



Task specificity and the timing of discrete aiming movements

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ARTICLE INFO

Keywords:

Speed and accuracy trade-off
Space-time constraints
Movement trajectory
Sub-movements

ABSTRACT

In discrete aiming movements the task criteria of time-minimization to a spatial target (e.g., Fitts, 1954) and time-matching to a spatial-temporal goal (e.g., Schmidt et al., 1979) tend to produce different functions of the speed-accuracy trade-off. Here we examined whether the task-related movement speed-accuracy characteristics were due to differential space-time trade-offs in time-matching, velocity-matching and time-minimizing task goals. Twenty participants performed 100 aiming trials for each of 15 combinations of task-type (3) and space-time condition (5). The prevalence of the primary types of sub-movement (none, pre-peak, post-peak, undershooting and overshooting) was determined from the kinematics of the movement trajectory. There were comparable distributions of trajectory sub-movement profiles and space-time movement outcomes across the three tasks at the short movement duration that became increasingly dissimilar over decreasing movement velocity and increasing movement time conditions. Movement time was the most influential variable in mediating sub-movement characteristics and the spatial/temporal outcome accuracy and variability of discrete aiming tasks – a role that was magnified in the explicit task demands of time-matching. The time-matching and time-minimization task goals in discrete aiming induce qualitatively different control processes that progressively contribute beyond the minimal time conditions to task-specific space-time accuracy and variability characteristics of the respective movement speed-accuracy functions.

The speed-accuracy trade-off, whereby moving a limb more quickly to an aimed target (time-minimization task) tends to decrease movement spatial accuracy, is one of the most robust findings in motor control (Fitts, 1954; Gueugneau, Pozzo, Darlot, & Papaxanthis, 2017; Plamondon & Alimi, 1997; Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979; Woodworth, 1899). Several functions for this general trend of the movement-speed spatial accuracy relation have been proposed. Moreover, the number of sub-movements in the trajectory of aiming movements has been related to the extant linear (Schmidt et al., 1979), logarithmic (Fitts, 1954) and square-root (Meyer, Abrams, Kornblum, Wright, & Smith, 1988) speed-accuracy functions. Of particular relevance here is that the task criteria of time-minimization to a spatial target (e.g., Fitts, 1954) and time-matching to a spatial-temporal goal (e.g., Schmidt et al., 1979) tend to produce different functions of the speed-accuracy trade-off.

In contrast, timing accuracy improves in time-matching discrete aiming tasks with an increase in average movement velocity, even to the same task movement time (Newell, 1980; Newell, Carlton, Carlton, & Halbert, 1980; Tresilian, Plooy, & Carroll, 2004). These divergent trends in the movement speed-accuracy relation reflect that human movement takes place in both space and time and that error in each dimension is measured with respect to the other (Newell, 1980; Hancock & Newell, 1985). Furthermore, Hancock and Newell (1985) proposed that movement error in one dimension (space) can be traded for movement error in the other dimension

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<https://doi.org/10.1016/j.humov.2019.02.009>

Received 21 August 2018; Received in revised form 10 December 2018; Accepted 17 February 2019

Available online 22 February 2019

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(time), and vice-versa. There has been growing evidence for a cohesive space-time interpretation to the relation between movement speed and accuracy (e.g., Bongers, Fernandez, & Bootsma, 2009; Gori, Rioul, & Guiard, 2018; Heitz, 2014; Hsieh, Pacheco, & Newell, 2015; Kim, Carlton, Liu, & Newell, 1999).

In this study, we investigate the timing of discrete aiming tasks through the influence of spatial and temporal task constraints on the characteristics of trajectory sub-movements and their relations to movement outcome. Research on movement speed and accuracy has used predominantly two experimental paradigms that have operationally defined and emphasized spatial and/or temporal goals for studying the effect of speed-accuracy trade-offs. The time-matching paradigm constrains movement temporally and requires the participant's movement time to match an explicit time criterion (e.g., Schmidt et al., 1979; Woodworth, 1899). In contrast, the time-minimization task constrains movement outcome spatially and requires participants to move to the spatial target as fast and accurately as possible, as in the Fitts' Law experimental set-up (e.g., Fitts, 1954; Fitts & Peterson, 1964). The two types of task are, however, not as distinct as implied in the labels of time-minimization and time-matching.

In the Fitts' aiming protocol a specific target size and a particular tolerance of the miss rate (that usually is not reported) sets up the spatial constraint under an "as fast as possible" temporal condition. The temporally emphasized time-matching task, however, is usually designed with a specific task movement time goal while aiming for a spatial point or a line target. The spatial error from this target is also typically determined as it is usually part of the task goal (Hsieh et al., 2015). These differences lead the time-minimization and time-matching tasks to have a different set of task priorities on the movement space-time constraints.

In early studies on discrete aiming movements, Woodworth's (1899) proposal of a current control phase held (in effect) that a closed-loop control mechanism was used to guide a corrective movement toward a target and this phase was a significant factor in determining movement accuracy. Indeed, the central contemporary explanation of sub-movement still holds that when the primary sub-movement misses the target, the secondary sub-movement(s) is/are performed and correct(s) the movement error based on sensory information (e.g., Carlton, 1980; Crossman & Goodeve, 1983; Elliott & Khan, 2010). Woodworth's model of limb control provided the basis of subsequent efforts to decompose discrete aiming movements into sub-movements or units and develop models of movement control in rapid aimed movements (Carlton, 1980; Crossman & Goodeve, 1983; Elliott, Helsen, & Chua, 2001; Meyer et al., 1988; Walker, Philbin, Worden, & Smelcer, 1997).

In an error correction feedback model, Crossman and Goodeve (1983) proposed that a series of sub-movements was the result of visual feedback of the evolving trajectory and would vary according to the ratio between movement amplitude and target width. In terms of speed and accuracy, the number of sub-movements would increase when movement amplitude/target width become longer/smaller while intending to hit a target as quickly and accurately as possible. The initial movement or primary sub-movement generally fell short/long of the target, and was followed by corrective movements that brought the effector unit to either hit or be close to the target (Carlton, 1979; Meyer et al., 1988). More recently, Meyer et al. (1988, 1990) proposed a stochastic optimized sub-movement model of discrete aiming where the noise of system is higher in faster velocity movements (Schmidt et al., 1979) and the outcome is the product of optimizing the relative durations of the primary initial impulse and sub-movement segment of the movement trajectory.

Open-loop control processes have also been postulated as the main control mechanism when the sensory information is either unavailable or unusable given the time constraints (e.g., Plamondon & Alimi, 1997; Schmidt et al., 1979). Without movement corrections, the primary sub-movement (initial impulse) is rapid and relatively invariant in a way that is set-up before the movement is initiated (Elliott et al., 2001; Keele, 1968). Wright and Meyer (1983) proposed the temporal-precision hypothesis that movement kinematics are characterized as having a single acceleration and deceleration profile when the duration of task temporal requirement is short so as to prevent exploiting feedback information.

