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# Target-Directed Movements at a Comfortable Pace: Movement Duration and Fitts's Law

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**ABSTRACT.** Although many studies have supported P. M. Fitts's (1954) law as a description of the speed–accuracy trade-off for speeded movements, there has been a lack of research regarding movement duration for target-directed movements made at any other pace. In the present study, the duration of movements made at a naturally selected comfortable pace and a quick pace differed from Fitts's law in a way that was similar to the predictions of participants in previous studies of naive motor decisions and imagined movements (S. J. Young, J. Pratt, & T. Chau, 2008; S. J. Young, J. Pratt, & T. Chau, 2009). These results show that movements of various speeds have predictable patterns of movement duration. The results also suggest that individuals adjust more than the implicit target size when changing their desired movement speed.

*Keywords*: human, goal-directed action, instructions, speed–accuracy trade-off

Most humans make a multitude of hand movements every day. Many of those movements could be described as target-directed movements because they are approximately straight movements directed at an object or location in space with a defined size. For almost all hand movements, individuals move at a pace that most researchers would describe as natural—not fast or slow, but a type of medium speed. However, the research for target-directed movements in motor control literature does not adequately represent this observation. Many researchers have focused on paradigms in which participants move as quickly as possible to the target, whereas few researchers have examined target-directed movements made at the natural pace that is used for most movements. As a result, it is not known whether the duration of naturally paced movements shows consistent patterns similar to those seen in the duration of speeded movements. However, recent experiments have suggested at least two hypotheses. Results from a pair of studies on motor decisions and imagined movements suggest a consistent way in which the duration of naturally paced movements may differ from that of speeded movements (Young, Pratt, & Chau, 2008; Young, Pratt, & Chau, 2009). Similarly, Tanaka, Krakauer, and Qian (2006) suggested that movements of all speeds are made in the same way as the fastest movements, with only a change in the intended target size. We performed the present experiment to test both of these hypotheses.

The relation between movement duration and target parameters in target-directed movement was first formalized by Fitts (1954) and Fitts and Peterson (1964), who proposed an equation to relate mean movement time (MT) with the mean distance (D) and target width (W) of two-dimensional hand movements made as quickly and accurately as possible,

$$\mathrm{MT} = a + b \times \log_2(2 \times \mathrm{D/W}). \qquad (1)$$

In Equation 1, $a$ and $b$ are empirically derived real constants, and the log term is referred to as *index of difficulty* (ID). Fitts's equation states that (a) MT increases with increasing D, as the hand must travel further to reach the target; (b) MT increases with decreasing W, as the hand must travel at a slower average speed to land in the smaller target; and (c) any two targets with the same ID have the same mean MT. Although researchers have proposed variations of Fitts's equation (for a review, see Plamondon & Alimi, 1997), the general relation among D, W, and MT has been verified in such a wide variety of populations, movement tasks, and body parts that it is often referred to as *Fitts's law* (Crossman & Goodeve, 1963; Schmidt & Lee, 2005).

In a pair of recent studies, we found that participants who were naive to speeded movements expressed an expectation about the MT of those movements that deviated from Fitts's law in a consistent manner (Young et al., 2008; Young et al., 2009). Although participants expected MT to increase with ID, as Fitts's law suggests, they also expected MT to increase with increasing D for targets with a constant level of ID, something that is not consistent with Fitts's law. As a result, contours of participants' expected MT in W–D space were consistently at a lower slope than contours of constant ID. In addition, the decisions outlined contours that were convex (i.e., the slope of the contour decreased with increasing D and W). Although we originally made these observations with motor decisions (Young et al., 2008), further research indicated that the deviation from Fitts's law was not because of a perceptual bias, but seemed to be part of how participants thought about these movements (Young et al., 2009).

As a possible explanation for our participants' erroneous beliefs about the variation of MT in speeded movements, we hypothesized that because participants had little practice making speeded movements, their expectations may have arisen from considering movements for which they had more experience performing in everyday activities (i.e., movements at a naturally chosen pace). Researchers have

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shown previously that experience can have a large effect on accuracy in motor-decision tasks (Kording & Wolpert, 2004; Trommershauser, Maloney, & Landy, 2003). In addition, Johnson (2000) showed that judgments of maximum reaching distance were more indicative of how far individuals reach when making comfortable movements than the maximum distance that they can possibly reach at the extreme of their abilities. Perhaps our participants demonstrated a similar misjudgment when they attempted to estimate the MT of their fastest target-directed movements. Their judgments may reflect the targets to which they would generally move faster for everyday movements, and not the targets to which they could possibly move faster when pushed to the edge of their abilities. If this hypothesis is true, it suggests that the patterns of expected MT seen in participants' decisions and imagined movements may also be seen in the MT of movements made at participants' natural, everyday-movement pace.

