *** $p < .001$.

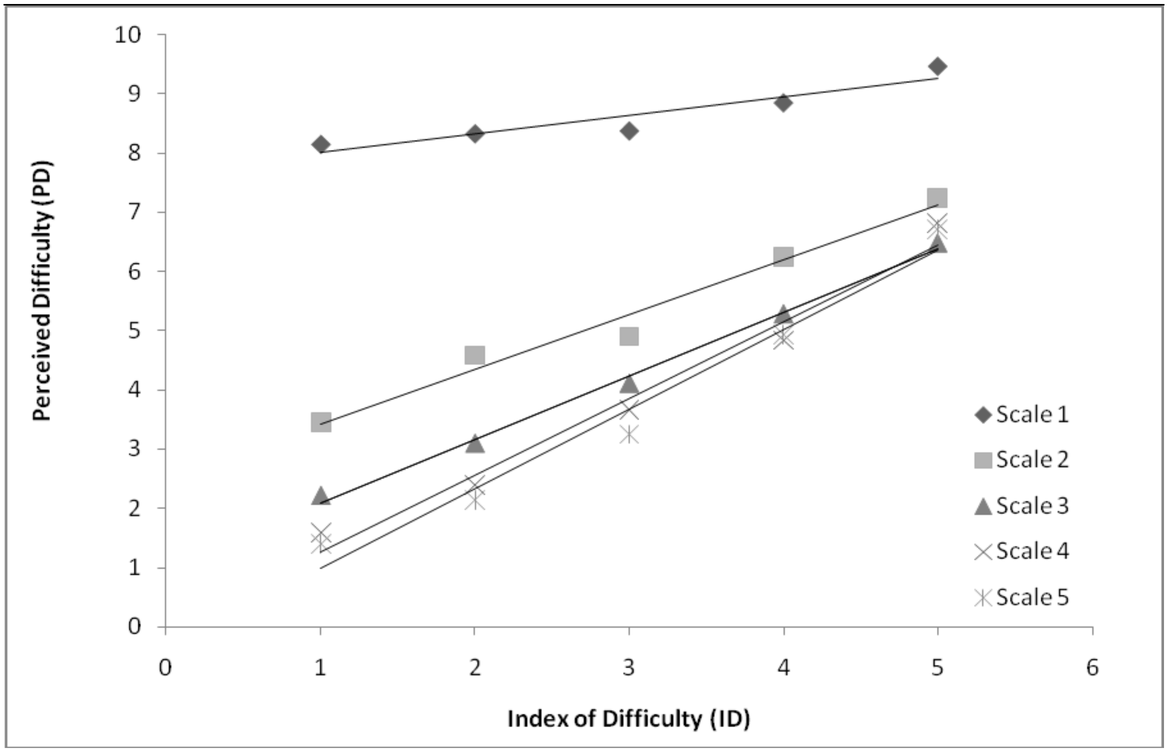

Figure 1. Changes in perceived difficulty (PD) as a function of Fitts's Index of Difficulty (ID) and scale in prospective action in Experiment 1. Data points are means across participants ($N = 20$) calculated from the transformed values of participants' magnitude estimates. Magnitude estimates reflect participants' PD of prospective performance in a Fitts task. Changes in scale correspond to changes in the size of the amplitude and width requirements characterizing a target display: From Scales 1 to 5, both the amplitude between targets and the size of target widths increased. Within a scale level, target width was constant and increases in ID corresponded to increases in the amplitude between targets. ID = $\log_2(2A/W)$ where A = amplitude and W = width. The solid lines represent the line of best fit according to linear regression; the corresponding regression equations are as follows: Scale 1, Y = 0.31X + 7.69, $t(3) = 4.65$ $p < .05$; Scale 2, Y = 0.93X + 2.50, $t(3) = 11.06$, $p < .01$; Scale 3, Y = 1.07X + 1.01, $t(3) = 27.29$, $p < .001$; Scale 4, Y = 1.29X - 0.02, $t(3) = 11.12$, $p < .01$; Scale 5, Y = 1.34X - 0.35, $t(3) = 10.30$, $p < .01$.