Recently, Hsieh, Liu, and Newell (2017) used Chua and Elliott (1993) algorithms to examine the characteristics of sub-movements across different amplitudes with a broad range of movement space and time criteria in a time-matching task. Four types of sub-movements were defined based on the trajectory velocity and acceleration profiles. The first (pre-peak) and second (post-peak) types of sub-movements were associated with acceleration deviation before and after peak velocity, respectively. The last two sub-movement types were associated with zero crossing of the velocity (overshooting) and acceleration (undershooting) profiles. The results showed that the overall number of sub-movements increased the longer the movement time criterion. In addition, there was only a very limited occurrence of sub-movements under a fast average movement velocity condition that showed predominantly an overshooting type of sub-movement.

An overshoot might not, however, be a correction that corresponds to reversals in the direction of the movement as in traditional closed-loop interpretations. Motion termination is a process that is necessary to stop the effector unit from moving at the target region (Dounskaja, Wisleder, & Johnson, 2005). By contrast, the number of sub-movements with pre- and post-peak type increased with a longer duration movement time criterion. These two types of sub-movement might reflect movement fluctuations rather than error correction in the low velocity condition (Fradet, Lee, & Dounskaja, 2008). Nevertheless, the existence of a sub-movement as a basic unit in the production of a variety of limb movements has received considerable support (Buchanan, Park, & Shea, 2006; Elliott et al., 2001; Jagacinski, Repperger, Moran, Ward, & Glass, 1980; Meyer et al., 1988; Milner, 1992; Morasso, Ivaldi, & Ruggiero, 1983; Shmuelof, Krakauer, & Mazzoni, 2012) although, as reflected in the above contrasting viewpoints, the interpretation of an error correction from a movement kinematic trajectory is not straightforward.

The extant speed-accuracy studies collectively point to the proposition that the movement time is a significant determiner of spatial and temporal accuracy and variability and the prevalence of the different types of sub-movements in discrete aiming movements. This is particularly the case in the time-matching protocol where movement times can be relatively longer with average velocities lower than in the time-minimization protocol. Moreover, and unlike the time-minimization protocol, the time-matching protocol provides no informational cues in the task environment, other than the initial instruction and trial feedback, that directly

relate to the movement time criterion that needs to be matched.

Carlton (1994) was the first to contrast directly the movement speed-accuracy trade-off in time-minimization and time-matching tasks under what were constructed to be essentially identical space-time movement constraints. Individuals were required to produce discrete aiming movements to match a 400 ms movement time criterion and then the obtained dispersion of 95% of movement outcome was used as the target width in a subsequent spatially constrained task. The results showed that movement time was shorter with two sub-movements rather than a single sub-movement (i.e., temporally constrained task) in the spatially constrained task even though movement accuracy was similar between the two tasks. However, the task space-time constraints of the two task protocols in Carlton's study were not equally controlled by the participants (Bongers et al., 2009; Hsieh, Pacheco, & Newell, 2016). Hsieh et al. (2016) have shown that by keeping the movement time and target width the same in the time-matching and time-minimization tasks, the respective space-time movement outcomes share similar distributional properties regardless of task category, but these findings were limited to a single rapid space-time movement condition.

In the present experiment, we investigate the spatial and temporal movement outcome error and characteristics of sub-movement trajectories in three discrete aiming movements that had different task goals. We manipulated movement time with a fixed amplitude and target size for the temporally constrained task (T_c) and also used the corresponding standard deviation of spatial errors from the T_c task as target widths for participants instructed to move as quickly and accurately as possible for a spatially constrained task (S_c) (Carlton, 1994). In a third task called velocity constraint task (V_c), we set up different amplitudes with a fixed time goal to match the average movement velocity that resulted from T_c task. As velocity is the ratio between a distance and time, a matching average velocity with fixed time but varying distance would compare/contrast the similar velocity conditions in the T_c task.

These manipulations provided us an opportunity to examine the contribution of space-time accuracy constraints in the timing of different types of discrete aiming tasks. We also used individually determined speed-accuracy criteria for the discrete movement protocols in contrast to the general externally derived space-time criteria for the speed-accuracy tasks. Given that the participants have different capacities for movement speed and accuracy the experimental time criteria were established on an individual intrinsic dynamic basis from pre-experiment speed-accuracy testing to provide representative proportional average movement velocity conditions. This holds similarities to the individual testing conditions in force variability protocols set-up as a percent of maximum voluntary contraction (e.g., Slifkin & Newell, 1999).

We examined three related hypotheses that: a) there would be a similar profile of sub-movements and movement space-time outcome accuracy and variability across discrete task types (time-minimization, time-matching, velocity matching) when the space-time accuracy requirements are comparable and the overall movement time is short producing close to maximal average movement velocity; b) the pre-peak and post-peak types of sub-movements will be most prevalent from middle to slow average velocity through longer movement times; and c) the overshooting or motion termination types of sub-movements would occur more often when participants were required to match a fast time goal in order to stabilize the arm-hand effector unit. This integrated approach to the analysis of movement outcome and trajectory sub-movements allows analysis of the differential engagement of control mechanisms as a function of the primary types of discrete space-time aiming tasks.

1. Methods

1.1. Participants

Twenty right-handed healthy adults volunteered for the experiment. The age of the participants ranged from 20 to 35 years, and all self-reported that their dominant hand was the right hand. Each participant provided informed written consent and the Research Ethic Committee at the National Taiwan Normal University approved all the experimental procedures.

1.2. Apparatus

Discrete aiming movements were made on a 770 mm × 465 mm digital tablet monitor (WACOM Cintiq 27, Model DTK-2700/K0-CX) using its cordless stylus (Pro pen, Model KP-503E) with a weight of 18 g, and target displays were viewed on an active surface area of 596.7 mm × 335.6 mm. The digital tablet monitor (will be referred to as the tablet from here on) was angled 15° forward on the tabletop and connected to a PC computer (the pixel range was set at 1680 × 1050). The tablet was placed directly in front of participants. A customized software running the experimental protocol was used to preset different goal criteria of movement time, target size and amplitude in different conditions and calculate the movement spatial, temporal errors and movement time for the participants immediately after each trial. The actual distance moved by the stylus on the tablet corresponding to the distance moved by the cursor was 1:1 and the sample frequency for data acquisition was 130 Hz.

1.3. Experimental task and design

1.3.1. Pre-testing

Prior to the experiment proper each participant performed an individualized pre-testing procedure to determine the individual specific space-time experimental conditions (intrinsic dynamics) of the T_c task. In this preliminary testing each participant completed 4 target-width conditions (1, 5, 20, and 100 mm squared targets) of the discrete aiming tasks all with 30 cm movement distance and 20 trials in each condition. The participants were instructed to perform these tasks as fast and accurately as possible. The trial was repeated if the target was missed.

