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The influence of foreperiod duration on the preparation and control of sequential aiming movements

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Abstract

Reaction time (RT) and movement times (MTs) to the first target are typically longer for two-target sequential movements compared to one-target movements. While this one-target advantage has been shown to be dependent on the availability of advance information about the numbers of targets, there has been no systematic investigation of how foreperiod duration (i.e., interval between presentation of the target(s) and stimulus) influences the planning and execution of sequential movements. Two experiments were performed to examine how the one-target advantage is influenced by the availability and timing of advance target information. In Experiment 1, participants performed one- and two-target movements in two separate blocks. In Experiment 2, target conditions were randomised from trial to trial. The interval between target(s) appearing and stimulus tone (i.e., foreperiod) was varied randomly (0, 500, 1,000, 1,500, and 2,000 ms). The results of Experiment 1 revealed that while the one-target advantage in RT was not influenced by foreperiod duration, the one-target advantage in MT increased as foreperiod duration increased. The variability of endpoints at the first target was greater in the two- compared to one-target condition. In Experiment 2, the one-target advantage in both RT and MT increased as the length of the foreperiod increased. However, there was no difference in limb trajectory variability between target conditions. The implication of these findings for theories of motor planning and execution of multiple segment movements is discussed.

Keywords

Sequential aiming movements; response complexity; movement planning; movement control

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Introduction

When movements are performed to two targets in a sequence, reaction time (RT) is typically longer compared to single target movements (Ketelaars et al., 1999; Lavrysen et al., 2003; Ricker et al., 1999). This one-target advantage in RT (OTA:RT) has been shown to be contingent on participants having advance knowledge of the number of targets (e.g., Khan et al., 2006, 2008a; also see Klapp, 1995, 2003). Likewise, movement time to the first target (MT1) in a two-target sequence is longer compared to a single target movement (i.e., Adam et al., 2000; Chamberlin & Magill, 1989; Fischman & Reeve, 1992). Similar to RT, the one-target advantage in movement time (OTA:MT) is contingent on advance information regarding the number of targets in the response (Bested et al., 2018; Khan et al.,

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2008a). This evidence that the OTA:RT and OTA:MT depend on a priori knowledge of the number of targets in a response implies that there is an interdependency between the processes underlying the planning and execution of multiple target movements. While studies have demonstrated the interplay between planning time and the online execution of responses (e.g., Ariani & Diedrichsen, 2019; Ghez et al., 1997; Haith et al., 2016), there has been no systematic study of how the time available prior to the stimulus (i.e., foreperiod) influences the OTA:RT and OTA:MT in sequential aiming movements. This has important theoretical implications on the distribution and integration of processes prior to response initiation and during the execution of sequential aiming movements.

Based on a series of experiments involving results of Morse code and speech articulation responses, Klapp (1995, 2003) proposed that when the number of response segments is known in advance of the stimulus (i.e., simple RT), participants load an abstract time frame in short-term memory prior to the RT interval. During the RT interval, the time frame is retrieved and scanned to place the segments in the correct order. This scanning process takes longer as the number of segments increases and hence RT increases as a function of the number of segments. When participants do not know the number of segments in advance (i.e., choice RT), Klapp proposed that the abstract time frame is loaded during the RT interval and therefore does not have to be scanned to order the segments. Hence, RT does not increase as a function of the number of segments in a sequence. Following from the work of Klapp, Maslovat et al. (2014, 2016) have refined this explanation by specifying that when the response is known in advance, the process associated with ordering segments can occur prior to the stimulus but timing of the initiation of segments must occur during the RT interval or even during movement execution when the response is not known in advance (i.e., choice RT). Consistent with this theoretical framework, Khan et al. (2006, 2008a) have shown that RT for two-target movements was longer than one-target movements when participants received information about the number of targets prior to the stimulus. This was the case even when the number of targets was known in advance, but other features of the response were not specified (i.e., movement amplitude). However, there was no difference in RT between one- and two-target movements when the number of targets was not known until presentation of the stimulus. Hence, the emergence of the OTA:RT was contingent on advance knowledge of the number of targets regardless of whether or not other response features were specified.