## Literature Review of Movements Performed With a Natural Speed

Although many studies have characterized the variation in MT for target-directed movements made as fast as possible, no studies have focused on the variation in MT for target-directed movements made at a pace selected naturally. Other authors also noted this lack of research (Shadmehr & Krakauer, 2008). Many experimenters who have investigated hand and arm movement have required participants to move at a comfortable speed (e.g., Gentili, Cahouet, Ballay, & Papaxanthis, 2004), but these experimenters have generally had other aims, so they did not consider the variation in MT with target parameters. Several researchers have also compared characteristics of movements made as quickly as possible with movements made as accurately as possible (Adam, 1992; Elliott, 1991; Fisk & Goodale, 1989; Zhai, Kong, & Ren, 2004). Although these studies have shown that participants' objectives had a large effect on the way in which they performed movements, none of these experiments specifically investigated the variations in MT relative to Fitts's law. Because of this lack of research on target-directed movements at speeds selected naturally, it is hard to surmise whether comfortable movements may share characteristics with the MT predicted by our participants' decisions and imagined movements.

In spite of a lack of studies specifically investigating target-directed movements at different movement speeds, at least two studies support the possibility that movements at a comfortable pace may increase in MT with D within a single ID value. This is a characteristic that was also observed in our participants' decisions. In a review of Fitts's (1954) original article, Sheridan (1979) showed that Fitts's law as usually stated—with the speed–accuracy trade-off represented by only the quotient D/W—may not accurately capture the relative contributions of D and W to MT for all tasks or individuals. Sheridan suggested that D may have a larger effect in tasks for which covering the D to the target is a larger portion of the MT, thereby resulting in MT increasing with D at the same ID. Similarly, Sheridan suggested that W may have a larger effect in tasks for which adjustment to the final target location is a larger portion of MT, resulting in MT increasing with decreasing W at the same ID. These patterns were seen with several of the tasks in Fitts's original paper, and other researchers have also observed them (C. L. Mackenzie & Graham, 1997; Meyer, Abrams, Kornblum, Wright, & Smith, 1988; Wallace & Newell, 1983).

The potential application of Sheridan's hypothesis to comfortable movements can be inferred from Gottlieb, Corcos, Agarwal, and Latash's (1990) results in their study of electromyographic patterns. Gottlieb et al. observed arm movements to targets at three Ds with speeded and comfortable movement paces. The plots displayed in Gottlieb et al.'s article show that, as D changes, peak velocity varies less for comfortable movements than it does for speeded movements, resulting in greater changes in MT with D for comfortable movements than for speeded movements. As a result, it is possible that D has a greater impact than W on the MT of movements made at a comfortable pace. This could result in MT that increases with increasing D for targets of a constant ID, as we have observed for decisions and imagined movements in our previous studies (Young et al., 2008; Young et al., 2009).

An alternate hypothesis about the MT of comfortable movements can be drawn from the results of Tanaka et al.'s (2006) modeling study. Tanaka et al. showed how Fitts's law arose from the minimization of movement duration in the presence of signal-dependent noise in motor action. Tanaka et al. also stated that this model should be valid for all target-directed movements, regardless of speed. The difference would reside in the implicit and explicit constraints placed on the movement by the environment and the individual making the movement. For speeded movements in a Fitts's law-like paradigm, participants would use the entire target as a potential endpoint for their movements. For movements made at a slower speed, however, participants would place an implicit restriction on their target size, moving to a subspace of the entire target. This restriction of target size would effectively increase the target ID, resulting in slower movements, even though the participant was still trying to minimize MT. The smaller target size could be measured by recording the distribution of endpoints across repeated movements. According to Tanaka et al., the ID of the movement that was created by considering the effective size of the target could be used with the original Fitts's law relation to describe the MT for movements of all speeds.

## Goals of Present Study

The primary goal of the present study was to determine whether the MT of movements at a natural pace deviated from Fitts's law in a way similar to that identified for individuals' naive decisions and imagined movements in previous experiments (Young et al., 2008; Young et al., 2009).

We chose three characteristics of MT for testing. First, we wanted to determine whether MT increased linearly with D for targets with the same value of ID. Second, we wanted to determine whether the contours of constant MT in W–D space had a lower slope than the contours of constant ID. Last, we also tested whether the MT contours had a convex shape in W–D space.

