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Are Sub-Movements Induced Visually in Discrete Aiming Tasks?

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Abstract

There is a long-held view that discrete movements aimed to a target are composed of a sequence of movement units (sub-movements) that have different roles in motor control (e.g., initial impulse, error correction and movement termination) depending on the task constraints (e.g., spatial-temporal requirements). Here we report findings from the manipulation of vision/no-vision on the prevalence and type of sub-movements in discrete movement tasks over a range of space-time task criteria. The presence of vision resulted in longer movement times compared to the no-vision counterpart in time-matching tasks. A similar vision effect was observed in the highest Index of Difficulty for time-minimization tasks. Conditions that resulted/required longer movement times demonstrated more pre-velocity-peak and post-velocity-peak types of sub-movements whereas short movement times increased the likelihood of overshooting sub-movements. The present study results are consistent with the idea that movement time is the variable associated with changes in sub-movement profiles.

Keywords: motor control, goal directed task, space-time constraint, Fitts law, feedback, visual corrections

Introduction

Since Woodworth (1899), there has been a long-held view that discrete movements aimed to a target are composed of smaller units of movement (sub-movements) that have different roles in movement production. Woodworth proposed that there was an initial large-amplitude sub-movement (impulse) in the direction of the target to change stylus location in a short time period followed by a secondary sub-movement performing a correction to the first initial impulse. These sub-movements have generally been characterized through “zero-crossings” in the velocity, acceleration or jerk profiles of movement over time (see, for instance, Meyer et al., 1990) and have been interpreted as primarily under visual control (Carlton, 1979; Crossman & Goodeve, 1983; Keele & Posner, 1968). This theoretical approach has provided experimental evidence for sub-movements and visually based intermittent models of movement control (Crossman & Goodeve, 1983; Elliott et al., 2001, 2017; Meyer et al., 1990; Milner, 1992).

The literature has diverged, however, on the interpretation of what would be the relevant sub-movements in movements aimed to a target. Elliott and colleagues (see Elliott et al., 2001, 2017), on the one hand, have provided evidence on the error correction account of Woodworth (1899) and have expanded this view in a model that includes changes with practice in aiming tasks. Dounskaia and colleagues (e.g., Dounskaia et al., 2005, 2009; Fradet, Lee, & Dounskaia, 2008), on the other hand, have shown that the zero-crossings in kinematic profiles can emerge from mechanisms other than visually-based movement corrections; namely, motion termination or slow movement control (see also Plamondon & Alimni, 1997 for other non-corrective sources of sub-movements). The former refers to sub-movements generated when the arm reaches the target with zero velocity but non-zero acceleration eliciting “dwelling on target” while the latter refers to irregular fluctuations that

1 occur commonly in slow/long duration movements (Fradet et al., 2008; Milner & Ijaz, 1990;
2 Wisleder & Dounskaia, 2007). Evidence for these “mechanically-based” sub-movements
3 comes from comparisons between task conditions in which corrective sub-movements were
4 deemed not necessary (i.e., reciprocal and “passing-through” aiming paradigms, see Fradet et
5 al., 2008).

6 In our view, the experimental approaches to untangle the role of vision in the control of
7 sub-movements have not been sufficient to reveal the involvement of visual control. First, the
8 general interpretations of the source of sub-movements are not mutually exclusive and not
9 differentiable through kinematic profiles. Corrections and mechanical oscillations will both
10 lead to zero-crossing patterns in the kinematic profile of the aiming trajectory and both can
11 occur in any given movement. Second, the reciprocal and passing-through paradigms were
12 used with the assumption that they require no corrective movements (submovements in the
13 latter were analyzed after the target was passed). Nevertheless, these assumptions, especially
14 for the reciprocal Fitts’ paradigm, might not hold. Third, the use of conditions that
15 manipulate directly visual control in the assessment of the role of vision in sub-movements
16 and error correction has not been implemented sufficiently.

17 In Fitts’ original reciprocal paradigm (Fitts, 1954), the instructional emphasis was on
18 accuracy and 95% or more was obtained as participants would exploit the allowed tolerance
19 during the task. Individuals could miss the target and might need to perform corrections on
20 some trials. In fact, it was commonplace to require adjustments in the accuracy achieved for
21 Fitts’ law to hold when individuals did not achieve 95% accuracy (see, for instance, Welford
22 et al., 1969). Thus, the reciprocal paradigm cannot be considered to result in no visually-
23 induced corrections. A proper test of sub-movements-as-more-than-just-corrections should be
24 performed on conditions where corrections are not actually made. Also, for the passing-

1 through paradigm, it is questionable as to what degree the findings from this paradigm relate
2 to sub-movements in other movement aiming paradigms.