Whereas several researchers have focused their efforts on the relationship between RT and the number of response segments (e.g., Fischman, 1984; Henry & Rogers, 1960; Klapp et al., 1974; Sternberg et al., 1978), Adam and colleagues have extensively studied the time it takes to execute sequential aiming movements (Adam et al., 1993, 1995, 2000, 2001; Adam & Paas, 1996). The OTA:MT has been shown to emerge across levels of practice (Lavrysen et al., 2003), regardless of participants' handedness or hand used (Helsen et al., 2001; Lavrysen et al., 2003), when vision is available or occluded (Lavrysen et al., 2002), and when there is a switch in limbs at the first target (Khan et al., 2010; Mottram et al., 2014).

It has been shown that MTs to the first target in two-target sequences are lengthened when eye movements are constrained (Adam et al., 2000), regardless of whether stimuli are symbolic (e.g., 1T, 2T; Khan et al., 2006, 2008a) or consist of the presentation of the targets (Bested et al., 2018). Hence, it appears that the one-target advantage is related to planning and execution processes rather than visual processing and attentional capture of the targets. Indeed, one of the most prominent explanations for the OTA:MT is the movement integration hypothesis (Adam et al., 2000). An underlying assumption of the movement integration hypothesis is that the movement segments for both targets are preloaded into a buffer prior to the initiation of the response (also see Ghez et al., 1997). To transition between movement segments, the implementation of the second segment is performed during the execution of the first segment (i.e., online). While some authors refer to online programming as a combination of the selection, planning, and implementation of segments during movement execution (cf. Ariani & Diedrichsen, 2019; Chamberlin & Magill, 1989), the movement integration hypothesis specifically refers to the implementation (i.e., initiation) of the pre-planned second segment during execution of the first. This assumption is consistent with evidence that indicates response preparation and initiation processes can occur independently and are not necessarily temporally coupled (Haith et al., 2016). In this way, the initiation process related to the second segment can be held back in time to ensure a smooth transition between response segments. The explanation forwarded by Adam et al. (2000) proposes that the overlap of processes associated with the initiation of the second segment during execution of the first segment causes interference resulting in longer MTs to the first target.

An alternative explanation for the OTA:MT is the movement constraint hypothesis (Fischman & Reeve, 1992). This explanation is based on the premise that variability in limb trajectories increases from one target to the next. Hence, to be accurate at the second target, the variability of movement endpoints at the first target must be constrained. In accordance with the speed accuracy trade-off (Fitts, 1954), this reduction in variability at the first target comes at the expense of longer MTs. While both these hypotheses have received support in the literature, research has indicated that the underlying processes of both the movement integration and the movement constraint hypotheses play an integrated role in the preparation and control of multiple

target sequential aiming movements (Bested et al., 2018; Khan et al., 2011; Lavrysen et al., 2002).

Similar to the theoretical framework of Klapp (1995, 2003), the movement integration hypothesis would imply that advance knowledge of the number of segments is needed to load segments into a buffer prior to response initiation. However, it is not clear whether the movement constraint hypothesis is contingent on advance movement planning or feedback-based processes during movement execution. To examine how advance target information influences the one-target advantage, Bested et al. (2018) varied the order of one- and two-target movements. Prior to this study, investigations had typically employed a blocked design in which one- and two-target movements were performed in separate blocks of trials. Therefore, participants knew in advance whether to perform one- or two-target movements. Bested et al. found that the OTA:MT emerged when one- and two-target movements were blocked and alternated on successive trials, but not when the number of targets was randomised from trial to trial. These results were consistent with the movement integration hypothesis by demonstrating that advance knowledge of the number of targets was required for the OTA:MT to emerge. Interestingly, evidence was also revealed for the movement constraint hypothesis. Variability at the end of the first movement segment was less for the two- compared to the one-target trials in the blocked condition, but not alternate and random conditions. Hence, movements to the first target were constrained to meet accuracy demands at the second target only when the same number of targets was repeated trial after trial. This would imply that both prior knowledge of the number of segments and the repetition of the same movement over successive trials were required for constraining mechanisms to be implemented.