In addition to measuring participants' movements at a naturally selected pace, we also instructed participants to make movements to the same targets at two other paces. First, we asked participants to move at their fastest pace. We used this pace to identify how comfortable movements were different than the speeded movements typically used in studies of Fitts's law. Second, we also asked participants to move at a pace that was quick but not as fast as possible. We used this pace to identify a transition in the pattern of MT as movement speed changed.

The final goal of the present study was to determine whether Tanaka et al.'s (2006) model could accurately represent MT for movements made at various speeds. To determine if this was the case, participants made many movements to each target, thereby allowing us to measure the effective target W based on the spread of movement endpoints. If Tanaka et al.'s model was correct, then for each participant, movements from all speeds would fall on the same line when plotted against ID values calculated using the effective target W.

## Method

### *Participants*

Participants were 12 healthy volunteers (8 women, 4 men) ranging in age from 19 to 42 years (*M* = 26 years, *SD* = 9 years). One participant was left-handed. All participants were naive to the hypotheses of the present study, and none of the participants had performed the task previously. The Bloorview Research Institute and University of Toronto's ethics review boards approved the study. All participants gave their informed consent prior to participating in the study. Participants were provided with remuneration for their time at a rate of $10 per hour.

### *Procedure*

Each participant attended a single experimental session between 2 and 3 hr in length. Participants sat at a table and used a stylus to interact with an LCD tablet (Cintiq 15X tablet and UP-813E-01A stylus, Wacom Company Ltd., Japan). For objects displayed on the tablet, the pixel pitch (i.e., horizontal and vertical distance between adjacent pixels) was 0.297 mm. The tablet sampled stylus position with a frequency of 100 Hz and a resolution of 0.05 mm. We placed the tablet flat on the table and adjusted the table to a comfortable height for each participant. A cursor indicated stylus position on the tablet (relative to the objects displayed), and each participant confirmed that the cursor was aligned with the stylus position.

During the session, participants completed a series of trials, each containing a single target-directed movement. Each movement trial adhered to the following protocol. Prior to each trial, a start square appeared on the right side of the screen (left side for the left-handed participant). When ready, participants placed the stylus on the surface of the tablet and within the start square. When the stylus had been stationary within the start square for 1 s, the start square disappeared and a rectangular target appeared to the left side of the stylus (right side for the left-handed participant). The center of the target was located a distance of D from the stylus, and the target had a horizontal width of W. The target height was always 100 mm, centered on the stylus position. When ready, the participant moved the stylus to a point within the target and held the stylus stationary. The participant held the stylus in contact with the surface of the tablet at all times during the movement. Once the stylus had remained in the target and stationary for 1 s, the trial ended and a new start square appeared.

Participants made movements for three different conditions of movement speed: for the Natural condition, we instructed participants to make a comfortable, natural movement to the target; for the Quick condition, we instructed participants to move quickly, as though in a hurry, but not as fast as possible; and for the Fastest condition, participants were instructed to move to the target as fast as possible, so as to minimize the time from starting the movement to being stationary within the target. We did not provide participants with any condition-specific instructions regarding the accuracy of the movement. In all conditions, the goal of the movement was to move the stylus to a stationary position within the target, and the trial did not end until that goal was satisfied.

For each condition of movement speed, participants made movements to 11 different targets, as outlined in Table 1. We chose four targets with an ID of 4.00[1] and various values of D. We chose five additional targets with a D + W value of 261.3 mm and various values of ID. We also chose two additional targets with D + W values of 194.8 mm each.

Participants first performed 33 practice trials to ensure that they understood the speed conditions. Participants then performed practice and test trials for each condition in turn. The order of condition presentation was counterbalanced across participants. We administered trials for the Natural condition for a set period of time instead of a set number of trials to ensure that participants did not have an incentive to perform trials any faster than the speed they found most natural. For practice, participants performed randomized blocks of 11 trials for 2 min. During testing, participants performed randomized blocks of 11 trials, in 10 periods of 3 min each, for a total of 30 min of test trials. Participants were allowed to take a break between each period of test trials. For the Quick and Fastest conditions, we administered testing on the basis of the number of trials. Participants first performed two randomized blocks of 11 practice trials, for

