

Dual-target interference for the ‘automatic pilot’ in the dorsal stream

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Abstract When a target moves to a new location during a rapid aiming movement, the hand follows it, even when the participant intends not to. Pisella et al. (Nat Neurosci 3:729–736, 2000) claim that the posterior parietal cortex, in the dorsal visual stream, is responsible for this ‘automatic pilot’. Here we study the limits of automaticity in the dorsal stream through analysis of aiming movements to two targets in sequence. Participants were given a goal of moving rapidly to two targets, with the first movement being completed within approximately 200 ms. On 30% of trials, the first or the second target jumped unpredictably to a new location at movement onset, allowing us to measure the automatic capture of the hand. The results showed that hand movements were less responsive to target jumps in a 2-target condition than in a 1-target control condition. This indicates that the ‘automatic pilot’ is susceptible to interference from multiple visual inputs, implying that the dorsal stream is less effective at guiding actions online when multiple targets are attended.

Keywords Pointing · Dorsal stream · Sequential aiming · Automatic guidance · Attention

Introduction

Online corrections to visually-guided movements are thought to be mediated by the dorsal visual stream (Pisella et al. 2000; Desmurget et al. 1999). This neural stream projects to the posterior parietal cortex (PPC), and has been shown to guide movements in the absence of conscious awareness (for a review, see Goodale and Westwood 2004). In fact, Milner and Goodale’s (1995) perception/action model of dual-stream visual processing relegates all conscious visual processing to the ventral stream (in the inferotemporal cortex), leaving the dorsal stream to carry out its tasks ‘automatically’. The robustness of this automaticity has been demonstrated by movement corrections to unperceived target perturbations (Goodale et al. 1986; Pelisson et al. 1986; Prablanc and Martin 1992) and by participants’ inability to inhibit corrections to perceived target perturbations (Pisella et al. 2000; Cressman et al. 2006). The PPC has, accordingly, been described as an ‘automatic pilot’ for visually guided action (Pisella et al. 2000). In the present study we investigate the limits of its automaticity by testing whether it is subject to interference from multiple visual inputs.

Direct evidence that the dorsal stream is involved in online control is provided by studies of PPC patients as well as studies of healthy individuals. Pisella et al. (2000), for instance, show that bilateral PPC lesions prevent rapid movement correction. Desmurget et al. (1999) show a similar effect when PPC function in healthy participants is inhibited with transcranial magnetic stimulation. The dorsal stream, therefore, appears critical for quick adjustments to movements that are already underway, and it can effect these changes in movements as short as 200 ms (Pisella et al. 2000; Cressman et al. 2006). A feed-forward mechanism, in which the predicted movement outcome is

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compared to the current target location, has been proposed to mediate these online corrections (Desmurget et al. 1999; Desmurget and Grafton 2000; Desmurget and Grafton 2003).

In the current study, we approach the dorsal stream as a non-conscious online processor and examine, through behavioural methods, its processing capabilities. Specifically, we examine the dorsal stream's ability to modify movements under single- and dual-target conditions. Previous studies of dorsal stream function have tended to examine single-target movements only. Many everyday actions, however, involve multiple targets and multiple movement components: Any time one dials a number on a telephone or places a sugar cube into a cup of tea, multiple targets are involved in the movement sequence. How does the visuomotor system contend with these targets, and does the dorsal stream suffer interference under multiple target conditions?

Although this type of interference has not been explicitly addressed in the literature, previous research on sequential aiming movements may provide relevant information. In sequential aiming studies, participants tap 2 or more targets in rapid sequence. When performance of a multiple-component movement is compared to performance of a single-component movement, movement time (MT) of the first segment of a multi-component movement is typically longer than the MT of the single component movement. This phenomenon is known as the 'one-target advantage', and there are competing explanations for its source (for a critical examination of these explanations, see Adam et al. 2000). The important feature of the one-target advantage for the current discussion is that a cost is incurred when a movement has to be executed to multiple targets versus a single target. This finding would seem to suggest that the dorsal stream does suffer interference when it is tasked with multiple targets. However, there is reason to be cautious in interpreting the one-target advantage this way. As Adam et al. (2000) point out, "Invariably, all studies showing the one-target advantage have emphasized speed of response and imposed low accuracy constraints." Indeed, the average MT of the single-component movements in the 6 one-target advantage studies summarized by Adam et al. (2000) is 128 ms. Such movements are subject to minimal, if any, online control, and are, therefore, dubious indicators of dorsal stream processing.