The present study goes a step further in testing the underlying assumptions of the movement integration and constraint hypotheses. Given that both the OTA:RT and OTA:MT depend on whether the number of targets is known in advance (Bested et al., 2018; Khan et al., 2006, 2008a), the present study was designed to investigate how the planning and control of sequential aiming movements are influenced by the time available to use target information. In the past, the foreperiod duration has typically been varied randomly but with no systematic investigation of how this interval influences the interplay between processes during RT and movement execution. In Experiment 1, we administered a blocked trial sequence in which participants always knew whether to produce a one- or two-target response. In Experiment 2, one- and two-target responses were randomised from trial to trial. In both experiments, the interval between the presentation of the target(s) and the stimulus tone (i.e., foreperiod) was varied randomly (0, 500, 1,000, 1,500, and 2,000 ms). The movement integration hypothesis is based on the premise that segments are loaded into a buffer prior to stimulus presentation. Based on the assumption that this storage process takes time, it was expected that the magnitude of both the OTA:RT and OTA:MT would be greater for longer foreperiods. Although the movement constraint hypothesis does not stipulate whether the OTA:MT is due to planning or online error corrections (Adam et al., 2000), the variability in limb trajectories at peak velocity and movement end points was analysed (see Khan et al., 2006; Lawrence et al., 2006). Evidence for the movement constraint hypothesis would be revealed if limb trajectories to the first target are less variable in the two- compared to one-target condition.

Experiment 1

Methods

Participants. A total of 30 students from the University of Windsor volunteered to participate in the study (male = 12; female = 18; range = 18–25 years). All participants self-declared being right-hand dominant and had normal to corrected-to-normal vision. The study was approved by the Research Ethics Board at the University of Windsor (Approval Number: 35433; Clearance Date: 17 December 2018). All participants provided written informed consent prior to enrolment in the study.

Apparatus. Participants were seated in front of a horizontal tabletop that was 76 cm above the ground. A Toshiba Portege M750-10J touchscreen laptop (28.5 cm long × 21.5 cm wide) was placed on the table in front of the participant. Participants were positioned so that their midline was centred with the middle of the touchscreen. The targets were presented on the touchscreen with the use of LabVIEW software (National Instruments, Austin, TX, USA). Participants performed aiming movements using a hand-held stylus. An infrared emitting diode (IRED) was attached to the tip of the stylus and was tracked using an NDI 3D Investigator (Northern Digital Inc., Waterloo, ON, Canada) and was further analysed with the use of LabVIEW software.

The start position consisted of a cross (1.3 × 1.3 cm) and was located 4 cm from the right edge of the touchscreen. The first target (2 cm in diameter) was located 6 cm to the left of the start position while second target (2 cm in diameter) was located along a horizontal straight line a further 6 cm to the left of the first target (centre to centre; see Figure 1).