**TABLE 1. Parameters, Mean Results, and Standard Errors Across all Participants for Each Target**

| | Parameters | | | | MT (s) | | | | | | Effective D (mm) | | | | | | Effective W (mm) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Natural | | Quick | | Fastest | | Natural | | Quick | | Fastest | | Natural | | Quick | | Fastest | |
| Target | D (mm) | W (mm) | ID | D + W (mm) | *M* | *SE* | *M* | *SE* | *M* | *SE* | *M* | *SE* | *M* | *SE* | *M* | *SE* | *M* | *SE* | *M* | *SE* | *M* | *SE* |
| 1 | 57.9 | 3.9 | 4.00 | 61.8 | 0.99 | 0.06 | 0.69 | 0.02 | 0.68 | 0.02 | 58.1 | 0.1 | 58.0 | 0.1 | 58.1 | 0.1 | 2.9 | 0.1 | 3.4 | 0.1 | 3.6 | 0.1 |
| 2 | 120.2 | 8.0 | 4.00 | 128.3 | 1.24 | 0.12 | 0.75 | 0.03 | 0.64 | 0.01 | 119.6 | 0.2 | 120.0 | 0.1 | 120.3 | 0.1 | 5.6 | 0.4 | 6.6 | 0.4 | 7.3 | 0.4 |
| 3 | 182.6 | 12.2 | 4.00 | 194.8 | 1.49 | 0.20 | 0.82 | 0.04 | 0.64 | 0.01 | 181.4 | 0.3 | 181.8 | 0.4 | 182.3 | 0.2 | 7.8 | 0.5 | 8.7 | 0.5 | 11.1 | 0.5 |
| 4 | 245.0 | 16.3 | 4.00 | 261.3 | 1.74 | 0.26 | 0.89 | 0.06 | 0.65 | 0.01 | 242.3 | 0.4 | 243.7 | 0.6 | 244.4 | 0.3 | 8.8 | 0.6 | 10.7 | 0.8 | 13.8 | 0.9 |
| 5 | 130.3 | 130.9 | 1.00 | 261.3 | 0.98 | 0.08 | 0.64 | 0.03 | 0.52 | 0.01 | 95.3 | 7.8 | 103.4 | 6.2 | 117.8 | 6.0 | 33.4 | 10.8 | 40.8 | 5.7 | 45.5 | 6.7 |
| 6 | 195.7 | 65.6 | 1.99 | 261.3 | 1.40 | 0.17 | 0.77 | 0.04 | 0.57 | 0.01 | 179.7 | 3.0 | 184.8 | 2.9 | 191.2 | 2.4 | 22.9 | 5.2 | 23.8 | 2.8 | 32.9 | 3.5 |
| 7 | 228.3 | 33.0 | 2.99 | 261.3 | 1.59 | 0.22 | 0.83 | 0.05 | 0.61 | 0.01 | 222.2 | 1.2 | 224.2 | 1.4 | 227.4 | 0.9 | 14.8 | 1.8 | 16.8 | 1.5 | 22.2 | 1.7 |
| 8 | 253.3 | 8.0 | 5.03 | 261.3 | 1.81 | 0.25 | 0.95 | 0.05 | 0.73 | 0.01 | 252.7 | 0.1 | 252.6 | 0.2 | 252.6 | 0.1 | 6.0 | 0.4 | 7.0 | 0.2 | 7.4 | 0.3 |
| 9 | 257.4 | 3.9 | 6.08 | 261.3 | 1.91 | 0.25 | 1.05 | 0.06 | 0.83 | 0.02 | 257.3 | 0.1 | 257.2 | 0.1 | 257.3 | 0.1 | 3.1 | 0.1 | 3.6 | 0.1 | 3.7 | 0.1 |
| 10 | 122.6 | 72.1 | 1.43 | 194.8 | 1.07 | 0.10 | 0.67 | 0.03 | 0.52 | 0.01 | 104.9 | 3.6 | 111.5 | 3.4 | 118.5 | 2.8 | 21.5 | 3.8 | 27.9 | 3.8 | 32.7 | 3.2 |
| 11 | 165.4 | 29.4 | 2.73 | 194.8 | 1.37 | 0.18 | 0.76 | 0.04 | 0.57 | 0.01 | 160.3 | 1.2 | 162.7 | 1.1 | 164.0 | 0.8 | 12.9 | 2.0 | 15.3 | 1.5 | 21.0 | 1.4 |

*Note*. D = distance; ID = index of difficulty; MT = movement time; W = width.

a total of 22 practice trials. Following that, participants performed 30 randomized blocks of 11 test trials, for a total of 330 test trials. We gave participants an opportunity to take a break from testing after every three blocks of test trials.

### *Analysis*

Although participants completed 30 trials for each target in the Quick and Fastest conditions, the number of trials per target varied in the Natural condition because participants made movements for a set period of time and not a set number of trials. The mean number of trials per target was 30.5 (*SD* = 3.9 trials, range = 23–38 trials). We included all trials in the analysis, unless otherwise noted. In each condition, we excluded a small number of trials because of problems during testing. In total, we included 4,017 trials for our analysis of the Natural condition, 3,944 trials for the Quick condition, and 3,939 trials for the Fastest condition.