To explore dorsal stream interference more directly, we borrowed from an experimental design developed by Pisella et al. (2000). In that study, participants made rapid (200–300 ms) pointing movements and were instructed to either modify their movement when a target jumped ('go' trials) or to halt their movement when a target jumped ('stop' trials). Pisella et al. found that on a significant number of the 'stop' trials, the aiming hand involuntarily

deviated in the direction of the jumping target, thereby demonstrating the automaticity of rapid online corrections. Furthermore, a patient with lesioned PPC did not succumb to the same involuntary capture. Based on their findings, Pisella et al. (2000) characterized the PPC as an online control 'automatic pilot', a system that can update rapid movements even when there is no conscious intention to do so—even, in fact, when there is a conscious intention *not* to do so.

Pisella et al.'s (2000) combination of a 'stop' instruction with a target perturbation provides a window into the operations of the dorsal stream. We reasoned that by incorporating the same type of design into a sequential aiming task, we could observe the impact of multiple targets on dorsally-mediated behaviour. Specifically, we set up a task in which participants made a fast sequential aiming movement to two targets, with a goal MT of 200 ms to reach the first target. At this MT, automatic capture of the hand can be reliably observed (Pisella et al. 2000; Cressman et al. 2006). We then compared the degree of hand capture caused by a jumping first target in this 2-target condition to the degree of hand capture caused by a jumping single target in a separate 1-target condition. If the processing of multiple targets causes interference in the dorsal stream, there should be less automatic capture in the 2-target condition than in the 1-target condition.

This 2-target protocol, therefore, allows us to examine processing constraints in the dorsal stream. In a rapid sequential aiming task, the visuomotor system must contend with two targets that are potentially competing for processing resources. If the dorsal stream is subject to attentional limitations, our protocol should allow us to detect this.

To anticipate our findings, we show that (1) the 'automatic pilot' in the dorsal stream suffers interference from multiple targets and (2) that the preparation of the second component of the sequential aiming movements occurred, at least in part, during the flight of the first component of the movements.

Methods

Participants

Eight volunteers (6 female, 2 male) from the University of British Columbia participated in the experiment. The average age was 25 (range 22–30). All participants were right-handed and had normal or corrected-to-normal vision. The experiment was conducted in accordance with the ethical guidelines set by the university and with the ethical standards set by the Declaration of Helsinki. All participants gave written informed consent prior to participating in the study.

Apparatus

The targets to which participants made aiming movements were red dots of light (5 mm diameter) produced by light emitting diodes (LEDs). The LEDs were set beneath an inclined Plexiglas surface (Fig. 1a). The ‘home’ position was located along the participant’s midline, at the near end of the display surface. The two LEDs used for stationary target presentation were vertically aligned at two distances from ‘home’ position: 220 mm (near target or T1), and 295 mm (far target or T2). The two LEDs used for perturbed target presentation were each located 50 mm to the right of their respective stationary target LEDs (Fig. 1b). Participants sat with their head in a chinrest, their eyes positioned approximately 60 cm from the display surface. Participants held a stylus in their right hand. An infrared emitting diode was fixed to the front surface of the stylus, and this allowed tracking of the movement with Optotrak (Northern Digital Inc.). The position of the stylus was sampled at a frequency of 500 Hz. The stylus’s micro-switch tip allowed precise recording of movement lift-off and touch-down.