3 One way to avoid the challenges of isolating task influences altogether would be to
4 compare conditions where visual corrections either are or are not possible. That is, one must
5 be sure that, in a given condition, online corrections are not possible and then compare these
6 with those conditions which corrections naturally emerge. The assumption in these aiming
7 paradigms is that if there are corrections, they are mainly visually-driven (Carlton, 1979;
8 Crossman & Goodeve, 1983; Chua & Elliott, 1993; Keele & Posner, 1968; Woodworth,
9 1899). Thus, a fundamental way to verify the existence of non-corrective sub-movements is
10 to compare aiming in situations that allow and do not allow the availability of visual
11 information during movement execution.

12 The present experiment was set-up to examine the presence of visually induced
13 corrections in discrete aiming movements over a range of spatial and temporal constraints.
14 We used the identifying movement correction protocol of Chua and Elliott (1993) to detect
15 the presence of the 4 types of movement corrections (Hsieh et al., 2017; 2019): namely,
16 initial primary impulse, pre-peak velocity, post-peak velocity and overshooting (Figure 1). To
17 examine a broad range of discrete task conditions, the experiment used two different discrete
18 aiming paradigms (time-minimization [Fitts & Peterson, 1964] or spatially constrained task
19 [cf. Meyer et al., 1988], and time-matching [Schmidt et al., 1979] or temporally constrained
20 task [cf. Meyer et al., 1988]) both with and without vision. The inclusion of no-vision
21 conditions allowed us to observe whether sub-movement occurrences are indeed dependent
22 on visual information. If sub-movements observed in the no-vision conditions are of the same
23 number and same type as those observed in the vision conditions, this would support the view
24 that sub-movements in the typical-vision-available conditions of aiming movements are not
25 visually-based corrections.

1 The target size in the time-minimization (Fitts' law) paradigm was manipulated over a
2 higher than usual range of index of difficulty (ID, 2 to 8) (Fitts, 1954) to require different
3 spatial-temporal strategies inducing changes in sub-movement profiles. The movement time
4 criterion was manipulated in the time-matching paradigm to examine the effect of movement
5 velocity in sub-movement presence and type and, as in the time-minimization paradigm, to
6 test whether these emerge as corrective processes by comparing with no-vision conditions.
7 The collective of movement conditions manipulated here provided for investigation of the
8 interaction of several variables and processes in speed and accuracy that are relevant to the
9 interpretation of sub-movements as being induced by visual information in the context of a
10 particular combination of spatial-temporal task constraints.

11
12 -----Insert Figure 1 in here-----

14 **Methods**

15 **Participants**

16 Twenty self-reported right-handed healthy young adults (age: 20-35 yrs) were recruited
17 for the experiment. All participants provided informed written consent before participating in
18 the experiment. The Research Ethic Committee at the National Taiwan Normal University
19 approved the experimental procedures.

20 **Apparatus**

21 Line drawing movements were made on a WACOM Cintiq 27 digital tablet (Model
22 DTK-2700/K0-CX, 770mm × 465mm with active surface area of 596.7mm × 335.6 mm) by
23 using a handheld stylus (Pro pen, Model KP-503E) with a weight of 18 g. The digital tablet
24 monitor was connected to a PC computer (the pixel range was set at 1680 x 1050) and angled
25 15° forward on the tabletop and placed in front of participants. A customized line drawing

software was used to manipulate different criteria of movement time, amplitude and target width in different conditions. The program also calculated the movement time and movement errors (spatial and temporal errors) immediately after each trial for the participants. The distance moved by the cursor represented on the screen to the actual distance moved of the stylus on the tablet was 1:1. The movement kinematics were recorded by the customized program for data collection at a sampling frequency of 130 Hz. The PLATO visual occlusion spectacles (Translucent Technologies Inc.) were used to occlude vision in certain conditions.

Task

Participants performed line drawing movements from left (home position: 2 mm x 2 mm) to right and hit the target with a stylus on the digital tablet in spatially constrained and temporally constrained tasks with and without visual information. In the spatial constrained task, the movement amplitude was fixed at 30 cm and the target varied in widths (2, 16, and 128 mm) that led to 3 IDs (Fitts & Peterson, 1964) that were 8, 5 and 2, respectively. Participants were instructed to hit the target as fast as possible. In the temporally constrained task, the imposed criteria of movement time were 300, 500, and 1200 ms, all with 30 cm amplitude and 2 mm target width. Participants were instructed to move with a duration that was within a 20% bandwidth of the temporal target ($\pm 10\%$ of the target time) and try to stop as close as they can to a spatial target in both vision and no-vision conditions. All participants completed 2 tasks within a day and each condition consisted of 20 trials. The order of the tasks was counterbalanced among the participants and each task took about 30 mins to complete.