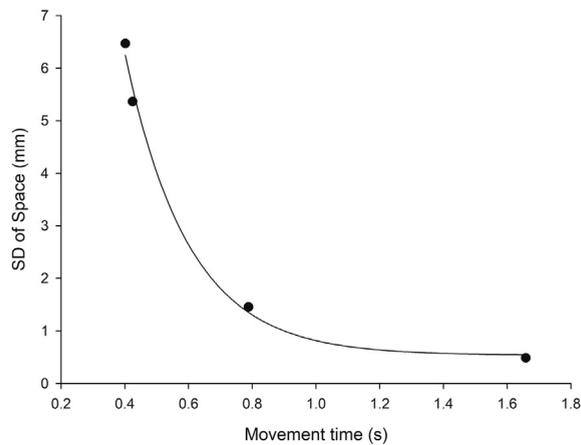


Fig. 1. Curve fitting of the pretest data of an individual for determining temporal criteria in time-matching task (T_c).

We then plotted the average movement time over the standard deviation of the end point distribution in the movement direction from the pretest data for individual participants, and fit the data with a 3-parameter exponential decay function, $y = y_0 + ae^{-bx}$ (Fig. 1). Fig. 1 shows that when a shorter movement time was emphasized the spatial variability was increased and vice versa. We used the times on the curve where the first derivative of the exponential function on those time points were -10 , -5 , -1 , -0.2 , and -0.1 mm/s as the bases to generate the five criteria times of the T_c task. The five locations on the space-time curve represented five spatial distribution-movement time ratios under the specific task constraints and could be described relatively as the fast (-10 mm/s), fast-middle (-5 mm/s), middle (-1 mm/s), middle-accurate (-0.2 mm/s), and accurate (-0.1 mm/s) conditions.

1.3.2. Experimental test conditions

The general task goal was to perform a sliding movement from left (home position: $2\text{ mm} \times 2\text{ mm}$) to right and hit the target with a stylus on the tablet. Every participant performed all of the 3 task-types each with 5 space-time conditions. The 3 tasks were temporally constrained (T_c), spatially constrained (S_c), and velocity constrained (V_c). All participants started with the T_c task using the individualized time criteria generated from the pre-test. The average movement time criteria of the 5 conditions were: fast 419 ± 48 ms, mid-fast 747 ± 142 ms, mid 1076 ± 270 ms, mid-accurate 1597 ± 376 ms, and accurate 2115 ± 594 ms, all with amplitude of 30 cm and target size of 1 mm. Participants were instructed to produce the sliding movements with a duration that matched the specific time goal in the five different conditions.

The criteria for each condition for the S_c and V_c tasks were developed for each participant from the results of the T_c task. For the S_c task, the target width for each of the 5 conditions was determined by multiplying 4.133 by the standard deviation of spatial error of the respective 5 conditions in the T_c task (Welford, 1968). The average target sizes of the 5 conditions for the S_c task were fast 26 ± 6 mm, mid-fast 13 ± 5 mm, mid 9 ± 4 mm, mid-accurate 6 ± 2 mm, and accurate 5 ± 2 mm, all with 30 cm amplitude. Participants were instructed to move as fast and accurate as possible to hit the target. The trial was repeated if the target was missed until 100 successful trials were recorded.

For the V_c task, the average velocity of the 5 conditions matched those of the 5 conditions in T_c task. This was done by varying the movement amplitude that was derived by multiplying the average velocity by the shortest average movement time of the T_c task. The average movement amplitudes of the 5 conditions for the V_c task were fast 30 cm, mid-fast 17.3 ± 3.2 cm, mid 12.4 ± 3.3 cm, mid-accurate 8.2 ± 1.6 cm, and accurate 6.3 ± 1.5 cm with target size of 1 mm. Participants were instructed to aim for the target and perform the sliding movement whose duration matched the single criterion time.

All participants completed 3 tasks \times 5 conditions over 3 days and each space-time condition consisted of 100 trials. It took approximately 1.5 hr to complete the pretest and the T_c task on day 1. The S_c and V_c tasks each took about 1 hr on day 2 and day 3. The order of the S_c and V_c tasks was counterbalanced among participants and the order of the 5 conditions within a day was randomly determined.

1.4. Procedures

The experimental procedures were identical for all tasks and conditions. The participant sat on a chair and was allowed to adjust the chair to a comfortable height and distance for working at a desk. Their body midline was aligned with the center of the digital tablet. The participants were given specific instructions before the start of each task/condition. The participant picked up the stylus to touch the tablet. A cursor (1 mm in diameter) showed up on the digital tablet. The participant then moved the cursor onto the home position. There was a beep sound from the computer once the participant had the stylus touched the home position for around 600 ms. Participants began a trial once they were ready after the beep sound and were informed not to respond to the beep sound as fast as possible because this was not a reaction time task. There was no trace of the stylus from the sliding movement that might be used as the concurrent feedback. Participants received terminal feedback in time (movement time for the S_c task; signed timing errors

for the T_c and V_c tasks) and space (spatial error from the center of the target) on the tablet immediately after completion of each trial for a few seconds. The participant returned the stylus back to the home position to start next trial once he/she was ready.

The initiation of movement was determined when the movement velocity exceeded a threshold of 3 mm/s for 30 ms and the termination of the movement was identified when the movement velocity was below 3 mm/s for 30 ms. The stylus was to remain in contact with the tablet during the whole movement until the trial was completed. The trial was finished once the stylus came to a stop or left the tablet surface. At the start of each task condition, 20 practice trials were performed to familiarize the participants with the appropriate movement time and target conditions. After each condition, a 5 min rest was provided to minimize boredom or fatigue effect. The last 90 trials for each task condition of each participant were used for data analyses to ensure a more stable performance of each manipulation.

1.5. Data analyses

1.5.1. Sub-movements

The movements of target aiming were performed primarily along the X coordinate, therefore, although the movement trajectory was recorded on both the horizontal (X) and vertical (Y) coordinates of the stylus tip on the tablet, only the displacement data recorded on the X coordinate were analyzed. The raw displacement data were low-pass filtered (second-order Butterworth filter, cutoff frequency 5 Hz). Movement velocity and acceleration were calculated as the first and second derivatives of movement displacement, respectively.

To examine the properties of the sub-movements, we used the algorithms described by Chua and Elliott (1993) to detect different types of sub-movements within a trial. Four types of sub-movements were defined as in a previous experiment (Hsieh et al., 2017). The first two types of sub-movements were related to a significant deviation from the acceleration profile in the period between start of the movement and peak velocity (pre-peak) and between the peak velocity and the end of the movement (post-peak). A search for a reversal point to identify significant deviations in the acceleration profile other than the first peak acceleration was performed. If a reversal point was found, then the subsequent reversal point was marked. Once these two reversal points were identified, two criteria had to be satisfied. First, the amplitude between these two reversal points had to fulfill at least 10% of the maximum absolute amplitude in acceleration. Second, the duration of these two points should equal or exceed 72 ms.