Task and procedure. Participants were required to perform one- and two-target aiming movements. At the beginning of each trial, the start position was presented, and participants were required to align the tip of the stylus on its centre. Once the stylus was steadily aligned, the target(s) appeared. Following a variable foreperiod (0, 500, 1,000, 1,500, and
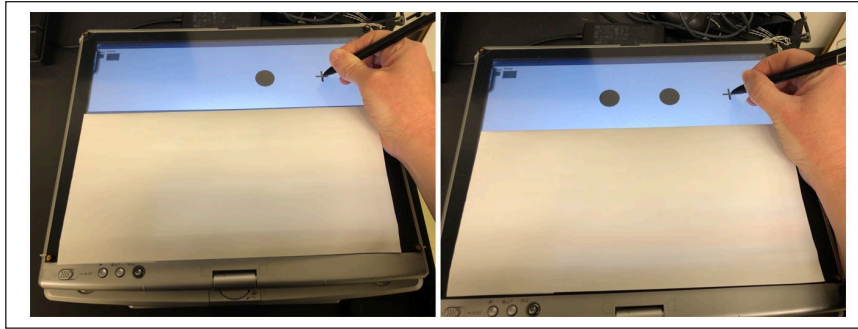
Figure 1. The experimental apparatus. Panel A depicts the one-target condition and Panel B the two-target condition.

2,000 ms), the stimulus was presented which consisted of a tone. In the one-target trials, participants were required to lift the stylus from the start position and touch down at the first target. In the two-target trials, participants were required to move to the first target and then continue their movement to the second target. Hence, in both the one- and two-target conditions, movements were likened to tapping the stylus at the targets. Participants were instructed to move as quickly and accurately as possible. To motivate participants, we employed a point system in which participants had to hit the targets to gain points and the number of points gained increased as RT decreased (i.e., ≤200 ms = 5 points, 201–250 ms = 4 points, 251–300 ms = 3 points, 301–350 ms = 2 points, 351–400 ms = 1 point). Trials were self-paced with an inter-trial interval of approximately 2–3 s.

Participants were first given four familiarisation trials consisting of two one-target and two two-target trials in an alternating sequence. The one- and two-target test trials were administered in two separate blocks. The five foreperiods (0, 500, 1,000, 1,500, and 2,000 ms) were randomised within each block with 20 trials performed for each foreperiod. Hence, participants completed 100 trials in the one-target condition and 100 trials in the two-target condition. The order of blocks was counterbalanced between participants. Participants received a break of approximately 5 min between blocks of trials. Testing took between 25 and 30 min for each participant.

Data reduction. IRED position data were sampled at 500 Hz and filtered using a second-order dual-pass Butterworth 16 Hz low-pass cut-off filter. Velocity information was then calculated from position data to obtain peak resultant velocity for each movement segment. Working backwards from peak velocity, movement start was determined as the point at which vertical velocity fell below 15 mm/s. The end of the first movement was defined at the point following peak velocity whereby vertical velocity fell below 15 mm/s.[1] For two-segment movements, this process was repeated to identify the start and end of the second movement segment.

Dependent measures and analyses. All trials in which RT was less than 100 ms or more than 800 ms or in which the participant missed the target(s) were discarded from the analysis. This accounted for less than 5% of the trials. The dependent measures consisted of RT, MT1, pause time (PT) at the first target, movement time from the first to the second target (MT2), peak velocity during the first movement segment (PKV1), peak velocity during the second movement segment (PKV2), and separate time to and time after peak velocity for both the first and second movement (TPKV1, TPKV2 and TAPKV1, TAPKV2, respectively). Our error measures at both target one and target two consisted of ellipse areas at movement end (EA1, EA2), and variability in ellipsoid volumes during peak velocity (EV1, EV2). EA1 and EA2 were obtained by calculating ellipse areas using within-subject standard deviations of the x and y positions as the radii ($\pi \times SDx \times SDy$). EV1 and EV2 were calculated using the within-subject standard deviations of the positions along the x, y, and z axis at peak velocity ($4/3\pi \times SDx \times SDy \times SDz$; Hansen et al., 2008).

The variables associated with the first movement segment (i.e., RT, MT1, PKV1, TPKV1, TAPKV1, EV1, and EA1) were analysed using separate 2 Target Condition (one-target and two-target) × 5 Foreperiod (0, 500, 1,000, 1,500, and 2,000 ms) fully repeated-measures analyses of variance (ANOVAs). The variables associated with the second movement segment (i.e., PT, MT2, PKV2, TPKV2, TAPKV2, EV2, and EA2) were analysed using separate 5 Foreperiod (0, 500, 1,000, 1,500, and 2,000 ms) one-way repeated measures ANOVAs. The omnibus ANOVAs were assessed for significance using a .05 alpha level. Any significant main effects and interactions were broken down using Bonferroni-corrected post hoc tests.