Procedures

Before the start of a trial, the participant sat on a chair at comfortable height. The experimenter positioned the center of the tablet at the midline-view of the subject and approximately 20 cm in front of the participant's body. Each participant was instructed to

1 move from the home position (left) to the target (right) and match the designed criteria for all
2 tasks and conditions. At the beginning of a trial, the home position and a target were shown
3 on the tablet screen. The cursor (1 mm in diameter) showed up on the screen when the
4 participant picked-up the stylus and touched the tablet.

5 After the participant moved the cursor onto the home position and held it there for 600
6 ms, there was a beep sound to indicate to the participant to move once he/she was ready. This
7 was not a reaction time task and the participants were informed that they could initiate their
8 movements any time after the beep sound. The terminal temporal feedback in time
9 (movement time for the spatial task; signed temporal error for the temporal task) and space
10 (hit/miss for both tasks) from the respective task criterion were each displayed on the tablet
11 immediately after participants completed a trial. On vision trials, participants knew vision
12 would be available for the duration of movement. The cursor was always visible but there
13 was no trace of the line drawing movement shown on the board that could be used as the
14 concurrent feedback during the whole trial. During the no-vision trials, vision information
15 would be occluded by a pair of liquid crystal spectacles after a beep sound until participants
16 hit the target or stopped moving. The lens of the spectacles would re-open once the
17 participant completed each movement trial.

18 For all conditions, the start of movement was determined by the movement velocity
19 crossing above a threshold of 3 mm/s for 30 ms and the end of the movement was defined
20 when the movement velocity was below 3 mm/s for greater than 30 ms. The time between the
21 start of movement and the end of movement was measured as the movement time (MT) of the
22 trial. The stylus was to remain in contact with the tablet during the whole movement until the
23 trial was completed. If the stylus left the tablet surface (a rare occurrence), the trial was
24 aborted and not considered for further analyses. After each trial, the participant moved the

stylus back to the home position and waited for the beginning of the next trial. A 3 min break was provided to minimize boredom and fatigue after each condition.

Data Analyses

Movement Performance. There were 3 performance variables analyzed, MT, spatial error, and success rate. MT of each trial was measured as the time duration between the start of the line drawing movement to the end of the movement. Spatial error was determined as the distance between the end point of the line drawing movement and the center of the target in the direction of the line drawing movement (x-axis/ horizontal). The average MT and spatial error (absolute error, AE) over 20 trials were calculated for each condition for all participants. The success rate of each visual condition of each task was calculated for each participant by the number of successful trials divided by 20. A successful trial for the spatially constrained tasks was identified as the trials on which the end of the movement occurred within the target. For the temporally constrained tasks, a successful trial was identified when the MT of the trial was within 90% to 110% of the target movement time.

Sub-movements. The movement trajectory was recorded in both the primary direction of movement to the target (x-axis/ horizontal) and in the orthogonal plane (y-axis/ vertical) coordinates of the stylus tip on the tablet. Only the displacement data on the x-axis were analyzed. The raw displacement data were low-pass filtered (second-order Butterworth filter forward and reverse order, cutoff frequency 5 Hz). Movement velocity and acceleration were calculated as the first and second derivatives of movement displacement, respectively.

To identify sub-movements, we used the algorithm of Chua and Elliott (1993) (see also Hsieh et al., 2017; 2019 and Figure 1 here). The first two types of sub-movements were determined by first identifying the reversal points, or local extrema, in the acceleration in the period between the start of the movement and the peak velocity (pre-peak) and between the peak velocity and the end of the movement (post-peak). When the magnitude between

consecutive local extrema of the acceleration reached 10% of the maximum amplitude of the acceleration, we considered it a significant deviation therefore a sub-movement. The third type of sub-movement was overshooting which was characterized by a movement reversal (negative velocity). For this sub-movement, the absolute amplitude of negative velocity had to reach values above 10 mm/s. We did not consider undershooting sub-movement type from Chua and Elliott (1993) based on the observation that there was hardly any occurrence in these tasks (Hsieh et al., 2017; 2019).

Each movement trial had at least one sub-movement (primary-only). When the pre-peak, post-peak, or overshooting types of sub-movements were identified in a trial, the number of each type of the sub-movement would be added to the primary sub-movement. For example, if one overshooting type of sub-movement was identified in a trial, the total number of sub-movements for that trial would be 2. The number of each type of sub-movement and total number of sub-movements within a trial were determined for each participant. In addition, the proportion of each type of sub-movement was computed for each condition as the number of trials that contained the specific type of sub-movement divided by the number of trials performed in this condition (20).