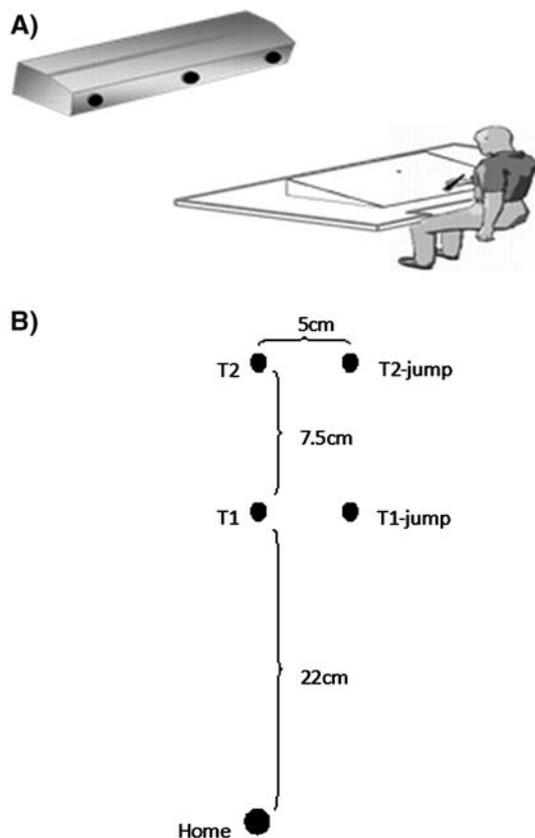


Fig. 1 Participant seated at the display surface, with Optotrak system recording the stylus position (a). The layout of the stimuli on the display surface (b)

Procedure

Participants completed 4 different conditions: 1-target GO, 1-target STOP, 2-target GO, and 2-target STOP. Participants completed the 1-target conditions in a separate session from the 2-target conditions. The order of sessions was counterbalanced across participants, and the order of the GO and STOP instructions within the sessions was also counterbalanced across participants. Participants completed a practice block of 50 stationary 1-target trials prior to the 1-target session, and they completed a practice block of 50 stationary 2-target trials prior to the 2-target session.

In all conditions, participants began the trial with the stylus placed at the home position. In 1-target trials, one target (T1) was displayed, and participants were told to aim with the stylus to the single target. In 2-target trials, two targets (T1 and T2) were displayed, and participants were told to hit both targets in rapid sequence, tapping T1 prior to T2. Participants were told to initiate their movement as soon as the target(s) appeared on the display (i.e. reaction time (RT) was stressed). Participants were also told to try to complete their movement to T1 with a MT as close to 200 ms as possible. Precise MT feedback was provided to participants after every trial in all conditions. Finally, participants were told to aim as accurately as possible, while still adhering to the RT and MT instructions.

In each of the four conditions, 70% of the trials were stationary trials (the illuminated LEDs did not change during the trial). The remaining 30% of trials were jump trials, in which a target would jump to a new position at movement onset. (A target ‘jump’ consisted of one LED being extinguished and a new LED being simultaneously illuminated at a position 50 mm to the right of the extinguished LED.) In 1-target trials, only one type of jump occurred: the target (T1) jumped 50 mm to the right. In 2-target trials, two types of jump occurred: T1 jumped 50 mm to the right or T2 jumped 50 mm to the right. Stationary and jump trials were randomly interspersed, and in all conditions the target(s) remained illuminated until the end of the trial.

In the 1-target GO condition, participants were told that if the target jumped they should try to move to the target’s new position. In the 2-target GO condition, participants were told that if one of the targets jumped, they should try to go to its new position during that component of the movement (i.e. if T1 jumped, they should move to its new position and then continue on to T2; if T2 jumped, they should move to T1 and then continue on T2’s new position).

In the 1-target STOP condition, participants were told to immediately stop their movement if the target jumped. In the 2-target STOP condition, participants were told to immediately stop their movement if either target jumped.

Data analyses

Movement lift-off and touch-down were determined according to the analog status of the stylus's microswitch tip, sampled at 500 Hz. The 3D position data from the Optotrak were filtered using a second order, dual-pass, Butterworth filter with low-pass cutoff of 10 Hz. To calculate mean hand paths, the position data for each movement were first resampled at 100 evenly-spaced points along the path length, with linear interpolation between neighbouring points (Goodbody and Wolpert 1998).

Results

Excluded trials

Trials were excluded from analysis based on the following criteria: RT less than 100 ms or greater than 1,000 ms, MT to T1 less than 100 ms or greater than 350 ms, and MT from T1 to T2 less than 50 ms. Jump trials in which participants successfully stopped their movements prior to touch-down on T1 (12.9% of STOP condition jump trials, on average) were not included in the analysis. Overall, these criteria led to the exclusion of less than 5% of all trials.