For each trial, we calculated stylus speed using stylus position data that we had smoothed using a running average of five consecutive values. We determined the movement start time to be the first time at which the stylus speed exceeded 15 mm/s for at least 150 ms. To determine the stop time and location in the target, we identified the first period for which the stylus remained inside the target and the stylus speed remained ≤ 15 mm/s for 200 ms. We took the stop time and location from the last sample of this 200-ms period. We chose this sample to ensure that we accounted for any slow movement that occurred as the movement came to a stop.

We calculated effective movement D and W for each combination of target, participant, and condition. For effective D, we used the mean of the horizontal D from the start to the stop point. We calculated effective W by multiplying the standard deviation of the horizontal stop location by 3.92, as this is the W of the central range containing 95% of the observations in a standard normal probability density function with standard deviation equal to 1. This approach for calculating effective W was one that Tanaka et al. (2006) used and was also recommended by other researchers (I. S. MacKenzie, 1992).

## Results

For each target, the means and standard errors of the means for MT, effective D, and effective W are shown in Table 1. For the four targets with ID = 4.00, overall means and mean standard errors for each target are shown in Figure 1. To determine whether the observed increases in MT with D were significantly greater than 0, we calculated a linear regression of MT for D for each participant's results. We then used a *t* test to determine whether the slopes of the regression lines were significantly greater than zero. For the Natural condition, the mean increase in MT for each 100 mm of D was 398 ms (*SE* = 110 ms), which was significantly greater than zero, *t*(11) = 3.63, *p* = .004. For the Quick condition, the mean increase in MT for each 100 mm of D was 106 ms (*SE* = 21 ms), which was also significantly

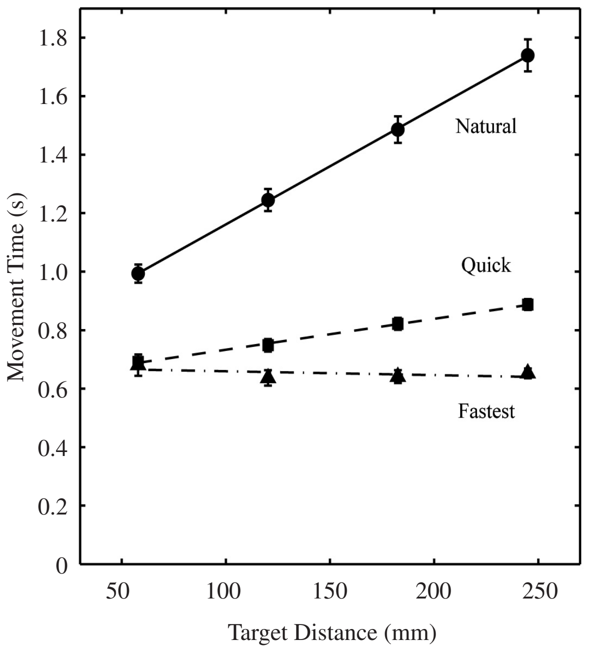

**FIGURE 1.** Mean movement time for targets (index of difficulty = 4.00). Labels indicate the condition corresponding to each set of data points and regression line. Error bars indicate the mean of participants' standard errors.

greater than zero, $t(11) = 5.07$, $p < .001$. For the Fastest condition, the change in MT with D was not significantly different than zero, $t(11) = -0.946$, $p = .364$.

To determine whether the contours of constant MT for the Natural and Quick conditions had a lower slope than the contours of constant ID, we used linear interpolation to find the ID of targets with D + W = 194.8 mm and 245.0 mm, respectively, that had the same mean MT as the targets with ID = 4.00 and D = 120.2 mm and 182.6 mm, respectively. We then used a *t* test to determine whether the ID values were significantly lower than 4.00. Figure 2 shows the results plotted in W–D space. For the target with ID = 4.00 and D = 120.2 mm, the ID of targets with the same MT and D + W = 194.8 mm and 245.0 mm, respectively, were 2.42 and 1.69, respectively, in the Natural condition, and 2.73 and 2.03, respectively, in the Quick condition. For the target with ID = 4.00 and D = 182.6 mm, the ID of the target with the same MT and D + W = 245.0 mm was 2.49 in the Natural condition and 2.93 in the Quick condition. Each of the measured ID values were significantly lower than 4.00 ($p < .001$, $df = 11$). The Fastest condition is not shown in Figure 2 and was not included in the hypothesis tests, as the previous hypothesis test indicated that fastest movements had no significant change in MT across targets with ID = 4.00. Therefore, the ID = 4.00 contour can be used as the contour of constant MT for all targets with ID = 4.00 in the Fastest condition.

