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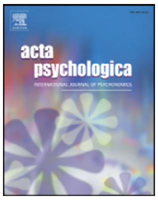

Degree of target utilization influences the location of movement endpoint distributions

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ABSTRACT

According to dominant theories of motor control, speed and accuracy are optimized when, on the average, movement endpoints are located at the target center and when the variability of the movement endpoint distributions is matched to the width of the target (viz., Meyer, Abrams, Kornblum, Wright, & Smith, 1988). The current study tested those predictions. According to the speed-accuracy trade-off, expanding the range of variability to the amount permitted by the limits of the target boundaries allows for maximization of movement speed while centering the distribution on the target center prevents movement errors that would have occurred had the distribution been off center. Here, participants ($N = 20$) were required to generate 100 consecutive targeted hand movements under each of 15 unique conditions: There were three movement amplitude requirements (80, 160, 320 mm) and within each there were five target widths (5, 10, 20, 40, 80 mm). According to the results, it was only at the smaller target widths (5, 10 mm) that movement endpoint distributions were centered on the target center and the range of movement endpoint variability matched the range specified by the target boundaries. As target width increased (20, 40, 80 mm), participants increasingly undershot the target center and the range of movement endpoint variability increasingly underestimated the variability permitted by the target region. The degree of target center undershooting was strongly predicted by the difference between the size of the target and the amount of movement endpoint variability, i.e., the amount of unused space in the target. The results suggest that participants have precise knowledge of their variability relative to that permitted by the target, and they use that knowledge to systematically reduce the travel distance to targets. The reduction in travel distance across the larger target widths might have resulted in greater cost savings than those associated with increases in speed.

1. Introduction

According to an influential model—the stochastic optimized submovement model—on the average, movement endpoints should occur at the target center (Meyer, Abrams, Kornblum, Wright, & Smith, 1988, p. 346). In addition, the same model predicts that noise in the motor system gives rise to a normal, symmetrical distribution of movement endpoints and the size of the distribution should be scaled to the size of the target region (Meyer et al., 1988, p. 346). Ideally, participants would produce a distribution of movement endpoints that would fill the target region, without exceeding the target boundaries (Zhai, Kong, & Ren, 2004, p. 825). The advantage of making use of the full range of permissible variability is that it allows movement speed to be maximized. That is, it is well known—according to the movement speed-accuracy trade-off—that a consequence of moving faster is increased movement endpoint variability (e.g., Elliott et al., 2010; Elliott, Helsen, & Chua, 2001; Fitts, 1954; Meyer et al., 1988; Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979; Woodworth, 1899).

If variability has expanded to the limits of the target region, then centering the distribution of movement endpoints on the target center becomes especially important. In that case, if the endpoint distribution center deviates from the target center, then one of the distribution tails would extend beyond the edge of the target boundary, resulting in an increase in movement errors. Thus, maximizing movement speed and accuracy would entail coordination between 1) the planning of movement endpoints to reach the target center and 2) scaling the amount of movement endpoint variability to the width of the target. The main purpose of the current study was to examine the predictions that distributions of movement endpoints should be centered on the target center and the range of distribution variability should be scaled to the size of the target region and should fill the target region (Meyer et al., 1988, p. 346; Zhai et al., 2004, p. 825). In addition, we were interested in examining the potential coordination of (i.e., dependencies between) mean movement endpoint location and the amount of endpoint variability.

Some research has reported how the spatial variability of endpoint distributions varies with increases in the target width: Both Welford (1968) and Meyer et al. (1988) reported that the scatter of movement endpoints was larger than the narrowest targets they used, but the

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scatter of movement endpoints did not take up the full width of their widest targets. More recent research by Zhai et al. (2004) examined the range of variability produced relative to the range permitted by the target (target utilization) as a function of the movement amplitude requirement and the target width conditions. The results of that study showed that target utilization decreased as the target width increased and target utilization changed to a much lesser extent as the movement amplitude requirement varied (Zhai et al., 2004: Table 2, p. 832; Fig. 10, p. 841; Table 8, p. 842). However, the reports by Welford (1968), Meyer et al. (1988), and Zhai et al. (2004) did not include formal statistical analyses of mean movement endpoint locations relative to target center locations. For example, Meyer et al. (1988, Footnote 24, pp. 354–355) reported that deviations of the mean movement endpoint location from the target center (constant error) were negligible, and Zhai et al. (2004, Footnote 2, p. 826) thought such deviations should be small and instead they focused their analyses on the variability of endpoint distributions (effective target width). In addition, like the vast majority of studies on targeted aiming (Plamondon & Alimi, 1997, Table 3, p. 293), the aforementioned studies used a limited range of small target widths (Meyer et al., 1988, Table 3, p. 352: 1.66 to 6.34 angular degrees; Welford, 1968, Fig. 5.6, p. 155: 4 to 32 mm; Zhai et al., 2004, Experiments 1 to 3: 2.47 to 14.80 mm).