Reaction time (RT)

Table 1 shows the mean RTs for each of the four conditions. A 2 instruction (GO/STOP) \times 2 target number (1-target/2-target) repeated-measures ANOVA revealed that RT was affected by neither instruction, $F(1,7) < 1$, nor the number of targets, $F(1,7) < 1$. There was also no interaction effect, $F(1,7) < 1$. The lack of a significant target number effect is not consistent with previous studies that have shown an increase in RT with an increase in target number (Henry and Rogers 1960; Ricker et al. 1999; Lajoie and Franks 1997). A possible reason for the absence of the effect in our study is the addition of a MT goal, which has not been included in studies showing an RT difference between 1- and 2-target trials. This MT goal may have emphasized planning of the first movement component, an issue that will be explored further in the discussion section.

Table 1 Mean reaction time and movement time, in milliseconds, of the movement to T1

	1targetGO	1targetSTOP	2targetGO	2targetSTOP
Reaction time				
Stationary	258.2	256.6	260.2	260.8
Movement time				
Stationary	209.6	211.3	211.2	211.6
Jump	214.0	213.9	221.2	212.0

Movement time (MT) to T1

Table 1 shows the mean MTs to T1 for jump and stationary trials in each of the four conditions. A 2 instruction (GO/STOP) \times 2 target number (1-target/2-target) \times 2 jump (jump/stationary) repeated-measures ANOVA revealed no significant main effects or interaction effects (all P -values were greater than 0.20). Given that participants were instructed to maintain their MT to T1 as close to 200 ms as possible, this is not a surprising result.

Dwell time on T1 during two-component movements (GO condition only)

We also measured the dwell time on T1 (time between touch-down on and lift-off from T1) during two-target GO trials. The mean dwell times on stationary, T1-jump, and T2-jump trials were 41, 47, and 44 ms, respectively. A 1-way repeated-measures ANOVA revealed a significant effect, $F(2,14) = 11.85$, $P < 0.001$. Post-hoc analysis (Newman-Keuls) revealed that all means differed significantly from each other at $P < 0.05$.

Spatial accuracy and variability to stationary targets

Radial error (RE) around T1 (stationary trials)

We used RE, the average of the two-dimensional distances between the target and the movement endpoints, as a measure of spatial accuracy. The average RE around T1 on stationary trials is displayed in Table 2. A 2 instruction (GO/STOP) \times 2 target number (1-target/2-target) repeated-measures ANOVA was applied to the RE scores. There was no significant effect of instruction, $F(1,7) = 1.3$, $P > 0.20$. There was no significant effect of target number, $F(1,7) < 1$. There was also no significant interaction between the two factors, $F(1,7) = 1.1$, $P > 0.30$.

95% Endpoint confidence ellipses for movements to T1 (stationary trials)

We used the surface area of a 95% endpoint confidence ellipse as a further measure of spatial outcome. This ellipse captures 95% of the endpoints of movements to a given target, and its surface area thereby provides a measure of the

Table 2 Mean radial error (mm) and 95% endpoint confidence ellipse surface area (mm²) of the movement to T1 on stationary trials

	1targetGO	1targetSTOP	2targetGO	2targetSTOP
Radial error	10.4	9.8	10.1	10.6
Ellipse surface area	769.5	786.6	707.4	778.9

two-dimensional variability of these endpoints. The average ellipse surface areas for movements to T1 are shown in Table 2. A 2 instruction (GO/STOP) \times 2 target number (1-target/2-target) repeated-measures ANOVA was applied to the ellipse surface area values. No significant effects were found (all F -values < 1). These results, along with those for radial error, suggest that movement accuracy to T1 on stationary trials was affected by neither the number of targets nor the instruction type.