As shown in Figure 2, the MT contours for the target with ID = 4.00 and D = 120.2 mm were noticeably convex (i.e., the slopes decrease with increasing D and W). To determine whether this convexity was significantly greater than zero, we measured the difference in ID between the target with D + W = 194.8 mm on the contour and the target with D + W = 194.8 mm that would be expected if the contour was straight. For the Natural condition, the mean difference between the actual contour and a straight line was 0.30 (*SE* = 0.08), which was significantly greater than zero, $t(11) = 3.79$, $p = .003$). For the Quick condition, the mean difference between the actual contour and a straight line was 0.31 (*SE* = 0.10). This was also significantly greater than zero, $t(11) = 3.06$, $p = .010$.

To determine whether Fitts's law with effective D and W could be used to express MT for all speeds, as Tanaka et al. (2006) suggested, we used the effective D and W to calculate the effective ID for each combination of target, participant, and condition. For each participant, we then calculated the linear regression of mean MT on effective ID for each condition using the six targets with D + W = 245.0 mm.

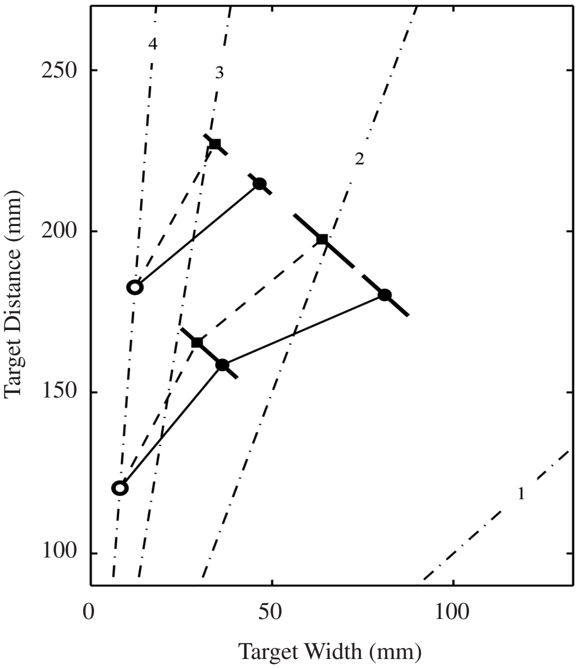

**FIGURE 2.** Contour lines of constant movement time (MT) in width–distance space for the natural and quick conditions. Targets are represented as points in a two-dimensional width–distance space. The *x* axis indicates the target's width, and the *y* axis indicates the target's distance. The reference targets are indicated by open circles, and points of constant MT are indicated by solid shapes connected to their respective reference target, with a fine line representing the contour. The natural condition is indicated by circles (with solid contour lines), and the quick condition is indicated by squares (with dashed contour lines). Error bars indicate the standard error of the participants' means. The contour lines of MT have a lower slope than the contours of constant index of difficulty (ID; dash–dot lines labeled with their respective ID value), and the lower pair of MT contours is noticeably convex.

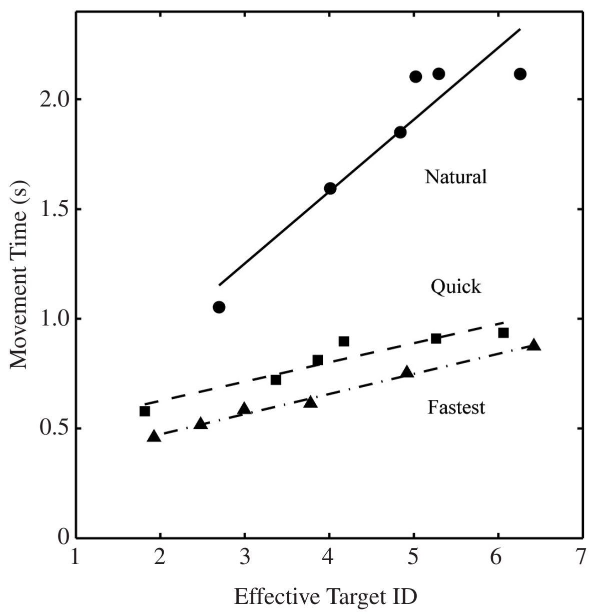

**FIGURE 3.** Mean movement times for targets (distance + width = 245.0) plotted against effective index of difficulty (ID) for Participant 4. Labels indicate the condition corresponding to each set of data points and regression line.