The third type of sub-movements was identified as undershooting where a zero crossing from negative to positive value that occurred following the peak velocity in the acceleration profile. The amplitude of such transition in acceleration corresponds to the velocity profile had to equal or exceed 50 mm/s. The last type of sub-movements was overshooting where the movement reversal had occurred. In addition to identifying a change in the sign of velocity, for the overshooting sub-movements, the absolute amplitude of negative velocity had to maintain above 10 mm/s. We counted the number of respective types of sub-movement and total number of sub-movements within a trial. In addition, the incidence of different types of sub-movement was computed for each condition as the number of trials with respective type of sub-movement divided by the total number of trials performed in this condition.

1.5.2. Statistical analyses

The movement times of the T_c and V_c tasks were compared with the criterion times of each condition, respectively, using paired t tests. Additionally, a one-way repeated measure ANOVA was used to examine the movement times of the fast condition of the T_c task and all conditions of the V_c task because these task conditions shared the same movement time criterion. The movement times of the 5 conditions in the S_c task were compared with the 5 conditions of the T_c task, respectively, using paired t tests to examine the effect of task constraint on the movement time performance.

Multivariate analysis of variance (MANOVA) was used to examine the effect of the space–time conditions and movement task-types on each performance variable that included the standard deviation of the movement time as the temporal error, the spatial constant error to the target position, and the standard deviation of the spatial constant error. In addition, repeated measure ANOVAs were used to examine the effects of the tasks and the space-time conditions on the number of sub-movement and the proportional incidence of each sub-movement type. The Greenhouse–Geisser method was used to correct for violations of sphericity and the Bonferroni correction was applied for the post hoc comparisons, with partial eta square (η_p^2) revealing the effect size.

2. Results

2.1. Movement times

We first compared the movement times of the T_c task with their individual criterion times. Paired t -tests showed that only the movement times in the fast condition were significantly longer than the criterion times, $t(19) = 3.51$ ($p < .01$), the fast-mid, $t(19) = 0.96$, mid, $t(19) = 0.20$, mid-accurate, $t(19) = -0.07$, and the accurate, $t(19) = -0.33$, conditions were all not different from the respective criterion times ($ps > .3$). We also compared the movement times of all 5 conditions of the V_c task with the shortest criterion times of the T_c task because those were the criterion times used in the V_c task. The results from the paired t -tests showed no significant differences for the mid, $t(19) = -0.11$, $p = .92$, mid-accurate, $t(19) = -0.16$, $p = .87$, and the accurate conditions, $t(19) = 0.16$, $p = .87$, but the fast, $t(19) = -2.55$, $p < .02$, and the fast-mid, $t(19) = -2.05$, $p = .06$, conditions showed the trend of longer than the criterion times.

Given that the fast condition of the T_c task and all five conditions in the V_c task shared the same criterion time, we performed a one-way repeated measure ANOVA on the movement times of the 6 conditions to check if the movement times performance of these

Table 1
Average movement times and movement time SDs (ms) in 5 conditions of 3 tasks.

task	Condition				
	fast	fast-mid	mid	mid-accurate	accurate
Time-constrained	471.40	772.29	1085.48	1593.02	2079.49
	68.52	142.22	271.61	380.36	562.40
Space-constrained	409.98	565.66	653.63	726.58	836.59
	54.89	96.31	139.18	173.61	223.11
Velocity-constrained	457.23	447.78	420.63	421.48	416.54
	68.46	54.33	54.80	53.74	53.50

conditions were different from one another. The results showed a significant condition effect, $F(5, 95) = 13.15, p < .001, \eta_p^2 = 0.41$, and the post hoc paired comparisons revealed that the fast condition of the T_c task and the fast and the fast-mid conditions of the V_c task were not different from one another ($ps > .2$) but all were significantly longer than the mid, mid accurate, and the accurate conditions of the V_c task ($ps \leq .05$). The movement times of the mid, mid-accurate, and the accurate conditions were not different from one another ($ps = 1$).

Unlike the T_c and V_c tasks where the participants were instructed to match the specific criterion times as the task goal, the movement times of the S_c task were the emergent property of the spatial target sizes that were based on the spatial distribution of the end points of the respective conditions of the T_c task. Therefore, the paired t -tests were used to compare the movement times between the S_c and T_c tasks for each condition. The results showed significant differences for all conditions, the fast condition, $t(19) = 5.23$, fast-mid condition, $t(19) = 8.96$, mid condition, $t(19) = 8.03$, mid-accurate condition, $t(19) = 9.33$, and the accurate condition, $t(19) = 9.39, ps < .001$. The movement times from the 5 conditions of the S_c task were all shorter than those of the T_c task. Table 1 presents the movement times and the movement time SDs of the 5 conditions of the 3 tasks.

2.2. Temporal and spatial measures of performance

Fig. 2 shows the relation between movement time and movement spatial variability for each of the three tasks as a function of their imposed spatial and temporal criteria. The Figure illustrates that decreasing movement time is accompanied by an increase in spatial error in a way that follows the established general trend of the speed-accuracy trade-off. The performance outcomes fell in a similar range in the fast condition, and gradually diverged from the near-maximum average movement velocity. These findings show the qualitatively different functions of the movement speed and accuracy trade-off in each of the three types of aiming tasks.

We examined the overall movement speed-accuracy effects with a MANOVA. The two way (3 tasks \times 5 conditions) MANOVA showed a significant main effect for tasks, $F(6, 72) = 26.47, p < .001$, Wilk's $\Lambda = 0.10, \eta_p^2 = 0.69$, and conditions, $F(12, 196.08) = 24.01, p < .001$, Wilk's $\Lambda = 0.09, \eta_p^2 = 0.56$ as well as a significant interaction effect, $F(24, 435.65) = 14.61, p < .001$, Wilk's $\Lambda = 0.18, \eta_p^2 = 0.44$.

2.2.1. Temporal error

The left panel of Fig. 3 shows the standard deviation (SD) of movement time as a function of average movement velocity. The SD of movement time showed a significant effect for task, $F(2, 38) = 65.70, p < .001, \eta_p^2 = 0.78$, condition, $F(2.09, 39.74) = 60.63$,

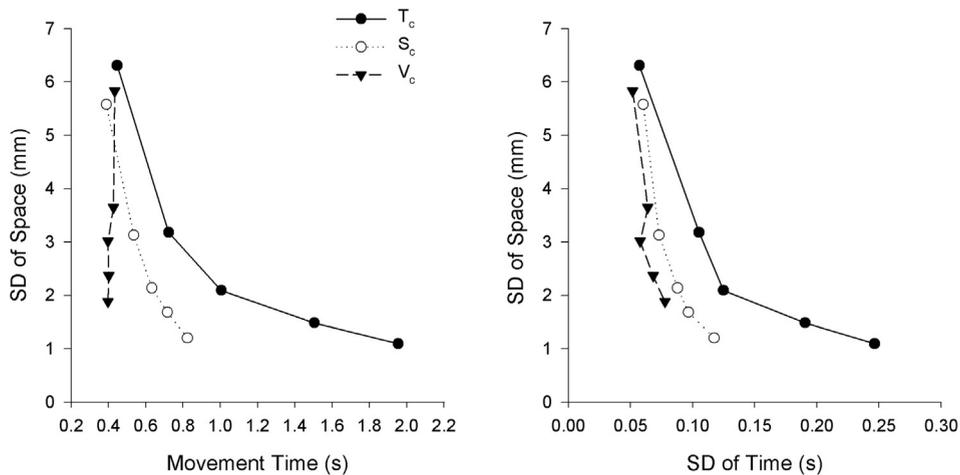


Fig. 2. Relations between the spatial and temporal performances of the 3 tasks. Left panel: relation between MT and SD of space; right panel: relation between SD of MT and SD of space observed in T_c, S_c , and V_c tasks, respectively.