Impact of target perturbation

Lateral deviation difference score in movement to T1

The variable we were most interested in was one that would indicate the degree of horizontal shift in the movement to T1 caused by a T1 jump. The measure we used was the difference between the mean horizontal endpoint on T1-jump trials and the mean horizontal endpoint on the corresponding stationary trials. We then compared the difference scores on 2-target trials to the difference scores on 1-target trials (Fig. 2). A 2 instruction (GO/STOP) \times 2 target number (1-target/2-target) repeated-measures ANOVA was applied to these scores. There was a marginally significant effect of instruction, $F(1,7) = 5.4$, $P = 0.053$, suggesting that participants deviate more when intending to ‘go’ than when intending to ‘stop’. More importantly, there was a significant effect of target number $F(1,7) = 15.25$, $P < 0.01$, indicating that there is more deviation to the perturbed target in the 1-target trials than in the 2-target trials. Finally, there was no significant interaction, $F(1,7) = 1.03$, $P > 0.30$, indicating that the effect of target number was consistent across instruction condition.

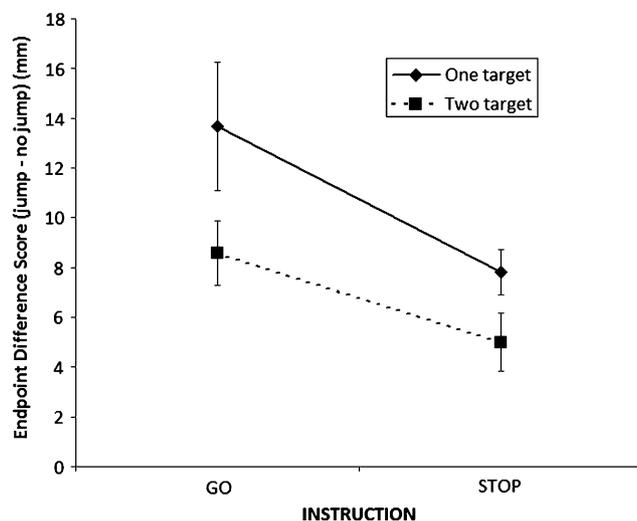


Fig. 2 Amount of lateral deviation in movement to T1 caused by a T1 jump as a function of target number and instruction type. Error bars represent standard error of the mean

Figure 3 shows some sample trajectories from one participant for 1- and 2-target conditions. The trajectories show deviation toward the perturbed T1 in both cases, but the degree of deviation is larger in the 1-target condition.

Proportion of movements captured by a jumping T1

We also examined the impact of the T1 jump by classifying movement endpoints as ‘captured’ or ‘not captured’ by the T1 jump. Similar to Pisella et al. (2000), we used a 95% confidence interval derived from stationary target trials to determine whether movements on jump trials were captured. Endpoints falling outside the interval (on the side of the target jump) were classified as ‘captures’. The results are displayed in Fig. 4. Prior to statistical analysis, the binomial proportion data were normalized using an arcsine-root transformation. A 2 instruction (GO/STOP) \times 2 target-number (1-target/2-target) repeated-measures ANOVA was then applied. There was a marginally significant effect of instruction, $F(1,7) = 5.44$, $P = 0.052$, and a significant effect of target number, $F(1,7) = 11.57$, $P < 0.05$. No

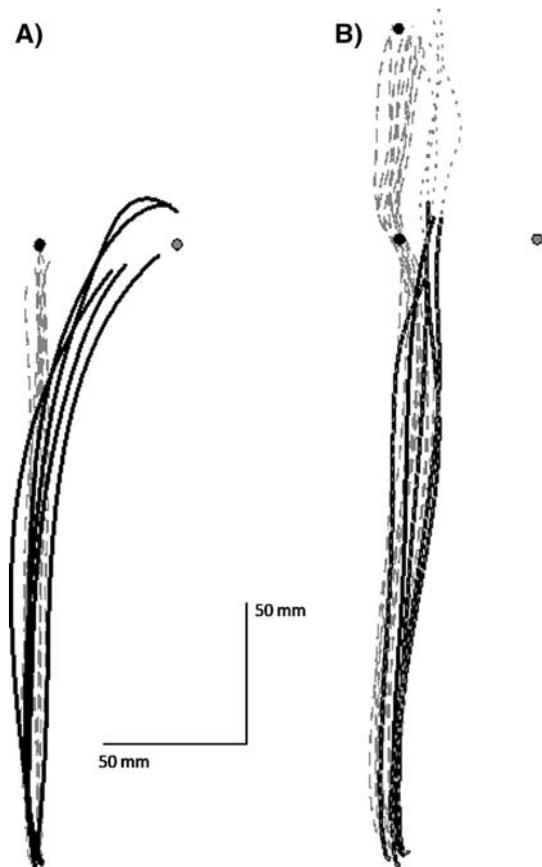


Fig. 3 Sample trajectories from one participant for the 1-target GO condition (a), and the 2-target GO condition (b). Solid black lines indicate T1-jump trials; thick grey dashed lines indicate stationary trials. The thin grey dashed lines in (b) indicate the second movement component (i.e. the movement to T2) on T1-jump trials