If effective ID accounts for the change in MT between conditions, then one would expect all three conditions to fall on the same line for each participant. Figure 3 shows the results from a representative participant. For each combination of participant and condition, the regression generally fit MT well. All $r^2$ values in a single condition were > .72, and a majority were > .90. However, when comparing conditions, all participants were similar to the participant in Figure 3 in that the regression lines for all conditions did not appear to be collinear. To compare the regression lines, we compared (a) the slope and (b) the constant value (represented by the predicted MT at ID = 4.21, the mean effective ID for all targets with D + W = 245.0 mm). The slope and the constant value decreased with increasing movement speed. To determine if these differences were significant, we used a set of three paired *t* tests to compare all pairs of movement speed conditions. All three slopes were significantly different ($p \leq .008$, $df = 11$), and all three constants were also significantly different ($p < .003$, $df = 11$). These differences were also significant when we used a Bonferroni correction for each parameter and specified an adjusted alpha value of .017 (i.e., .05 / 3 = .017).

## Discussion

To determine how MT varies with target parameters for movements of different speeds, participants made target-directed movements at three different paces: a naturally-selected comfortable pace, a quick pace, and the fastest pace possible. Both comfortable and quick movements deviated from Fitts's law in ways that were similar to the pattern of decisions and imagined movements observed in our previous experiments (Young et al., 2008; Young et al., 2009). MT increased with increasing D for targets at the same ID; contours of constant MT in W–D space had a lower slope than contours of constant ID; and the contours of constant MT were convex. In addition, we found that the approach that Tanaka et al. (2006) suggested did not accurately describe movements of all speeds. Movements of each condition formed distinct regression lines that were different than the regression lines from the other conditions. These results have implications for our understanding of movement decisions, movement duration, and models of movement generation.

To better represent the observed variation in MT for all targets, we searched for a function that could approximate the pattern of mean MT seen for each movement speed. In our previous studies on movement decisions and imagined movements, we had found the greatest $r^2$ values with a group of functions in which a logarithmic function of D/W (as seen in most expressions of Fitts's law) was combined with a linear function of D. We found that this same form of function also fit the results from the present study. For example, the function

$$MT = 0.470 + 0.0746 \times \log_2(D/W + 1) + 0.391 \times D \quad (2)$$

fit the mean MT of the Natural condition with $r^2 = .991$; the function

$$MT = 0.446 + 0.0444 \times \log_2(D/W + 1) + 0.115 \times D \quad (3)$$

fit the mean MT of the Quick condition with $r^2 = 0.983$; and the function

$$MT = 0.428 + 0.0573 \times \log_2(D/W + 1) + 0.00633 \times D \quad (4)$$

fit the mean MT of the Fastest condition with $r^2 = .933$. In each function, the values D and W are in decimeters, so that D has the same order of magnitude as $\log_2(D/W + 1)$. The form of these functions—and especially the relative weighting of the D/W and D factors—can provide an intuitive interpretation of the observed behavior. When participants made movements at a comfortable pace, the D component of the function played a large role in determining MT. However, at increasing speeds, the contribution of the D component decreased, to the point that the D/W component played a dominant role for the fastest movements and the function approximated the usual description of Fitts's law. This progression can be seen graphically in Figure 2, as the contours of constant MT increase in slope to approach the ID = 4.00 contour with increasing speed.

The results of the present study support our hypothesis that the pattern of MT for movements made at a natural pace is similar to the patterns of MT predicted in our previous studies of motor decisions and imagined movements (Young et al., 2008; Young et al., 2009). These results suggest that it is possible for our participants' erroneous expectations about the MT of speeded movements to result from a consideration of movements made at a pace more frequently encountered, such as comfortable or quick movements. This idea is in agreement with research indicating that experience with a task is important for decisions to be accurate (Kording & Wolpert, 2004; Trommershauser et al., 2003), while also suggesting that without extensive practice, individuals may rely on their best memories of related tasks. At the same time, it is important to note that the results of the present study do not necessarily suggest that the consideration of movements at a natural pace is a better explanation than other potential hypotheses for the results of previous studies (Slifkin, 2008; Young et al., 2008). It is not clear how results from our previous studies would fit into the continuum of MT identified in the present study. Changes in imagined MT within a constant value of ID (Young et al., 2009) seem to fit between the results from the Natural and Quick conditions, whereas the expected MT contours from movement decisions (Young et al., 2008) would seem to fit between the results from the Quick and Fastest conditions. Therefore, a more definitive understanding of the origin of our participants' decisions and imagined movements cannot be identified at the present time.