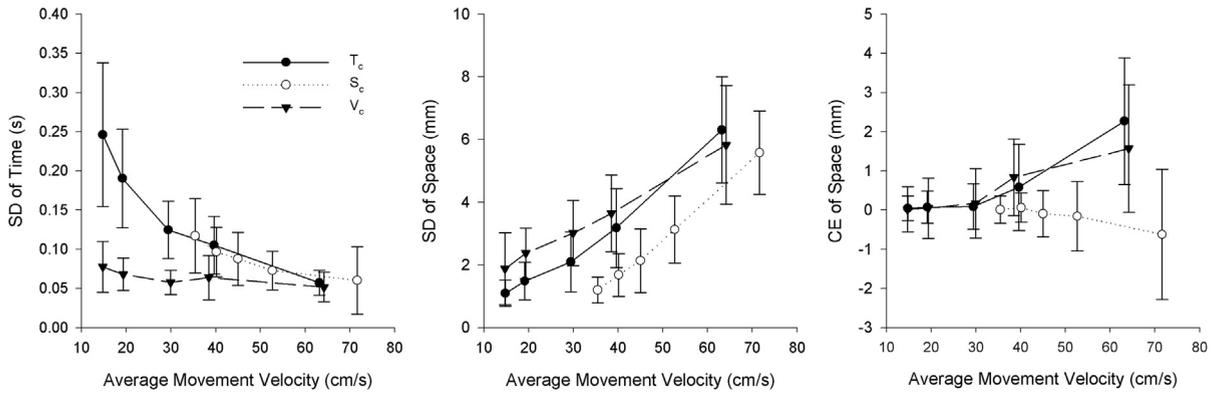


Fig. 3. SD of Time (left), SD of Space (middle), and spatial constant error (CE) (right) for discrete aiming movement at the three task types for five space-time conditions as a function of average movement velocity (cm/s). The error bars denote the between-participant standard deviation.

$p < .001$, $\eta_p^2 = 0.76$, and a task by condition interaction, $F(3.54, 67.26) = 26.31$, $p < .001$, $\eta_p^2 = 0.56$. For the simple main effect of tasks, SD of movement time of the T_c task was greater than those of the S_c and V_c tasks for the fast-mid conditions, mid, mid-accurate and accurate conditions, and the movement time SD of the S_c task was also greater than those of the V_c tasks for the mid, mid-accurate and accurate conditions ($ps < .05$).

For the simple main effect of conditions in T_c task, the SD of movement time showed a decreasing trend over the decreasing movement time conditions where each pair of movement time conditions reached significant level, $ps < .05$. For the S_c task, although the similar decreasing trend over the increasing target size conditions, the results of paired comparisons showed SD of movement time of accurate condition was larger than fast, fast-mid, and mid conditions, SD of movement times of mid and mid-accurate conditions were both larger than the fast condition ($ps < .05$). No significant differences were observed between any pairs in V_c Task conditions.

2.2.2. Spatial error

The middle and right panels of Fig. 3 show the mean spatial constant error (CE) and standard deviation (SD) of the spatial constant error as a function of average movement velocity, respectively. For CE, there was a main effect for task, $F(2, 38) = 16.38$, $p < .001$, $\eta_p^2 = 0.46$, condition, $F(1.64, 31.08) = 10.44$, $p < .001$, $\eta_p^2 = 0.36$, and for the task by condition interaction, $F(3.59, 68.29) = 16.76$, $p < .001$, $\eta_p^2 = 0.47$. For the simple main effect of task, CE of the T_c and V_c tasks were larger than that of S_c task for the fast and fast-mid conditions ($ps < .05$) and no other paired comparisons reached significant level. For the simple main effect of condition in the T_c task, CE of the fast condition was larger than that of the fast-mid, mid, mid-accurate and accurate conditions. In the V_c task, CE of the fast condition was larger than that of the mid, mid-accurate and accurate conditions, and CE of the fast-mid condition was larger than that of the mid-accurate and accurate conditions ($ps < .05$). No significant paired comparisons on the spatial CE were found for the S_c task.

The SD of spatial error showed a significant effect for task, $F(1.14, 21.69) = 9.28$, $p < .005$, $\eta_p^2 = 0.33$, condition, $F(2.29, 43.41) = 99.34$, $p < .001$, $\eta_p^2 = 0.84$, and for the task by condition interaction, $F(3.70, 70.26) = 6.21$, $p < .001$, $\eta_p^2 = 0.25$. The simple main effect of task showed that SDs of spatial error for the T_c task were larger than the SDs of the S_c task for the fast condition but was smaller than that of the S_c task for the mid-accurate condition ($ps < .05$). The SDs of spatial error of T_c task were smaller than those of the V_c task for the mid, mid-accurate and accurate conditions ($ps < .05$). SD of spatial error of S_c task was smaller than V_c task for the mid-accurate condition ($p < .05$). For the simple main effect of condition, the three tasks showed similar increasing trend over increasing movement velocity and post hoc analyses revealed significant differences for all paired comparisons ($ps < .05$), except the mid from mid-accurate in T_c, S_c and V_c tasks ($ps > .05$).

2.3. Sub-movements

2.3.1. Number of sub-movements

Fig. 4 shows the total number of trials (average of participants) with a given number of sub-movements in a trial as a function of the movement space-time condition for T_c, S_c, and V_c, respectively. For the T_c task, the distribution of the number of sub-movements shifted over the fast, fast-mid and middle conditions and the mid, mid-accurate and accurate conditions had the largest range of the number of sub-movements occurring within a trial. In both S_c and V_c tasks, however, the distribution of the number of sub-movements was positively skewed and essentially the same from fast-mid to accurate conditions.