Statistical Analyses

To understand the effect of vision per movement goal condition in each task, we performed 2 (visual conditions) X 3 (movement goals) repeated measure ANOVAs to examine the success rate, MT, AE, average number of sub-movements within a trial, and the proportion of each type of sub-movement. The three movement goals were ID2/ 300ms (fast), ID5/ 500 ms (moderate), ID8/ 1200 ms (slow), respectively for spatially and temporally constrained tasks. The Greenhouse–Geisser method was used to correct for violations of sphericity and post-hoc comparisons were adjusted using Bonferroni correction, with partial eta square (η_p^2) revealing the effect size. The significant level was set at $\alpha = .05$. We used

Friedman's ANOVAs to examine those cases where the normal distribution assumption was not fulfilled. The effect sizes were Kendal's W. Paired Wilcoxon tests were used as nonparametric post-hoc tests.

Results

Performance

Success Rate. We first compared the success rate between vision and no-vision across the three movement goals [fast-no-vision: ID2 (309.3±41.4ms)/300ms (328.0±18.8ms), fast-vision: ID2 (314.3±34.5ms)/300ms (345.9±29.0ms), moderate-no-vision: ID5 (399.6±98.2ms)/500ms (503.0±19.5ms), moderate-vision: ID5 (390.8±65.9ms)/500ms (518.3±16.4ms), slow-no-vision: ID8 (597.5±219.6ms)/1200ms (1155.6±55.7ms), and slow-vision: ID8 (1040.0±306.3ms)/1200ms (1207.8±54.3ms)] for the spatially constrained tasks and temporally constrained tasks. Figures 2a and 2b show the success rate for spatially and temporally constrained tasks in each visual condition.

The ANOVA result for the spatially constrained tasks showed a significant movement goal effect, $F(2, 38) = 269.09, p < .001, \eta_p^2 = .93$, significant visual effect, $F(1, 19) = 82.34, p < .001, \eta_p^2 = .81$, and significant interaction effect, $F(2, 38) = 44.41, p < .001, \eta_p^2 = .70$. The simple main effect of movement goal for both vision and no-vision conditions showed significantly higher success rate for the fast movement than the moderate and slow movements, and significantly higher success rate for the moderate movement than the slow movement condition ($ps < .001$). The visual condition had different effect for the three movement goal conditions where vision conditions had higher success rates than the no-

vision conditions for the moderate and slow movement conditions ($p < .01$) but no significant difference was found for the fast movements ($p = .16$).

The similar ANOVA result was found for the temporally constrained tasks, where the movement goal effect, $F(2, 38) = 16.55, p < .001, \eta_p^2 = .47$, visual effect, $F(1, 19) = 8.80, p < .01, \eta_p^2 = .32$, and the interaction effect, $F(2, 38) = 6.16, p < .01, \eta_p^2 = .25$, all reached significant level. The simple main effect, however, showed a different trend from the spatially constrained tasks. For the simple main effect of the movement goals, no significant differences were found for the no-vision condition and between the moderate and slow movement of the vision condition ($ps > .2$), only the fast movement goal of the vision condition had significantly lower success rate than both the moderate and slow movements of the vision condition ($ps < .01$). For the simple main effect of vision, the only significant difference was found for the fast movement where the vision condition had significantly lower success rate than the no-vision condition ($p < .01$).

-----Insert Figure 2 in here-----

Movement time. Figures 2c and 2d show MT for each of the vision and no-vision conditions as a function of movement goals (for each task). For the spatially constrained tasks, the Friedman's ANOVA showed a significant effect for no-vision condition, $\chi^2(2) = 32.4, p < .001, W = .81$, and vision condition, $\chi^2(2) = 40, p < .001, W = 1$, across different movement goals. Post hoc analysis with Wilcoxon tests showed that, for both visual conditions, the MT of the fast movement was shorter than those of the moderate and slow movements, and MT of moderate movement was shorter than that of the slow movement ($ps < .001$). For MT of vision and no-vision within the same movement goals, the results from the Wilcoxon comparisons showed that the only significant difference was found in the slow

1 movement condition, where MT of vision was longer than that of no-vision ($Z = -3.88, p$
2 $< .001$).

3
4 For the temporally constrained tasks, the ANOVA showed that the main effect of
5 movement goal was significant, $F(1.41, 26.70) = 6007.60, p < .001, \eta_p^2 = 1.0$, where the fast
6 movement had a shorter MT than the other two conditions, and the moderate movement also
7 had a shorter MT than the slow movement. The effect of visual condition also reached a
8 significant level, $F(1, 19) = 26.91, p < .001, \eta_p^2 = .59$, where MT of no-vision was
9 significantly shorter than that of vision condition ($p < .05$). The interaction between
10 movement goals and visual conditions did not reach a significant level, $F(1.16, 22) = 2.21, p$
11 $= .15, \eta_p^2 = .10$.