The results of the present study also refute Tanaka et al.'s (2006) hypothesis that the brain always favors the fastest movement that can satisfy the desired endpoint accuracy. According to Tanaka et al.'s approach, as movement speed increases, the effective target W should also increase. Although this was true for all targets in the present study (see Table 1), movement speed varied more than predicted by the changes in effective D and W. Natural and Quick conditions' movements had a greater MT than those from the Fastest condition, indicating that individuals favored the fastest movement only when specifically trying to make the fastest movement. In the other conditions, individuals preferred slower movements.

What other factors could be used to determine an individual's preferred movement speed? Tanaka et al. (2006) used an optimal control framework and suggested that movements are planned using a cost function that minimizes MT. Meanwhile, other researchers have suggested approaches that minimize movement factors such as energy, jerk, or torque change (Hoff, 1994; Nelson, 1983; Todorov & Jordan, 2002; Uno, Kawato, & Suzuki, 1989). It is possible that individuals may choose different speeds of movement by changing the relative weightings of these various factors when planning the movement (Mazzoni, Hristova, & Krakauer, 2007; Shadmehr & Krakauer, 2008). MT would be a dominant factor when attempting to move as fast as possible, whereas one or more other factors would become more important when attempting to move at other speeds. Data from the present and future studies, in combination with models of movement planning, can lead to a better understanding of the way these cost functions change with an individual's change in movement objectives.

In addition to the particular hypotheses under question, the results of the present study also suggest a general approach for describing the pattern of MT for target-directed hand movements of various speeds. Although it has been clear that the MT for movements made as quickly as possible can be described by Fitts's law, it has not been clear how to describe the MT of movements made at any other speed, or even if there was a consistent pattern in the MT of movements made at other speeds. The results of the present study show that there are consistent and parsimonious patterns for the MT of movements made at speeds less than the fastest possible; MT can be represented as a sum of the speed–accuracy trade-off used in Fitts's law and the D to the target. As movement speed changes, the relative contributions of the two factors also change, with D playing a larger role in slower movements and the D/W factor playing a larger role in the faster movements. This is similar to the observation Sheridan (1979) made in which he identified that the factors involved in the task can have an effect on the form of the specific speed–accuracy trade-off that applies. In this case, the goal of the individual plays a role in determining how much the target D affects MT.

The idea that the speed–accuracy trade-off of movement can vary between tasks—and even between goals within the same task—is also valuable for the way that the speed–accuracy trade-off of movement is used in other fields of research. Fitts's law has been used in several areas as a model for the speed–accuracy trade-off of movement in those domains. At the same time, it is not clear that Fitts's law is the correct form for the speed–accuracy trade-off in each of those situations. For example, researchers have advocated using Fitts's law as a model for movement when individuals interact with objects on a computer screen (e.g., Zhai, 2004). However, the average computer user likely moves at a speed more similar to the comfortable or quick movements in the present study, and not at movements made as quickly as possible. Similarly, Fitts's law has been used as a model against which to assess vividness in motor imagery of walking (Bakker, de Lange, Stevens, Toni, & Bloem, 2007; Stevens, 2005), yet the data reported by at least two studies of motor imagery during walking show a substantial variation in MT with D within values of ID (Jeannerod; Stevens). In both of these domains (i.e., human–computer interaction and motor imagery during walking), using Fitts's law as a model of MT may underestimate the importance of D in determining MT. To alleviate this problem, the form of the speed–accuracy trade-off that applies to each specific domain could be measured and used to provide a more accurate model of MT.

In the present study, we evaluated two hypotheses describing an infrequently researched topic: the MT of target-directed movements made at a comfortable pace. We found support for a hypothesis gleaned from individuals' predictions in naive motor decisions and imagined movements, predicting ways in which the MT of comfortable movements would be different from Fitts's law. We also found that a hypothesis based on the adjustment of effective target W did not accurately describe MT. The results of the present study show that prospective motor predictions, even when apparently incorrect, may still provide insight into the movements in question or related movements. In this case, although individuals' predictions about speeded movements were incorrect, they accurately identified previously unknown regularities in movements made at slower speeds. This research also suggests that there is value in studying movements made at a pace other than the fastest possible. Although fast movements may uncover limitations of the motor system, movements at a self-selected pace may uncover something just as valuable, such as the preferences that guide everyday motor behavior.

## NOTE

1. All ID values cited in the present article are based on the Shannon formulation of Fitts's Law: ID = $\log_2(D/W + 1)$; (I. S. MacKenzie, 1989).

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