Results

Means and standard deviations of each dependent measure are reported in Table 1.

Reaction time. There were significant main effects of Target Condition, $F(1, 29) = 26.02$, $p < .001$, $\eta_p^2 = .47$, and Foreperiod, $F(4, 116) = 168.95$, $p < .001$, $\eta_p^2 = .85$. As shown in Figure 2, RTs were longer in the two- compared to one-target condition. Breakdown of the Foreperiod main effect indicated that RT was longer when the foreperiod duration was 0 ms compared to all other

Table 1. Experiment 1 means (standard deviations) of RT (ms), MT1 (ms), TPKV1 (ms), TAPKV1 (ms), PKV1 (ms), EV1 (mm^3), EA1 (mm^2), PT (ms), MT2 (ms), TPKV2 (ms), TAPKV2 (ms), PKV2 (ms), EV2 (mm^3), and EA2 (mm^2).

	One target					Two targets				
	0	500	1,000	1,500	2,000	0	500	1,000	1,500	2,000
RT	346 (36)	290 (33)	285 (32)	282 (33)	281 (31)	366 (42)	308 (34)	302 (43)	299 (37)	296 (35)
MT1	217 (39)	215 (42)	216 (42)	216 (41)	215 (41)	247 (42)	248 (42)	251 (40)	253 (41)	253 (40)
TPKV1	66 (12)	63 (11)	64 (12)	63 (11)	62 (11)	71 (14)	71 (18)	71 (17)	72 (18)	71 (16)
TAPKV1	152 (34)	151 (37)	152 (36)	152 (37)	153 (37)	176 (36)	177 (34)	180 (34)	182 (34)	182 (33)
PKV1	540 (125)	553 (128)	541 (124)	532 (123)	537 (125)	495 (87)	497 (100)	479 (86)	480 (93)	476 (87)
EV1	92 (48)	84 (51)	101 (61)	97 (59)	88 (45)	114 (98)	108 (91)	112 (89)	129 (129)	117 (104)
EA1	19 (12)	19 (11)	17 (6)	20 (12)	19 (9)	15 (8)	13 (5)	14 (7)	15 (10)	13 (6)
PT						48 (28)	46 (26)	48 (25)	50 (27)	52 (30)
MT2						220 (38)	220 (41)	223 (39)	224 (39)	225 (37)
TPKV2						96 (18)	94 (19)	95 (20)	96 (18)	97 (19)
TAPKV2						124 (26)	127 (29)	128 (25)	128 (27)	127 (25)
PKV2						434 (73)	432 (73)	431 (73)	429 (69)	425 (67)
EV2						149 (92)	152 (81)	153 (100)	152 (94)	153 (103)
EA2						21 (9)	19 (11)	21 (9)	20 (9)	19 (8)