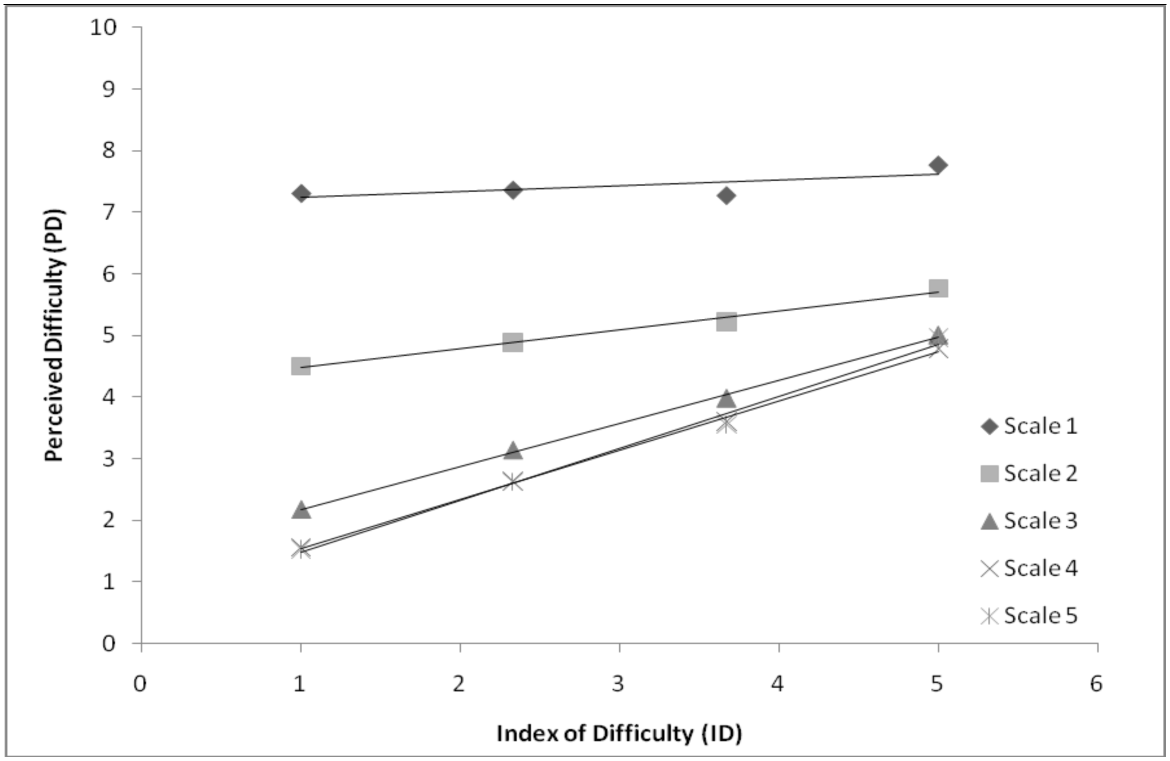

Figure 2. Changes in perceived difficulty (PD) as a function of Fitts's Index of Difficulty (ID) and scale in imagined action in Experiment 2. Data points are means across participants ($N = 40$) calculated from the transformed values of participants' magnitude estimates. Magnitude estimates reflect participants' PD of imagined performance in a Fitts task. Changes in scale correspond to changes in the size of the amplitude and width requirements characterizing a target display: From Scales 1 to 5, both the amplitude between targets and the size of target widths increased. Within a scale level, target width was constant and increases in ID corresponded to increases in the amplitude between targets. ID = $\log_2(2A/W)$ where A = amplitude and W = width. The solid lines represent the line of best fit according to linear regression; the corresponding regression equations are as follows: Scale 1, Y = 0.10X + 7.14, $t(2) = 1.49$, $p > .05$; Scale 2, Y = 0.31X + 4.17, $t(2) = 13.08$, $p < .05$; Scale 3, Y = 0.70X + 1.48, $t(2) = 38.13$, $p < .001$; Scale 4, Y = 0.80X + 0.75, $t(2) = 35.58$, $p < .001$; Scale 5, Y = 0.84X + 0.65, $t(2) = 16.63$, $p < .01$.