Fig. 5 shows the average number of sub-movements of the discrete aiming task as a function of the space-time constraints for the three tasks. The 3 (task) by 5 (condition) repeated measure ANOVA for the number of sub-movement showed that the main effect of task was significant, $F(1.02, 19.52) = 66.13$, $p < .0001$, $\eta_p^2 = 0.78$, where the number of sub-movements was significantly different from each other among all three tasks (T_c > S_c > V_c, $ps < .05$). The main effect of space-time conditions was also significant, $F(1.58, 30.10) = 53.69$, $p < .0001$, $\eta_p^2 = 0.74$. The post hoc paired comparisons showed that all space-time conditions were

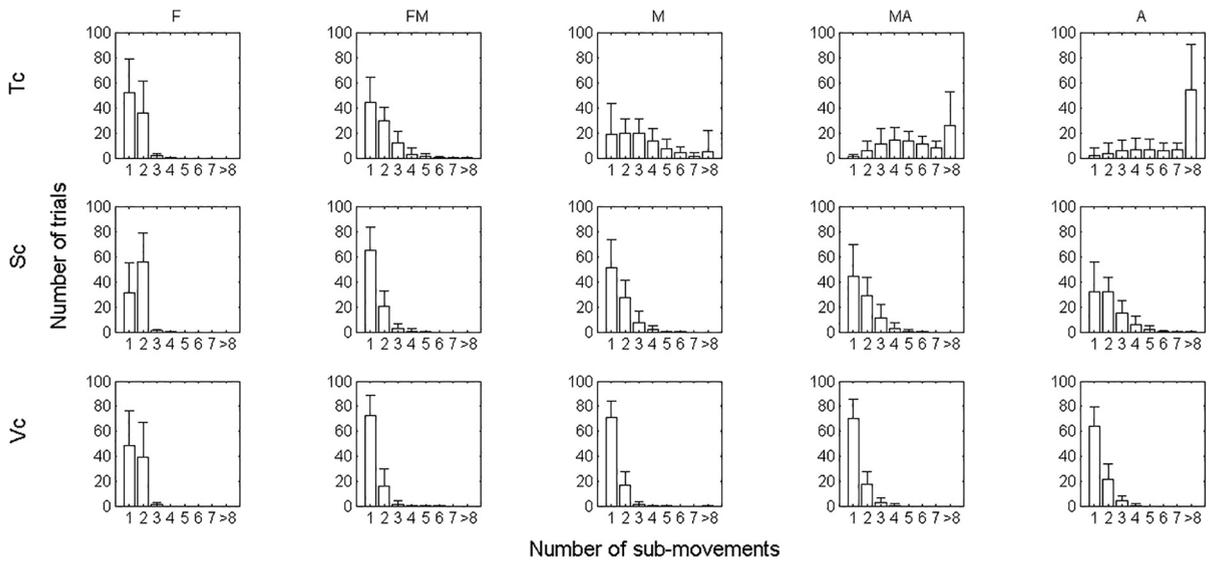


Fig. 4. Average number of trials as a function of number of sub-movements in a trial for different movement space-time conditions. On the abscissa, 1 indicates only the primary movement, 2 indicates the primary movement with one secondary sub-movement, etc. The top row indicates T_c task, middle row shows S_c task, and bottom row is V_c task. The error bars represent the between-participant standard deviation.

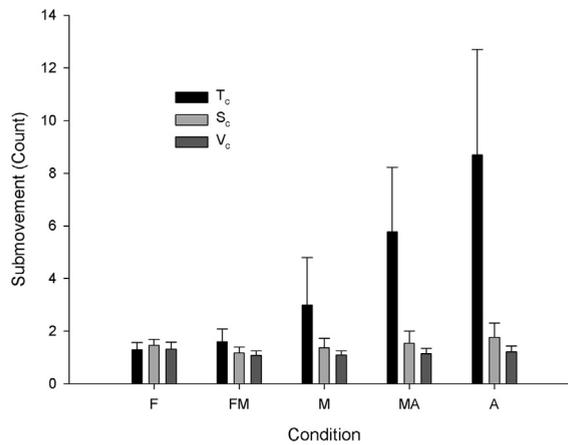


Fig. 5. The average number of sub-movements for 3 different tasks as a function of space-time conditions: -10 mm/s (fast), -5 mm/s (fast-mid), -1 mm/s (mid), -0.2 mm/s (mid-accurate) and -0.1 mm/s (accurate) conditions. The error bars represent the between-participant standard deviation.

significantly different from each other ($p_s < .05$) except for the fast from the fast-mid and mid conditions.

The task by space-time condition interaction was also significant, $F(1.56, 28.59) = 48.87, p < .0001, \eta_p^2 = 0.72$. The post hoc simple main effect analyses showed that the number of sub-movements of the T_c was significantly greater than those of the S_c and V_c in the fast-mid conditions. Moreover, all tasks were significantly different from one another (T_c > S_c > V_c) in mid, mid-accurate and accurate conditions ($p_s < .05$).

The simple main effect of condition showed that there were significant differences among all the space-time conditions for all three tasks. For the T_c task, the average number of sub-movements showed the general decreasing trend from accurate, mid-accurate, middle, fast-mid to fast conditions and all pair comparisons were significant except for the fast from fast-mid conditions ($p_s < .05$). For the S_c task, the average number of sub-movements over the decreasing movement velocity conditions (from fast to accurate) showed a concave shape where the number of sub-movements of the fast, mid-accurate and accurate conditions was significantly greater than those of the fast-mid condition ($p_s < .05$). For the V_c task, the fast and accurate conditions had significantly greater number of sub-movements than the fast-mid conditions ($p_s < .05$).

2.3.2. Type of sub-movement

Fig. 6 shows the mean proportional incidence of each sub-movement type in T_c, S_c, and V_c tasks across the space-time movement conditions. The figure illustrates that the no sub-movement (none, only primary movement) was more frequent in the fast and fast-

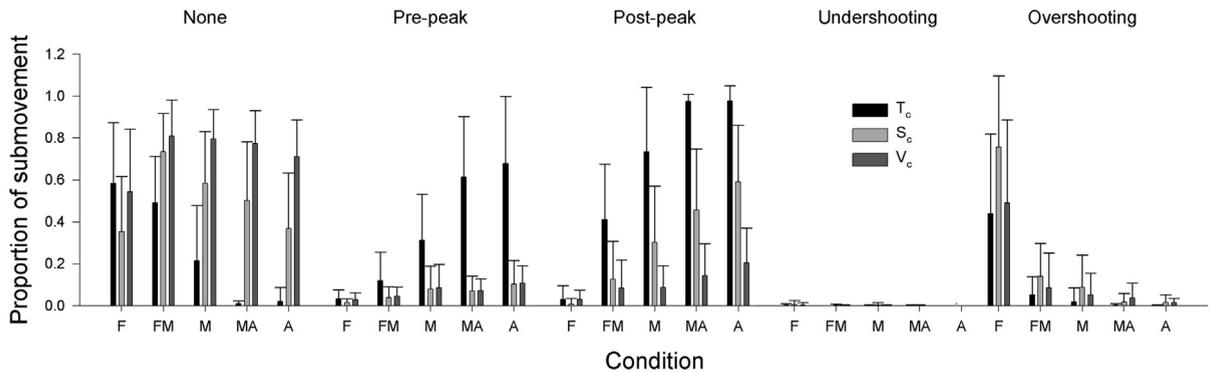


Fig. 6. The distributions of different sub-movement types for the 5 space-time conditions (-10 mm/s (fast), -5 mm/s (fast-mid), -1 mm/s (mid), -0.2 mm/s (mid-accurate) and -0.1 mm/s (accurate)) in T_c, S_c and V_c tasks. The error bars are the between-participant standard deviation.