RT: reaction time; MT1: movement time to the first target; TPKV1: time to peak velocity to the first target; TAPKV1: time after peak velocity to the first target; PKV1: peak velocity to the first target; EV1: variability ellipsoid volume at peak velocity to the first target; EA1: variability ellipse areas at the first target; PT: pause time; MT2: movement time to the second target; TPKV2: time to peak velocity to the second target; TAPKV2: time after peak velocity to the second target; PKV2: peak velocity to the second target; EV2: variability ellipsoid volume at peak velocity to the second target; EA2: variability ellipse areas at the second target.
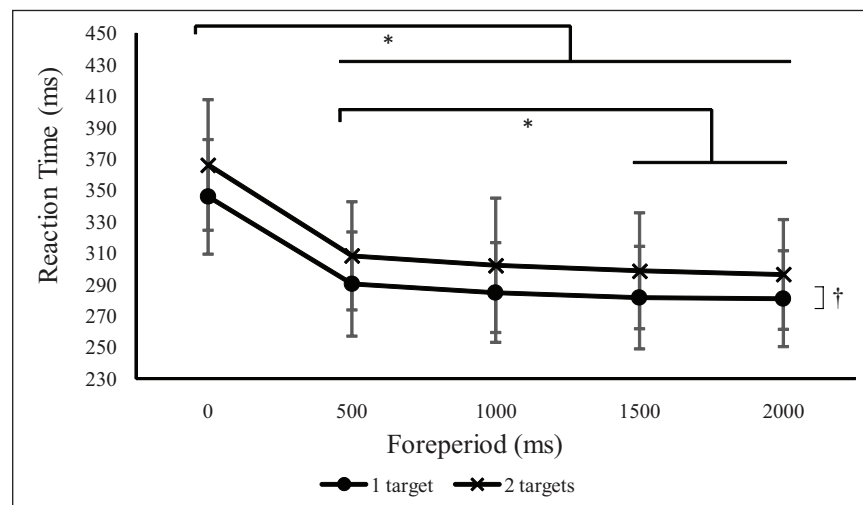
Figure 2. Mean reaction time as a function of foreperiod for both the one- and two-target conditions. Error bars represent standard deviation.
*The post hoc significant differences in the foreperiod main effect. Reaction time was significantly longer in the 0 ms foreperiod compared to all other foreperiod durations, and reaction time was longer in the 500 ms foreperiod duration as compared to 1,500 and 2,000 ms.
†The main effect of target condition.

foreperiod durations. Also, RT in the 500 ms condition was longer compared to both the 1,500 and 2,000 ms conditions.

MTs and PT. A significant main effect of Target Condition, $F(1, 29) = 39.73$, $p < .001$, $\eta_p^2 = .58$, revealed that MT1 was longer in the two- compared to one-target condition (see Figure 3). There was also a significant Target

Condition $\times$ Foreperiod interaction, $F(4, 116) = 2.82$, $p < .05$, $\eta_p^2 = .09$. Breakdown of the interaction indicated that there was no difference between foreperiods in the one-target condition. However, in the two-target condition, MT1 was longer in both the 1,500 and 2,000 ms foreperiod conditions compared to both the 0 and 500 ms conditions.

A main effect of Foreperiod revealed that PTs at the first target were shorter in the 500 ms condition compared
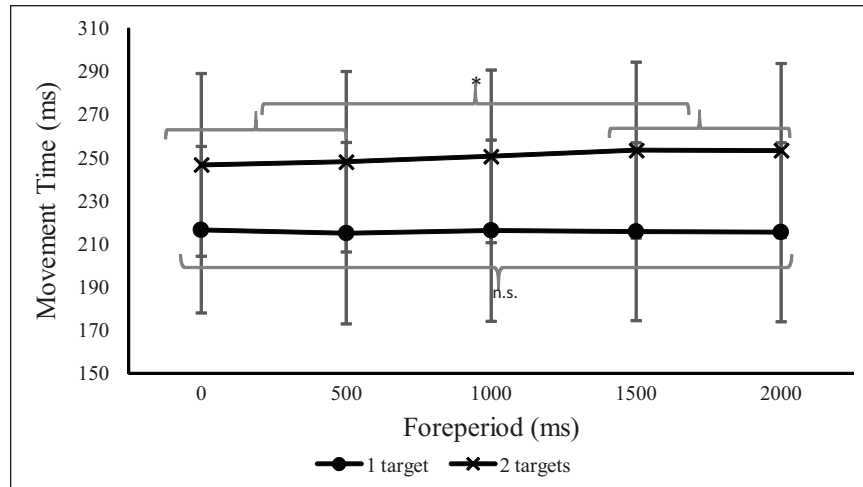
Figure 3. Mean movement time to the first target as a function of foreperiod for both the one- and two-target conditions. Error bars represent standard deviation.
*The post hoc significant difference within the Target Condition × Foreperiod interaction; movement time was significantly longer in both the 1,500 and 2,000 ms foreperiods compared to both the 0 and 500 ms foreperiods in the two-target condition.
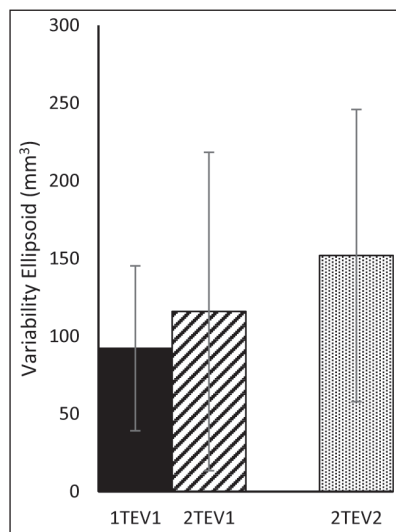†The main effect of target condition.