In the current study, participants were required to perform in a cyclical aiming task under instructions of movement speed and accuracy (e.g., Fitts, 1954; Slifkin & Eder, 2012; Slifkin & Eder, 2014). Participants produced aiming movements across a wide range of movement amplitude requirements (the distance between target centers) and target width conditions (the region specifying the degree of tolerance for endpoint variability): There were three movement amplitude requirements (80, 160, 320 mm) and five target widths (5, 10, 20, 40, 80 mm), producing 15 unique conditions. We were interested in examining the influence of target width and movement amplitude requirements on the mean location of distributions of *overall* movement endpoints and on the variability of those distributions. An overall movement can terminate either after a primary submovement, or, if necessary, after one or more corrective, submovements (Meyer et al., 1988). In either case, it is predicted that the mean of a distribution of overall movement endpoints should be centered on the target center and the range of variability of the distribution of overall movement endpoints should fill, but not exceed, the target region (Meyer et al., 1988; Zhai et al., 2004). In the current study, we were interested in testing those predictions for distributions of overall movement endpoints. In addition, we were interested in examining potential dependencies between mean movement endpoint location and the amount of movement endpoint variability. Namely, we examined the correlation between mean movement endpoint location (constant error) and a measure of target utilization reflecting the difference between the size of the target (target width) and the amount of movement endpoint variability (effective target width).

2. Method

2.1. Participants

Twenty healthy, young individuals, ten of whom were female, served as participants. The mean age of all participants was 19.15 ($SD = 1.31$), and all reported that they were right-hand dominant, had no prior history of neurological disease or damage, and had normal or corrected-to-normal vision. They responded to an advertisement made to students enrolled in introductory psychology courses. The advertisement requested that volunteers be healthy, right-handed, and between the ages of 18 and 30. Each participant provided informed consent that was approved by the local institutional review board. Upon completion of the experiment, they were given credit for the course in which they were enrolled. The study was conducted in accord with the ethical standards of the 1964 Declaration of Helsinki.

2.2. Apparatus

Movements were made on a 305 by 457 mm graphics tablet (Wacom Intuos2) using its cordless mouse (Wacom Intuos2 4D Mouse), and target displays were viewed on a 470 mm flat screen LCD video monitor (Acer X183H) with a refresh rate of 75 Hz and viewable dimensions of 230 mm in height by 430 mm in width. The graphics tablet was placed on a tabletop with a height of 743 mm and the video monitor was placed on a stand that, in turn, was placed on the tabletop. (Placing the video monitor on the stand raised the height of the video monitor by 235 mm so that the center of the video monitor was at eye level for the typical participant.) The tablet was placed directly in front of the video monitor, and when a participant was seated at the table their body midline was aligned with the midline of the tablet and monitor. Participants were allowed to adjust the chair to a comfortable height and distance from the table; the approximate distance from participants' eyes to the video monitor was 660 mm.

2.3. Procedure

Customized software ran the experimental contingencies and presented the target displays. Each target display consisted of two targets that were equidistant from the center of the monitor. The targets appeared as thin, white rectangular outlines overlaying a black background. Target height—the dimension of the target perpendicular to the primary direction of aiming—was always set at 139.70 mm. There were three movement amplitude requirements where the distance between target centers was 80, 160, or 320 mm, and at each movement amplitude requirement, participants performed under each of five target widths: 5, 10, 20, 40, or 80 mm. The combination of the movement amplitude requirements and target widths produced 15 unique target display conditions.

During each condition, a single target display was presented and 100 consecutive cyclical aiming movements were completed. During that time, a cursor was continuously displayed on the video monitor. The x-dimension control-to-display mapping was 1:1 such that a unit of mouse movement along the x-dimension of the graphics tablet translated to a unit of cursor movement along the x-dimension of the video display. The y-dimension control-to-display gain was 1.33:1.00 such that a unit of mouse movement along the y-dimension of the graphics tablet resulted in 0.75 units of cursor movement along the y-dimension of the video display. All data presented in this report came from the x-dimension of movement. Throughout each movement, data acquisition occurred every 15 or 16 ms ($M \approx 15.5$ ms), which translates to instantaneous acquisition rates of either 66.67 or 62.50 Hz ($M \approx 64.52$ Hz), respectively. The spatial resolution of each sample was 0.1 mm.

At the start of the experimental session, the experimenter demonstrated the movement task and concurrently delivered the task instructions. Participants were instructed that white crosshairs would serve as a *cursor* and its position on the video monitor would correspond to the position of the mouse on the graphics tablet. At the start of each movement condition, a white *marker*, also in the form of crosshairs, would appear in the center of the left target. Participants were told that the marker crosshairs identified the currently active target; however, it was emphasized that a target hit would register if the cursor crosshairs “landed” anywhere within the active target region at the time of a mouse button press. In contrast, any button press occurring when the cursor crosshairs were outside of the target would be classified as a target miss and would be accompanied by a “beep” sounded by the computer. Thus, it was the x-axis location of the movement trajectory at the time of the button