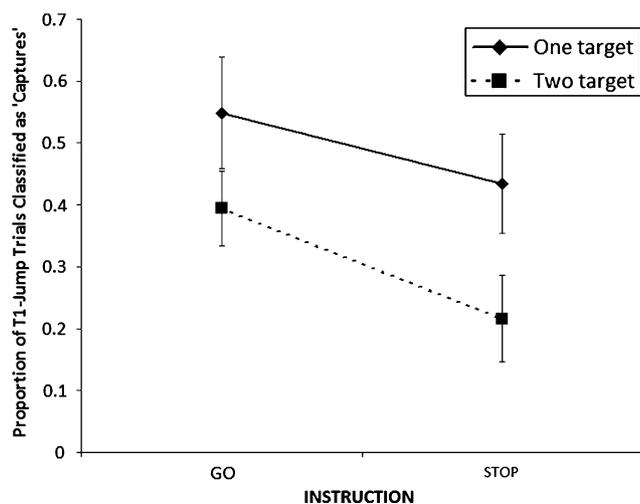


Fig. 4 The proportion of trials classified as ‘captures’ on T1-jump trials as a function of target number and instruction type. *Error bars* represent standard error of the mean

significant interaction was found, $F(1,7) < 1$. These results are consistent with those found in the endpoint difference score analysis.

Latency of movement deviation to jumping T1

We compared average movement trajectories from the jump and stationary trials of each participant to determine when the mean movement paths in the jump trials diverged from the mean paths in the stationary trials. To obtain our estimate of the latency of deviation, we recalculated the mean path in the jump trials at every 2 ms interval until the mean point of divergence was reached. The average latencies at which mean movements paths deviated in the direction of a perturbed T1 were 164 and 168 ms for the 1-target GO and 2-target GO conditions, respectively. A correlated t-test revealed no significant difference between the two trial types, $t(7) = 0.69$, $P > 0.50$, suggesting that the number of targets did not have a significant impact on the time at which movements began to deviate towards T1.

Deviation in movement to T1 caused by T2 jump (2-target trials only)

We were also interested in whether a perturbation to T2 had an impact on the movement to a stationary T1 during sequential aiming. We compared the mean horizontal endpoint of the movements to T1 on T2-jump trials to the mean horizontal endpoint of the movements to T1 on 2-target stationary trials (Fig. 5). A 2 instruction (GO/STOP) \times 2 jump (jump/no jump) repeated-measures ANOVA was applied to the data. There was no significant effect of instruction, $F < 1$. There was a significant main effect of jump, $F(1,7) = 11.71$, $P < 0.05$, indicating that there was a

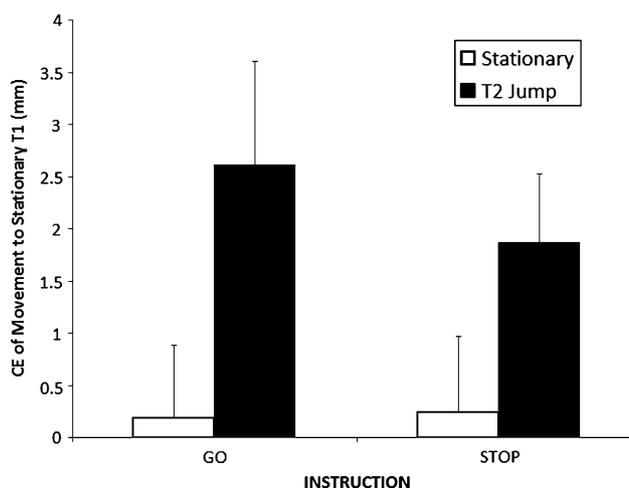


Fig. 5 Amount of lateral deviation in movement to a stationary T1 caused by a T2 jump. *Error bars* represent standard error of the mean. *CE* constant error (movement endpoint–target position)

reliable (albeit very small, ~ 2 mm) rightward shift in the endpoint of the movement to T1 when T2 jumped to the right. There was no significant interaction between instruction and jump, $F(1,7) = 1.05$, $P > 0.30$.