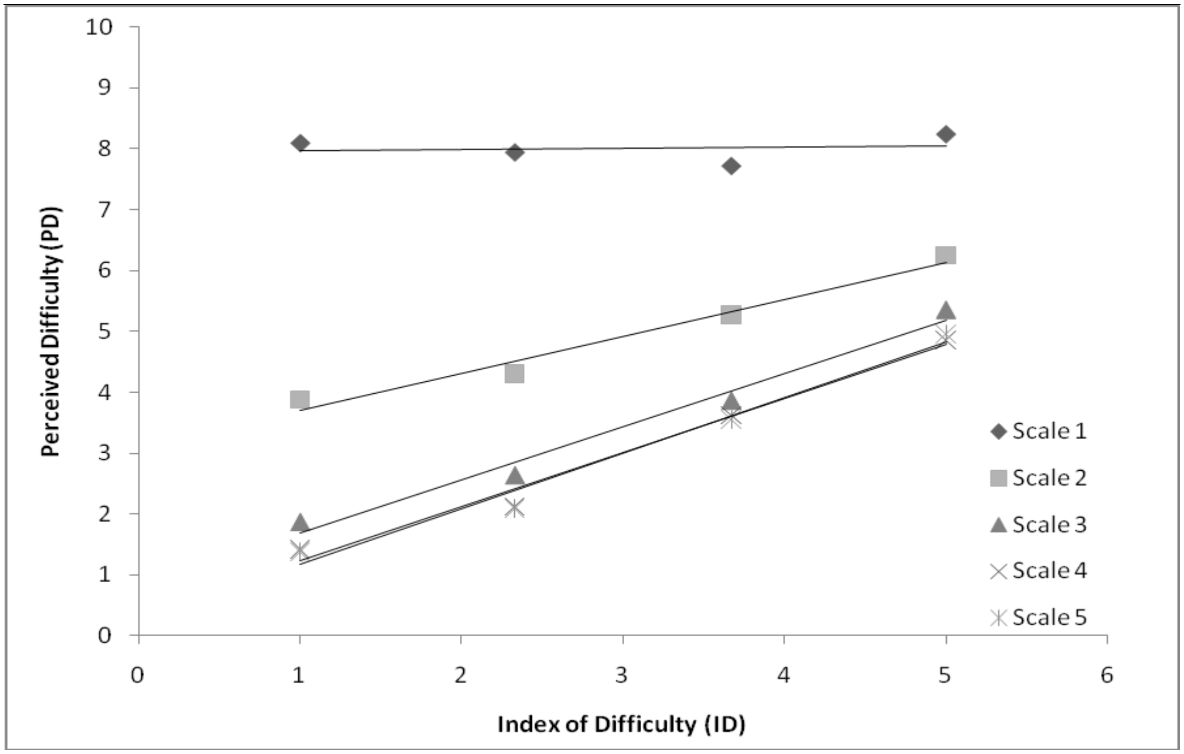

Figure 3. **C**hanges in perceived difficulty (PD) as a function of Fitts's Index of Difficulty (ID) and scale in actual action in Experiment 2. Data points are means across participants ($N = 40$) calculated from the transformed values of participants' magnitude estimates. Magnitude estimates reflect participants' PD of actual performance in a Fitts task. Changes in scale correspond to changes in the size of the amplitude and width requirements characterizing a target display: From Scales 1 to 5, both the amplitude between targets and the size of target widths increased. Within a scale level, target width was constant and increases in ID corresponded to increases in the amplitude between targets. ID = $\log_2(2A/W)$ where A = amplitude and W = width. The solid lines represent the line of best fit according to linear regression; the corresponding regression equations are as follows: Scale 1, Y = 0.02X + 7.96, $t(2) = 0.17$, $p > .05$; Scale 2, Y = 0.61X + 3.10, $t(2) = 8.39$, $p < .05$; Scale 3, Y = 0.88X + 0.80, $t(2) = 10.17$, $p < .01$; Scale 4, Y = 0.89X + 0.35, $t(2) = 10.46$, $p < .01$; Scale 5, Y = 0.91X + 0.26, $t(2) = 10.05$, $p < .01$.

APPENDIX

Prior to conducting the main analyses in Experiment 1, the data were inspected to ensure that the assumptions of ANOVA were met. Twenty-five PD distributions were formed, one for each ID × Scale combination. For each distribution, each participant contributed one mean score that reflected the mean of the magnitude estimates from Series 2 through 4 (Series 1 was treated as practice and, therefore, the Series 1 data were not included in this and subsequent analyses). The distributions were inspected visually through boxplots for evidence of normality and homogeneity of variances. (Violations of sphericity were not considered until the main analyses.) The boxplots showed that some of the distributions were skewed: Extreme positive outliers were present at Scale 1 at all ID levels and at Scales 4 and 5 at ID 1 (see first boxplot in Figure A1 for an example). In addition, the extent that the scores were dispersed within a distribution varied among distributions: For Scales 2 through 5, the size of the hingespreads (hingespreads correspond approximately to the interquartile ranges) increased as ID increased; for Scale 1, the hingespreads were fairly