12 *Spatial Error.* Figures 2e and 2f show AE for each of the vision and no-vision
13 conditions as a function of movement goals (for each task). For spatially constrained tasks,
14 the Friedman's ANOVA showed a significant movement goal effect for no-vision condition,
15 $\chi^2(2) = 27.1, p < .001, W = .68$. Post hoc analysis showed that the fast movement had larger
16 error than the moderate and slow movements ($ps < .001$). For vision condition, there was also
17 a significant movement goal effect, $\chi^2(2) = 40, p < .001, W = 1$. Post hoc tests showed the
18 similar trend as in no-vision condition where the fast movement had larger error than the
19 moderate and slow movements, and the moderate movement also had larger error than the
20 slow movement ($ps < .001$). Moreover, the results of the Wilcoxon comparisons showed
21 significant visual effect for all movement goals: fast movement, $Z = -2.84, p = .005$,
22 moderate movement, $Z = -3.73, p < .001$, and slow movement, $Z = -3.92, p < .001$, where
23 vision condition had smaller error than no-vision condition for the moderate and slow
24 movements, but larger error was found in the vision condition of the fast movement than the
25 no-vision condition.

For temporally constrained tasks, the Friedman's ANOVA showed no significant movement goal effect for no-vision condition, $\chi^2(2) = 4.3, p = .12, W = .11$. For vision condition, there was a significant movement goal effect, $\chi^2(2) = 40, p < .001, W = 1$. Post hoc tests showed that the fast movement had larger error than the moderate and slow movements, and the moderate movement had larger error than the slow movement ($ps < .001$). Moreover, the results of the Wilcoxon comparisons showed significantly smaller errors for the vision than no-vision conditions for the fast, $Z = -2.80, p = .005$, the moderate, $Z = -3.77, p < .001$, and the slow, $Z = -3.92, p < .001$, movements.

Sub-Movements

Number of Sub-Movements. Figures 3a and 3b show the average number of sub-movements in a trial for vision and no-vision as a function of movement goals. Because there would be at least one sub-movement (primary-only) in a trial, any additional number of sub-movements in a trial would be from pre-peak, post-peak, or overshooting types of sub-movements.

For spatially constrained tasks, the result from Friedman's ANOVA for no-vision condition showed a significant movement goal effect, $\chi^2(2) = 7.75, p = .02, W = .19$, where the number of sub-movements from the fast movement condition was greater than that from the moderate movement condition ($p < .05$). For vision condition, movement goal effect also reached a significant level, $\chi^2(2) = 24.72, p < .001, W = .62$. The post hoc comparisons showed that the number of sub-movements from the slow movement was greater than those from the fast and moderate movements, and the fast movement had greater number of sub-movements than the moderate movement ($ps < .05$). In addition, the visual effect was significant only for the slow movement ($Z = -3.88, p < .001$), where the number of sub-movements from the vision condition was greater than that from the no-vision condition ($p < .05$).

For the temporally constrained tasks, the ANOVA result showed the significant main effect of movement goal, $F(1.30, 24.75) = 213.70, p < .001, \eta_p^2 = .92$, where the slow movement had greater numbers of sub-movements than the moderate and fast movements, and the fast movement also had greater number of sub-movements than the moderate movement condition ($ps < .001$). The effect of visual condition, $F(1, 19) = 1.19, p = .29, \eta_p^2 = .06$, and the movement goal by visual condition interaction, $F(1.21, 22.89) = 3.10, p = .09, \eta_p^2 = .14$, did not reach the significant level.

-----Insert Figure 3 in here-----

Type of Sub-Movement. Figures 4a to 4h show the proportion of sub-movement type for vision and no-vision as a function of movement goals. Table 1 and Table 2 show the results from the non-parametric tests for each sub-movement type for spatially constrained tasks and temporally constrained tasks, respectively. For primary sub-movements, we found that the fast movement goal led to the least amount for the spatially constrained tasks and the moderate movement goal led to the most amount for the temporally constrained tasks. Additionally, the no-vision conditions of the slow movement goal had significantly greater number of primary-only sub-movements than the vision conditions of the slow movement goal for both the spatially and temporally constrained tasks.

For pre-peak sub-movements, we observed an increase of sub-movements for slower conditions (for both spatially and temporally constrained tasks). In addition, for the spatially constrained task, the vision condition had significantly greater number of the pre-peak sub-movements than the no-vision condition for the slow movement goal.

For post-peak sub-movements, the analyses revealed increases in sub-movements for the moderate and slow conditions for both spatially and temporally constrained tasks. In addition,

1 the vision condition led to greater number of the post-peak type of sub-movements than the
2 no-vision condition in the slow movement goals of both spatially constrained tasks and
3 temporally constrained tasks and also in the moderate movement goal of the temporally
4 constrained task.

5 Finally, for overshooting sub-movements, we found, mainly, that the number of sub-
6 movements increased as the task requirements induced faster movements. Additionally, the
7 only visual effect was found in the slow movement of the spatially constrained task where
8 vision condition led to less overshooting sub-movements than the no-vision condition.