mid conditions but its prevalence gradually decreased after middle condition in T_c task. For both S_c and V_c, the incidence of no sub-movement increased from fast to fast-mid conditions and stay nearly constant over decreasing movement velocity conditions. The incidence of pre-peak type gradually increased from fast to accurate in T_c, but in the S_c and V_c tasks, the proportional incidence maintained unchanged over the decreasing movement velocity conditions after the increase from fast to fast-mid condition. The prevalence of the post-peak type increased over the decreasing movement velocity conditions but the incidence of overshooting decreased in all 3 tasks. The undershooting type was rare in all space-time movement conditions and no significant statistical effect was found on either the main factors or the interaction. Table 2 presents the results of the analyses of variance for task, space-time conditions and their interaction effects for each type of sub-movement. Table 3 shows the significant post-hoc paired comparisons for the simple main effects of the significant interaction for each type of sub-movement.

3. Discussion

The focus of the experiment was to investigate the accuracy and variability of movement timing in different types of discrete aiming tasks. The approach allowed us to investigate why the task criteria of time-minimization to a spatial target (e.g., Fitts, 1954) and time-matching to a spatial-temporal goal (e.g., Schmidt et al., 1979) tend to produce different functions of the speed-accuracy trade-off in both spatial and temporal error, even when the amplitude and time outcomes are matched in the task demand (Carlton, 1994). The movement trajectory kinematic profiles and spatial-temporal outcomes of different discrete aiming task goals (time-minimization, time-matching and velocity-matching) were analyzed over a range of movement space-time constraints. The tasks afforded a contrast of whether the demands of time-matching and time-minimization would influence differentially both the outcome variability and the number and type of trajectory sub-movements (Elliott et al., 2017; Hsieh et al., 2017). The findings are robust in showing across the 3 types of aiming tasks that movement time is the primary variable that influences the task dependent speed-accuracy outcome relations, in addition to the task-specific distinct sub-movement characteristic profiles.

3.1. Timing accuracy/variability across task type

The T_c and V_c tasks were performed with specific goal times (Schmidt et al., 1979) whereas the movement times of S_c task were emergent properties under the specific target width constraint and an intention to move ‘as fast and accurately as possible’ (Fitts, 1954). Although the fast condition of the T_c task and all conditions of the V_c task had the same criterion times, the movement time performance of these 6 conditions was divided into clear longer/shorter time groups. Based on the results of the similar movement times, post-hoc comparisons were performed on the number of the 5 types of sub-movements for these conditions. The pair of the fast condition of the T_c and V_c tasks, as well as the pair of the mid and mid-accurate conditions of the V_c task showed no significant differences for all 5 types of sub-movement (*ps* > .11). Moreover, the similar movement durations observed from the results of the

Table 2
ANOVA results for task, space-time conditions and their interaction effects for each type of sub-movement.

	Effect of task			Effect of space-time condition				Interaction effect				
	<i>F</i>	<i>df</i>	<i>P</i>	η_p^2	<i>F</i>	<i>df</i>	<i>p</i>	η_p^2	<i>F</i>	<i>df</i>	<i>p</i>	η_p^2
None	126.23	2, 38	< .001	0.87	15.49	2.09, 39.67	< .001	0.45	19.89	3.75, 71.17	< .001	0.51
Pre-peak	64.07	1.15, 21.84	< .001	0.77	42.58	2.31, 43.89	< .001	0.69	31.27	2.79, 52.94	< .001	0.62
Post-peak	146.73	2, 38	< .001	0.89	96.76	2.06, 39.11	< .001	0.84	39.14	4.09, 77.63	< .001	0.67
Undershooting	1.80	1.20, 22.73	> .05	0.18	0.96	1.19, 22.65	> .05	0.05	0.23	2.12, 40.27	> .05	0.01
Overshooting	15.45	1.32, 24.98	< .001	0.45	66.90	1.95, 37.12	< .001	0.78	7.16	3.56, 67.64	< .001	0.27

Table 3

Significant statistical results for incidence of sub-movement types (post hoc simple main effect analyses).

Type\Condition	–10 mm/s (F)	–5 mm/s (FM)	–1 mm/s (M)	–0.2 mm/s (MA)	–0.1 mm/s (A)
None	$S_c < T_c$	$T_c < S_c, V_c$	$T_c < S_c < V_c$	$T_c < S_c < V_c$	$T_c < S_c < V_c$
Pre-peak	–	$T_c > S_c, V_c$	$T_c > S_c, V_c$	$T_c > S_c, V_c$	$T_c > S_c, V_c$
Post-peak	$S_c < V_c$	$T_c > S_c, V_c$	$T_c > S_c > V_c$	$T_c > S_c > V_c$	$T_c > S_c > V_c$
Overshooting	$S_c > T_c, V_c$	$T_c < S_c, V_c$	$T_c < S_c, V_c$	$T_c < V_c$	$T_c < V_c$
Type/Task	T_c		S_c	V_c	
None	$F > M, MA, A; FM > M, MA, A; M > MA$		$F < FM; FM > M, MA, A$	$F < FM, M$	
Pre-peak	$F < M, MA, A; FM < M, MA, A; M < MA, A$		$F < MA, A$	$F < A; FM < A$	
Post-peak	$F < FM, M, MA, A; FM < M, MA, A; M < MA, A$		$F < M, MA, A; FM < M, MA, A; M < A$	$F < M, MA, A; FM < A; M < A$	
Overshooting	$F > FM, M, MA, A$		$F > FM, M, MA, A; FM > MA, A$	$F > FM, M, MA, A; FM > A$	

post-hoc paired comparison for the fast-mid of T_c and the mid-accurate of S_c ($t(19) = 0.91, p = .37$) lead to further evidence of similar characteristics of sub-movements in the trajectory profiles ($ps > .17$). It appears that the trajectory sub-movement structures are primarily influenced by the same movement durations of the discrete aiming tasks even under different aiming goals (Milner, 1992; Shmuelof et al., 2012). The movement average velocity, which was modulated by the movement distance in the current study, also plays a role in the characteristics of the trajectory sub-movements. This finding is consistent with the synthesis of Hancock and Newell (1985) that showed the relative effects of movement time, amplitude and average velocity on movement outcome and the CV of timing error is typically higher than the CV of spatial error.