Discussion

Our goal was to investigate multi-target processing in the dorsal visual stream. We used participants’ non-intentional online modifications of fast aiming movements as an indicator of dorsal stream processing, and we examined the impact of one vs. two targets on the participants’ ability to execute such modifications. Our reliance on non-intentionality as a clear indicator of dorsal stream processing meant that the STOP condition, in which participants had no conscious intention to modify their movements, was of primary interest. The effects of 1 versus 2 targets were consistent, however, across GO and STOP conditions (i.e. none of our analyses showed an interaction between target number and instruction type). The following discussion of the results will, accordingly, focus on the effects of 1 versus 2 targets on movement corrections irrespective of instruction condition.¹

¹ It should be noted, however, that we found a marginally significant main effect of instruction on the degree of movement correction (more deviation under ‘go’ instruction than under ‘stop’ instruction). This is likely a result of late, intentionally driven, online corrections that can occur in the ‘go’ condition. Pisella et al. (2000), for instance, found equivalent amounts of correction in ‘go’ and ‘stop’ for MTs between 200 and 240 ms, but when MTs were greater than 240 ms, they found more corrections in the ‘go’ condition. Since we only excluded trials with MTs greater than 350 ms, some trials with MTs longer than 240 ms may have contributed to the observed difference between instruction conditions.

With respect to the issue of dual-target interference, our results show that automatic movement corrections are reduced when two targets are involved in the movement sequence. Participants' movements deviated less to a jumping T1 in 2-target trials than they did in 1-target trials. This result suggests that the visuomotor processing of the second target interfered in some way with the processing of the first target. It is worth noting that movement modifications to a jumping T1 were not eliminated in the 2-target trials—they were merely reduced relative to the 1-target trials. Thus, T1 was still being processed in the 2-target trials, just not as effectively.

Online programming of the movement to T2 (i.e. programming occurring during the execution of the movement to T1) might explain the interference that was observed. This would be consistent with previous research suggesting that refinement of the programming to the second target occurs online (Ricker et al. 1999). In fact, by stressing a MT goal for the movement to T1, and thereby indirectly emphasizing the preplanning of the first movement component, our design likely encouraged online programming of the movement to T2. Our finding that the endpoint of the movement to T1 was biased by a T2 jump further supports the idea that online programming of the second movement interferes with execution of the first.

Interestingly, the number of targets did not appear to affect the latency at which mean movement paths began to deviate to T1 when it jumped to a new location. The onset of deviation occurred just as early in 2-target trials (~168 ms) as it did in 1-target trials (~164 ms). So, while the amount of correction to the T1 jump suffered interference from the presence of T2, the latency of the onset was not affected. This result may indicate that the interference arises from processes occurring *after* the hand deviation has been initially triggered. The online processing of T2, which we have postulated as a source of interference, may not manifest itself until later in the movement (i.e. sometime after approx. 170 ms).

In fact, the processing cost associated with the 2-target trials appears to be entirely restricted to a reduction in the amount of automatic deviation to a perturbed T1. No other measures (reaction time, movement time, radial error, and endpoint confidence ellipse surface area) showed any significant difference between the 1-target and the 2-target trials. One might expect the lack of a MT difference, given that MT was constrained, but the lack of any difference in spatial accuracy on stationary trials is puzzling. If there is an online processing cost associated with multiple targets, one would expect it to emerge in the parameter that is free to vary—in this case spatial accuracy to T1. (Our design was, in a way, the inverse of most sequential aiming movement studies, which usually constrain accuracy and then infer processing costs through increases in MT.)