9
10 -----Insert Figure 4 and Tables 1 and 2 in here-----
11

12 **Exploratory Analyses**

13 In order to facilitate interpretation, we have reconfigured the occurrence of sub-
14 movements as a function of the average MT over the tasks, visual conditions, and the
15 movement goals. Figure 5 shows these results. The data reveal that the task type and the
16 space-time task constraints lead to a different sub-movement profile that is minimally
17 influenced by visual information. That is, the presence of each of the 4 sub-movement types
18 is dependent on task type and space-time task requirements that is mediated by the movement
19 times.

20
21 -----Insert Figure 5 in here-----
22

23 **Discussion**

24 The current experiment was set-up to examine the characteristics of sub-movements in
25 both spatially and temporally constrained discrete aiming tasks (e.g., Fitts & Peterson, 1964;

Schmidt et al., 1979) under vision and no-vision conditions. The experimental conditions provided a wide range of task constraints to examine the prevalence and type of visually induced sub-movements and their effect on movement accuracy. An experimental emphasis was the inclusion of matched no-vision conditions to act as controls in interpreting the role of sub-movements in the visual control of aiming movements.

Visual control of aiming performance

The pattern of sub-movement probabilities in each space-time and visual condition needs to be interpreted in the context of performance in the speed and accuracy of the aiming outcome. In concert with Fitts' law (Fitts, 1954; Fitts & Peterson, 1964) the difference of the percentage of success between vision and no-vision conditions became larger when target size of the spatially constrained movement task became smaller. In contrast, the difference of the success rate between vision and no-vision conditions of the time-matching tasks diminished over increasing movement times. Thus, the vision manipulation had differential effects on the task type with it significantly and predominantly enhancing the spatial matching /time-minimization task of the Fitts' law protocol (Wallace & Newell, 1983).

The differential decreasing rate of the success for the spatial tasks between the vision and no-vision conditions reflects the known importance of visual information in the spatial aiming tasks. Providing a visual cue (e.g., size or location of target) and concurrent feedback (e.g., knowing where the limb is during aiming) facilitates the movement accuracy, especially when the requirements of accuracy are more stringent (Crossman & Goodeve, 1983; Meyer et al., 1990; Newell, Carlton, & Kim, 1994; Wallace & Newell, 1983; Zelaznik et al., 2008). The higher success rate of the vision condition at the slow movement goal of ID8 was accompanied with longer movement times and smaller spatial errors (see Figure 2). These

1 results indicated a possible error correction mechanism of vision that was involved in the
2 execution of the spatial aiming tasks at the slow movement goal.

3 For the timing task, although there was a general direction of longer movement times
4 and smaller spatial errors for the vision condition than the no-vision condition over all
5 movement goals, the only significantly higher success rate between the visual conditions was
6 observed in the no-vision condition of the fast movement goal. The availability of vision
7 seems to have a negative effect on the success rate in the fast movement goal of the
8 temporally constrained (time-matching) tasks. This provided evidence of non-essential role of
9 vision in performing a timing task. It is important to highlight that such a decrease in success
10 rate led to less spatial error in temporally constrained conditions – as the task is known, a
11 “trade-off” occurred. Indeed, the presence of a target with the instruction to finish the
12 movement as close as possible to the target clearly induced spatial constraints on the task –
13 despite the emphasis on the temporal requirements.

15 **Sub-movement characteristics and vision**

16 The traditional interpretation of sub-movement holds that if the primary sub-movement
17 misses, or is anticipated to miss the target, a second or even more sub-movements are
18 performed (Elliott et al., 2001), resulting in a longer movement time. Furthermore, the
19 number of corrective sub-movement increases when the requirements of the target are
20 stringent (Crossman & Goodeve, 1983; Meyer et al., 1990; Milner & Ijaz, 1990; Novak,
21 Miller, & Houk, 2002). Our findings show that there are different probability patterns for
22 each kind of sub-movement as a function of the task space-time conditions that were
23 differentially influenced by the presence or unavailability of vision.

24 The number of sub-movements increased over the longer movement times from about
25 the moderate movement goal of 500 ms where the trajectories of over 50% of the trials

showed only the primary sub-movement (Table 2 and Figure 4b). The 2 mm target size of ID8 (slow movement goal) elicited a long movement time of about 1s in the vision condition (Figure 2c) and about 80% of these trials exhibited the post-peak sub-movement (Figure 4e) that is consistent with the error correction interpretation (Elliott et al., 2001; Milner, 1992). The no-vision condition of ID8 (slow movement goal) had considerably shorter movement time (Figure 2c) and significantly fewer number of sub-movements than those in its vision counterpart (Figure 3a). In fact, there was about 40% trials of the no-vision condition of ID8 (slow movement goal) that had only primary sub-movements (Figure 4a) and another 40% trials had overshooting sub-movements (Figure 4g). The increased number of sub-movements in the vision condition may be attributed to the increased movement time. Without visual guidance and feedback, the sub-movements observed in the ID8 no-vision condition do not seem to reflect error correction.