The manipulation of task constraints, whether movement time, amplitude, target width, or average movement velocity influenced the trade-off between spatial and temporal movement errors. The range of movement times between T_c , S_c and V_c tasks was substantially different (see also, Bongers et al., 2009 for only T_c and S_c). Although we sought to make the task constraints of T_c (time-matching) and S_c (time-minimization) approximately equal, asking participants to move as fast and accurately as possible (S_c task) led to a shorter movement times and decreased temporal error even though the spatial distributions of these two tasks were comparable based on the individualized procedure using effective target width (Welford, 1968) for setting the space-time conditions (Carlton, 1994). It is possible that the order of the task manipulation (the session commenced with T_c task and these results were used to compute the task criteria for the following tasks) influenced the movement duration.

The SD of target position and movement time was different for the 3 task types but the trend in the change of each variable over average velocity conditions was similar. This shows that the relative effect of movement speed on movement variability is consistent across task types. In the relatively low rate of sequential sub-movements (especially pre- and post-peak types) and the absent target boundaries of the V_c task, the SDs of target positions were higher than those of the T_c task, particularly in the low average movement velocity conditions. These findings support the inference that pre- and post-peak types of sub-movement reflect the traditional interpretation of visually guided corrections given sufficient movement time (Carlton, 1994; Woodworth, 1899). On the other hand, matching the fixed short time goal with a consistent number of sub-movements keeps the SD of movement time relatively constant. In contrast to the T_c task where the movement distance was constant, the increasing movement time induced a greater number of pre- and post-peak sub-movements and resulted in decreased SD of the spatial target position.

In the matching tasks (V_c and T_c) the CE increased with average velocity whereas in S_c the CE decreased with an increment in average velocity. This qualitative difference in the directional change of the mean CE as a function of task type is probably due to the area target task (time-minimization) allowing the participant to hit the target but on the near side of it's center (Pacheco, Hsieh, & Newell, 2018; Welford, 1968). This strategy reduces (to varying degrees) the average distance moved from the center of the target in the S_c (time-minimization) protocol – a factor that is typically underplayed in speed-accuracy studies with the emphasis on variability and the assumption that CE is zero. Despite this qualitative difference in aiming strategies, similar sub-movement profiles with a large proportion of the overshoot type of sub-movement were observed for the fast condition of the three types of aiming tasks.

As is typical in discrete aiming tasks, the experiment here provided no preparatory external cues for the timing criteria (beyond the task goal instructions and trial feedback of the movement time in time-matching) unlike those that are available for the participants to continuously see the spatial layout of the movement trajectory and the task demands. This is a critical factor for the movement time effect in the time-matching conditions of discrete aiming movements that might be possible to reduce with augmented information of the movement timing properties – such as with a metronome (Woodworth, 1899) and other forms of augmented information. Indeed in interceptive tasks, for example, the timing information is provided by the change in position over time of the approaching object to be hit, reflecting a true complementary space-time criterion, unlike the space-time criteria of the discrete aiming tasks used here that can to a degree be independently satisfied (Hancock & Newell, 1985).

3.2. Sub-movement characteristics

The number and type of sub-movements in the different discrete movement task types varied as a function of the movement space-time condition. The short duration movement time conditions led to essentially no sub-movements and to overshooting and a more common trajectory profile irrespective of the task type categories (Fig. 6). The finding of no sub-movements in the short movement time condition, which included all conditions in the V_c task, is consistent with the perspective of the impulse variability model for short duration aiming movements (Keele, 1968; Schmidt et al., 1979). In this view, closed-loop corrective processes are not adaptive

in rapid aiming movements due to their latency and execution taking more time than that remaining in the trajectory to movement termination.

The traditional interpretation of the origins of sub-movements in discrete aiming holds that there is a greater number of corrective sub-movements when the requirements of spatial target become narrower (Crossman & Goodeve, 1983; Meyer et al., 1988; Novak, Miller, & Houk, 2002). It has also been proposed that there is only a single sub-movement when matching the goal of a short movement time task (Carlton, 1994; Wright & Meyer, 1983). Our task type manipulation allowed comparison of T_c and V_c with a similar range of average movement velocity conditions. The number of the overshoot type of sub-movements showed a similar decreasing trend with decreasing movement velocity for both the T_c and V_c tasks. For the number of primary sub-movement only (“none” type), however, the 4 lower velocity conditions of the V_c task maintained a relatively high proportion while a decreasing trend was apparent for the T_c task. These results support the view that the overshoot type of trajectory emerged from motion termination causing the increment of sub-movement in the fastest average velocity condition (e.g., longest amplitude with shortest time goal and largest target width).

Indeed, the large proportion of the overshooting type of sub-movements found in the fast conditions indicates that there is a similar strategy to anchoring the distribution of aimed outcomes. Dounskaia et al. (2005) and Fradet et al. (2008) have pointed out that the origins of an overshoot trajectory might not be a corrective sub-movement from the traditional closed-loop point of view (Crossman & Goodeve, 1983). Rather, that the processes of movement termination were another interpretation of the kinematic trajectory inflections. Our findings are consistent with their proposal in that this type of sub-movement is found predominantly in the fast velocity conditions where decelerating the moving effectors to stop/hit the target is necessary and independent of the task constraints.

The sub-movement distributions, however, reveal very different profiles for the longer movement durations, again particularly in the T_c task (see also Hsieh et al., 2017). The pre- and post-peak types of sub-movement gradually increased when the movement duration became longer in T_c , where there was a relatively large number of average sub-movement in mid-accurate and accurate conditions. When comparing the similar movement velocity conditions of T_c and V_c tasks, a relatively constant rate over increasing movement velocity in the pre- and post-peak types of sub-movement was observed for the V_c task.

The results of our study do not allow us, however, to distinguish the pre- and post-peak type of sub-movement as a motion fluctuation or movement correction. It is possible that the functional assignment of these sub-movements can also make contributions to be movement corrections when the participants are instructed to achieve the narrower target width as fast and accurate as possible or in other task conditions. In addition to the pre-, post-peak, and the overshoot types of sub-movements, there is a small amount of undershooting in the combinations of task and conditions. Elliott et al. (2017) considered any discontinuity in the movement trajectory that occurred short of the target as an undershooting type. In this view, one might combine number of post and undershooting type into the same category in future experiments.

In summary, the findings of the present study show that movement time is the primary factor that structures the characteristics of sub-movements with the movement velocity acting as a secondary influence to the task outcome of discrete aiming tasks. The task effect is, however, minimal in short duration rapid discrete aiming movements but is amplified over progressively longer movement times and slower average velocity movements. In the more typical middle parameter range of discrete limb movements the time-matching and time-minimization tasks appear to be, in effect, two distinctly different tasks as reflected in the qualitatively different control mechanisms that lead to different space-time characteristics of the respective movement speed-accuracy functions.

Acknowledgements

We thank Bo-Cheng Lin for developing the algorithms used for data analysis. This research was supported by Ministry of Science and Technology of Taiwan Grant MOST 106-2811-H-003-007 and MOST 105-2811-H-003-011 awarded to T-Y Hsieh, and MOST 105-2410-H-003-060-MY2 awarded to Y-T Liu.

Conflicts of interest

None.

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