It is possible that the endpoints to T1 on stationary trials largely reflect preplanning, and that movement endpoint was specified with equal fidelity in the 1- and 2-target trials. We argued above that the MT constraint may have emphasized planning to T1 in 2-target trials, making movement preparation in these trials similar to 1-target trials. This is supported by the equal RTs in 1- and 2-target trials, as RT correlates with the complexity of the movement that has been prepared (Henry and Rogers 1960; Lajoie and Franks 1997). However, for this argument to account for the similar accuracy in stationary 1- and 2-target trials, it must assume that minimal online control is occurring on stationary trials. (Otherwise, the online programming to T2 would interfere with the online control to T1, reducing accuracy to T1 on stationary 2-target trials.) This is hard to reconcile with the finding that movements *are* modified online when T1 jumps, unless one posits that automatic corrections to large target perturbations engage different online processes than movement corrections to stationary targets. It may be for instance, that a large error signal (such as that produced by a target perturbation) allows feed-forward correction systems in the PPC to detect a discrepancy between the predicted outcome of the programmed movement and the target location sooner (and thus to modify the movement sooner) than in stationary target conditions. In the latter case, the discrepancy between the programmed movement and the target location would be much smaller and, therefore, might take longer for the system to detect. In fact, if the discrepancy is small enough, the PPC may be unable to detect it at all, potentially leading to no feed-forward online correction on some stationary trials.

The idea that larger discrepancies between the intended movement and the target location enable earlier movement corrections does have empirical support. Elliott and Allard (1985), for instance, showed that participants benefited from visual feedback at shorter MTs when displacing prisms were worn (which produce a large discrepancy) compared to normal vision (small discrepancy).

Although our design is quite different from one-target advantage designs we described in the introduction, there are some issues from the one-target advantage literature that deserve to be addressed. We have suggested that the dual-target cost in the current study arises from interference by the online programming of the second movement component with the execution of the first movement component. While some researchers (e.g. Chamberlin and Magill 1989; Ricker et al. 1999) argue that online programming of the second movement component occurs during the first movement component, other studies (e.g. Fischman and Reeve 1992) discount the role of online programming in the one-target advantage. Adam et al. (2000) also discount the online programming explanation, although their proposal, the movement integration hypothesis, does not remove

online processing from the equation. Rather, their theory suggests that interference is caused by online *implementation* of a pre-programmed second movement component, not online *construction* of a second movement component.

While it is possible that the movement integration hypothesis might account for our findings, there are several reasons to suspect that it does not. First, we show no RT difference between 1- and 2-target conditions. If the second movement component had already been programmed and was simply awaiting implementation, one would predict longer RTs in the 2-target trials. Second, as mentioned earlier, our design's emphasis on achieving a goal MT to T1 probably encouraged online programming of the second movement component. Finally, our finding that a T2 jump influenced the movement to a stationary T1 suggests that some degree of programming of the second movement component was occurring during the execution of the first movement component.

In 2-target trials, target jumps also appeared to influence the amount of time spent on T1 (dwell time). We saw a very small but significant increase in dwell time when T1 jumped (6 ms increase) and when T2 jumped (3 ms increase) relative to stationary trials. This increase in dwell time probably reflects a cost associated with having to modify the original movement plan as a result of the perturbation. This also suggests that the second target was taken into consideration prior to movement initiation, since we would expect no difference in dwell time between stationary and perturbed trials if all programming of the second movement component occurred online. However, the very small magnitude of the dwell time increase also suggests that this consideration of the second target prior to movement initiation was quite limited; almost as much online programming time was required for a stationary T2 as for a perturbed T2. Still, the dwell time data raise the possibility that interference in the 2-target condition might be a result not only of the online programming of the movement to T2, but also the need to respond to a target perturbation that compromises the initial movement plan.²

Conclusion

Our results show that rapid online updating of a movement to a target jump is impaired when two targets are involved in the movement sequence. Our results also suggest that this dual-target interference arises because online programming of the second movement component reduces the dorsal stream resources that can be dedicated to executing the first movement component. So, although dorsal stream

movements may be 'automatic' in that they elude conscious control (Pisella et al. 2000; Cressman et al. 2006) and also elude interference from simultaneous perceptual targets (Liu, Chua and Enns 2006, Unpublished data), they do not escape interference from simultaneous action targets. This points to resource-limitations among unconscious visual processes that resemble those that have been explored for many years in conscious visual processes (Pashler 1998). The challenge for future research will be to find methods for exploring the limited resources of unconscious processes that go beyond what can be learned from the GO-STOP action paradigm.

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