Figure 4. Mean variability ellipsoid volume at peak velocity to the first target for both the one- (1TEV1) and two-target conditions (2TEV1), and at peak velocity to the second target for the two-target condition (2TEV2). Error bars represent standard deviation.

to all other foreperiods, $F(4, 116) = 3.73, p < .01, \eta_p^2 = .11$. There was also a main effect of Foreperiod on MT2, $F(4, 116) = 2.56, p < .05, \eta_p^2 = .08$. MTs to the second target were shortest for the both 0 and 500 ms foreperiod conditions compared to the 2,000 ms condition.

Time to peak velocity, time after peak velocity, and peak velocity. Significant main effects of Target Condition revealed that TPKV1, $F(1, 29) = 12.51, p < .001, \eta_p^2 = .30$, and TAPKV1, $F(1, 29) = 38.46, p < .001, \eta_p^2 = .57$, were longer

in the two- compared to one-target condition. The analysis of TAPKV1 also revealed that the main effect of Foreperiod approached conventional levels of significance, $F(4, 116) = 2.43, p = .05, \eta_p^2 = .08$. Specifically, TAPKV1 was shortest when the foreperiod was 0 ms and longest when the foreperiod was 2,000 ms.

The analysis of PKV1 revealed main effects for Target Condition, $F(1, 29) = 19.02, p = .001, \eta_p^2 = .39$, and Foreperiod, $F(4, 116) = 8.31, p = .001, \eta_p^2 = .22$. PKV1 was greater in the one- compared to two-target condition. Also, PKV1 was greatest when the foreperiod was 500 ms and least when the foreperiod was 2,000 ms.

The analysis of TPKV2 and TAPKV2 revealed no significant effects of Foreperiod ($p > .05$). However, a significant main effect of Foreperiod, $F(4, 116) = 2.9, p < .05, \eta_p^2 = .09$, was revealed for PKV2. Specifically, PKV2 was significantly greater at 0 ms compared to the 2,000 ms condition.

Variability. Analysis of variability ellipsoid volume at peak velocity of the first movement (EV1) did not reveal any significant main effects or interactions, $F(1, 29) = 3.33, p = .08, \eta_p^2 = .10$ (see Figure 4). However, analysis of variability ellipse areas at the first target (EA1) revealed a main effect of Target Condition with movement endpoints at the first target being more variable in the one- compared to two-target condition, $F(1, 29) = 19.61, p < .001, \eta_p^2 = .40$ (see Figure 5). The analysis of EV2 and EA2 did not reveal any significant effects of Foreperiod ($p > .05$).