The fast and moderate movement goals of the spatially and temporally constrained tasks produced average movement times of under 600ms (Figure 2c, 2d). The trajectory profiles of these tasks produced on average less than 2 sub-movements per trial (Figure 3). The proportion of primary-only sub-movement peaked at the moderate movement goal of about 500ms (c.f., Milner, 1992) (Figure 4b) and the proportion of the overshooting sub-movement decreased from 300ms (fast movement goal) to 500ms (moderate movement goal) in movement times (c.f., Fradet et al., 2008) (Figure 4h). These sub-movement characteristics were observed in both the vision and no-vision conditions. Furthermore, there was no visual effects found for the fast (ID2 and 300ms) and the moderate (ID5 and 500ms) ranges for the primary-only as well as the overshooting type of sub-movement (Table 1 and Table 2, effect of condition).

The target size of ID5 (moderate) is about 13% of ID2 (fast) and the movement times for both visual conditions were significantly longer in ID5 than those in ID2, yet not only were

there significantly more sub-movements per trial in ID2 than ID5, but ID2 also had consistently additional overshooting sub-movement per trial (Table 1 and Figure 4g). A similar trend was also observed in the two shorter movement time goals of the temporal task where there was a higher number of sub-movements in the 300ms (fast) condition than the 500ms (moderate) condition and the type of the extra sub-movements were mainly the overshooting (Table 2 and Figure 4). Taken together, the large enough target size that accommodated almost 100% successful trials, or the short duration movement time of about 300ms were associated with a predominant overshooting sub-movement that is consistent with the “braking” action of abrupt movement termination (Dounskaia et al., 2005, Fredet et al., 2008; Hsieh et al., 2019) but is unlikely to be visually induced given the associated short movement time duration.

Visual control of sub-movements

The vision/no-vision conditions of the slow movement of the time-matching task showed no significant difference in the number of sub-movements. Both visual conditions had very high proportions of pre-peak and post-peak type of sub-movements (Figure 4d, 4f) but very low to none in the overshooting or primary-only categories (Figure 4h, 4b). These results are consistent with the interpretation that the sub-movements are used to regulate the movement duration in the prolonged movements where the accuracy requirement on the spatial target is relaxed (Milner & Ijaz, 1990; Milner, 1992; Wisleder & Dounskaia, 2007; van der Wel et al., 2009). Across all of the conditions examined here movement time emerged as the most consequential variable in sub-movement profiles, *no matter* the other task conditions. Collapsing all the experimental conditions, we were able to observe the number of sub-movements and the proportions of each type of sub-movements as a function of movement time (Figure 5). Very short time movements tend to have overshooting sub-

1 movement and longer time movements have pre-peak and post-peak sub-movements while
2 moderate time movements most likely have only primary sub-movement.

3 However, as was observed in the slow movement goal of spatially constrained task,
4 there were also significantly more post-peak type of sub-movements observed in the vision
5 condition than the no-vision condition for the slow movement of the temporally constrained
6 task, and significantly more primary-only sub-movement in the no-vision than vision
7 condition (Table 1 and Table 2, effect of condition). This suggests that when vision is
8 available, the visually guided sub-movement may be an adaptation toward the visible target
9 evidenced by the smaller AE of spatial target and longer movement time in the vision than
10 no-vision condition of the slow movement tasks.

11 The no-vision control conditions across task types and space-time constraints showed
12 for each of the sub-movement types a *similar* probability profile of occurrence as the
13 respective vision conditions. The similar no-vision control findings in the time-matching task
14 conditions open the interpretation that the sub-movements in this task, unlike those of the
15 time-minimization protocol of Fitts' law, are *not* necessarily visually induced given that they
16 are essentially the same as in the no-vision conditions. These parallel vision/ no-vision sub-
17 movement profiles provide further evidence of different control strategies in time-
18 minimization and time-matching discrete movement tasks.

19 The profile of sub-movements and the effects of vision/no-vision on them and
20 movement outcome accuracy is strongly task dependent on spatial and temporal constraints
21 as well as their interaction. Vision plays the most important role in the success of the spatially
22 constrained task especially when the target size is small whereas the success of the
23 temporally constrained task does not benefit from vision. However, regardless of the effect of
24 vision and the nature of task constraints, the number of sub-movements as well as the
25 characteristics of sub-movements are directly related to movement times. Very fast

1 movements tend to have an overshooting sub-movement in addition to the primary sub-
2 movement; movements with moderate speed have higher probability of only primary sub-
3 movement and slow movements usually consist of pre-peak and post-peak sub-movements.
4 Although movement time appears to be the most important variable associated with sub-
5 movement profiles, we could not rule out the possibility of visually induced corrective sub-
6 movement when vision is available.