uniform across the ID range, but they were larger than the hingespreads at the other scale levels. The concern of heterogeneity of variances was explored further by simply observing the distribution variances. The variances varied widely, especially because of the extreme variances under Scale 1. For example, across distributions, the ratio of the largest variance to the smallest variance was 254.37 (Scale 1, ID 5) to 0.44 (Scale 5, ID 1). Given the evidence of non-normality and heterogeneity of variances, the data were transformed.

Several data transformations were considered. All transformations were applied to the unaveraged data from Series 2 through 4. Logarithmic and reciprocal transformations were considered because they are often used when distributions of data exhibit positive skewness (Tabachnick & Fidell, 2001, pp. 81-83). Prior to transforming the data, for both transformations, a constant was added to each magnitude estimate to accommodate restrictions in the transformation calculations—logarithms cannot be computed when a value is zero or negative and reciprocals cannot be computed when a value is zero. Constants of 11 and 1.5 were added to each magnitude estimate for the logarithmic and reciprocal transformations, respectively. A third transformation was considered that reduced the frequency of extreme positive scores. It will be referred to as the maximum-value transformation. This transformation involved establishing a common upper limit for the magnitude estimates among the participants' distributions. First, the maximum value within each participant's distribution of magnitude estimates for Series 2 through 4 was determined. Then, the common upper limit was determined by finding the mode of the maximum values among the participants' distributions. The mode was 10, a value preferred by participants in studies using magnitude estimation procedures (Stevens, 1956). For participants with maximum values that were not equal to 10, a linear transformation was applied that involved multiplying each magnitude estimate within a participant's distribution by the ratio of the common upper limit (i.e., 10) to the maximum value within the participant's distribution. With this transformation, the absolute values within a participant's distribution may have changed, but the dispersion of their magnitude estimates remained the same.