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Table 1. Statistical results for movement goals and visual conditions for each type of sub-movement in spatial task.

		Effect of movement goals (MG)					Effect of visual conditions		
		χ^2	<i>df</i>	<i>p</i>	W	Post hoc	MG	Z & post hoc	<i>p</i>
Only Primary	V	15.36	2	.001*	.38	slow > fast, moderate > fast	fast mod	-1.13 -.33	.28 .74
	NV	17.36	2	.001*	.43	slow > fast, moderate > fast	slow	-2.79 N > V	.005*
Pre-peak	V	22.13	2	.001*	.55	slow > moderate, slow > fast	fast mod	-.54 -1	.59 .32
	NV	8.73	2	.01*	.21	slow > fast	slow	-2.75 V > N	.006*
Post-peak	V	36.20	2	.001*	.91	slow > moderate > fast	fast mod	-1 -.91	.31 .37
	NV	23.63	2	.001*	.59	slow > moderate, fast	slow	-3.79 V > N	.001*
Over-shooting	V	38.00	2	.001*	.95	fast > moderate > slow	fast mod	-.71 -.24	.48 .81
	NV	23.68	2	.001*	.59	fast > moderate > slow	slow	-2.97 N > V	.003*

**p* < .05

1 Table 2. Statistical results for movement goals and visual conditions for each type of sub-
2 movement in temporal task.

		Effect of movement goals (MG)					Effect of visual conditions		
		χ^2	<i>df</i>	<i>p</i>	W	Post hoc	MG	Z & post hoc	<i>p</i>
Only primary	V	31.09	2	.001*	.78	moderate > fast, moderate > slow	fast mod	-.26 -1.38	.79 .17
	NV	29.69	2	.001*	.74	moderate > fast, moderate > slow	slow	-2.31 N > V	.02*
Pre-peak	V	34.43	2	.001*	.86	slow > moderate > fast	fast mod	-1.3 -.21	.18 .83
	NV	37.14	2	.001*	.93	slow > moderate > fast	slow	-1.57	.12
Post - peak	V	36.20	2	.001*	.91	slow > moderate > fast	fast mod	-.71 -2.10 V > N	.48 .04*
	NV	37.69	2	.001*	.94	slow > moderate > fast	slow	-2.69 V > N	.007*
Over-shooting	V	37.03	2	.001*	.93	fast > moderate > slow	fast mod	-.72 -1.76	.47 .08
	NV	39.00	2	.001*	.98	fast > moderate > slow	slow	-1.09	.28

3 **p* < .05

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Figure Captions

1. Examples of different types of sub-movements as defined by Chua and Elliott's (1993) algorithms. The different columns indicate types of sub-movement in displacement (top), velocity (middle) and acceleration (bottom) profiles (from left to right: only primary, pre-peak velocity, post-peak velocity and overshooting). The horizontal lines represent the zero level of each kinematic measure and the vertical dash lines indicate the end time for the respective movement. The numbers in parentheses at the bottom of each column indicate the number of the specific type of sub-movement observed in that trial. The primary-only type is always one, four sub-movements of the pre-peak type were found in the second column, two sub-movements of the post-peak type were found in the next column, and one sub-movement of overshooting type was found in the right most column.
2. Performance of space constrained (left) and time constrained (right) tasks in vision (light symbols) and no-vision (dark symbols) conditions as a function of three movement goals. Panels "a" and "b" display the success rate, panels "c" and "d" display the movement time, panels "e" and "f" are the absolute spatial error to the center of the target position.
3. The average number of sub-movements per trial in vision and no-vision conditions as a function of three movement goals for (a) the space constrained tasks and for (b) the time constrained tasks. Because there would be at least one sub-movement (primary-only) in a trial, the minimum number of sub-movements per trial is 1.
4. The proportion of each type of sub-movements in vision and no-vision conditions as a function of three movement goals for the space constrained tasks (left panels) and for the time constrained tasks (right panels). Panels "a" and "b" are the primary-only sub-movements; panels "c" and "d" are the pre-peak type of sub-movements; panels "e" and "f" are the post-peak type of sub-movements; panels "g" and "h" are the overshoot type of sub-movements.

1 5. The occurrence of sub-movements as a function of average movement times of each
2 experimental conditions. Panel “a” shows the average number of sub-movements per
3 trial; panel “b” shows the proportion of primary-only sub-movements, panel “c” shows
4 the proportion of pre-peak type of sub-movements, panel “d” shows the proportion of
5 post-peak type of sub-movements, and panel “e” shows the proportion of overshoot type
6 of sub-movements.
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1 Figure 1

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1 Figure 2

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1 Figure 4

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1 Figure 5

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