After each transformation was applied, the data were averaged across Series 2 through 4 for each ID × Scale combination. As a result, there were 25 unique PD distributions for each transformation. The boxplots of the untransformed and transformed datasets were compared to determine the best transformation. (For an example of the different boxplots reflecting the transformed and untransformed data, see Figure A1, which shows the data for ID = 1.00 bit, Scale 4.) The boxplots showed that, overall, the frequency of outliers and the variability in the sizes of the hingespreads reduced for the transformed versus untransformed data. The distribution variances within a transformed dataset also reduced compared to the untransformed data: The ratios of the largest to smallest variances were 0.29 to 0.01, 0.02 to 0.002, 7.75 to 0.36, and 254.37 to 0.44 for the logarithmic, reciprocal, and maximum-value transformations, and the untransformed data, respectively. Ultimately, the maximum-value transformation was selected for the main analyses since it provided the greatest reduction in the number of outliers, reduced heterogeneity of variances to a considerable degree, and provided the least manipulation of the original data in the transformation process.

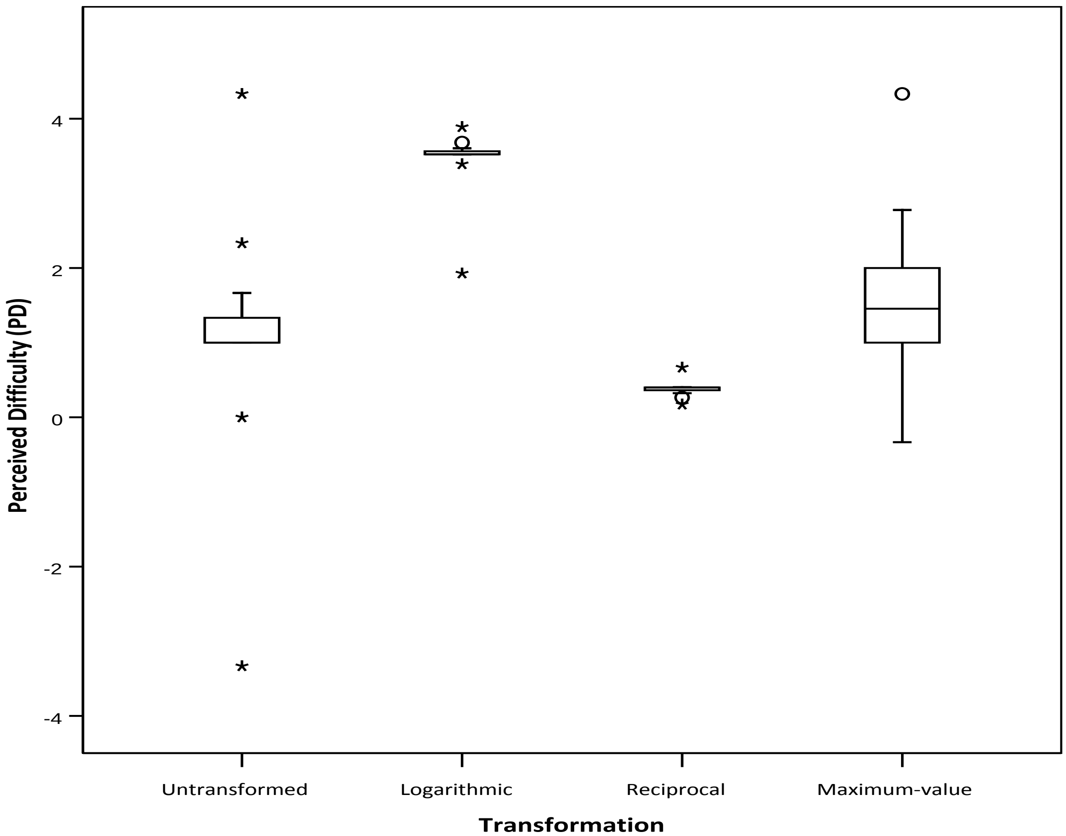

Figure A1. Boxplots of perceived difficulty (PD) as a function of transformation for a single target display condition (ID = 1.00 bit, Scale 4) in Experiment 1. The data for each transformation are magnitude estimates averaged across Series 2 through 4 (*N* = 20). The magnitude estimates reflect participants' PD of prospective performance in a Fitts task. Circles denote magnitude estimates that are outliers; asterisks denote magnitude estimates that are extreme outliers.