To compare variability between the two movement segments in the two-target condition, we performed separate 2 Movement Segment (first target and second target) × 5 Foreperiod (0, 500, 1,000, 1,500, and 2,000 ms) repeated
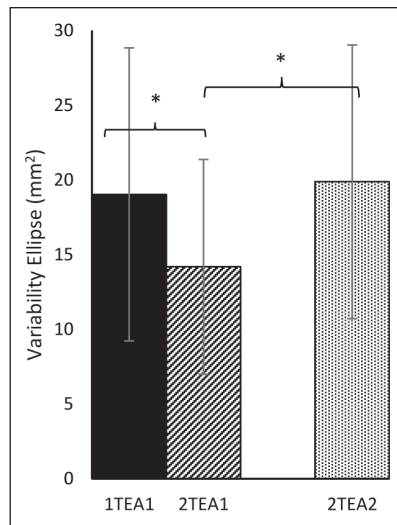
Figure 5. Mean variability ellipse area at the first target for both the one- (1TEA1) and two-target conditions (2TEA1), and at the second target for the two-target condition (2TEA2). Error bars represent standard deviation.
*Significant differences in variability ellipse area whereby the variability at peak velocity was significantly smaller for the first segment of the two-target condition compared to one-target condition, and was significantly larger for the second compared to first segment in the two-target condition.

measures ANOVAs on both the variability ellipsoids at peak velocity and the variability ellipses at the targets. While the analysis of variability ellipsoids at peak velocity only approached conventional levels of significance (Figure 4), $F(1, 29) = 3.57$, $p = .07$, $\eta_p^2 = .11$, variability ellipses at the targets were significantly greater at the second compared to first target, $F(1, 29) = 37.34$, $p < .001$, $\eta_p^2 = .56$ (Figure 5).

Discussion

As expected, RT decreased as foreperiod duration increased (Drazin, 1961). This was the case for both one- and two-target responses. Since the one- and two-target trials were administered in blocks, participants had advance knowledge of the number of targets. Consistent with past research where the number of targets was known in advance (Bested et al., 2018; Khan et al., 2006, 2008a), RT was longer in the two- compared to one-target responses. As might be expected when the number of targets is known in advance of the RT interval, the difference in RT between one- and two-target responses was not influenced by foreperiod duration.

However, while the RT difference between one- and two-target responses was not influenced by foreperiod duration, the OTA:MT did increase in magnitude as a function of the foreperiod duration. Indeed, MTs to the first target increased as the foreperiod lengthened in the two- but not in the one-target condition. This finding

supports the movement integration hypothesis (Adam et al., 2000) by showing that when there is more time available to load segments into a buffer prior to the RT interval, there is greater interference during movement execution due to the implementation of the second segment during execution of the first. Interestingly, this slowing of MTs at longer foreperiods persisted throughout the response as PTs and MTs to the second target were also generally greater for longer foreperiods.

While the current results are consistent with the underlying assumptions of the movement integration hypothesis, there is also some support for the movement constraint hypothesis (Fischman & Reeve, 1992). According to the movement constraint hypothesis, the dispersion of movement endpoints at the first target is reduced to meet the accuracy demands of the second target. Consistent with the movement constraint hypothesis, the present experiment found that variability at the end of the first movement was significantly less in the two- compared to one-target condition. In addition, both the time to peak velocity and the time after peak velocity were longer in the two- compared to one-target condition, indicating that both planning and online correction processes were responsible for constraining movement endpoints at the first target.

Also consistent with the underlying assumption of the movement constraint hypothesis, limb trajectory variability increased from the first to second segment. Khan et al. (2011) reported a similar result when participants were required to move to the first target in a criterion MT (i.e., 450 ms) but without vision of the limb. In the current study, we find a similar result when participants were instructed to move as quickly as possible (mean MT = 250 ms) and when visual feedback was available. Despite the increase in variability from the first to the second segment, participants reduced limb trajectory variability from peak velocity to the second target to achieve the required levels of accuracy.

Experiment 2

Introduction

In Experiment 1, one- and two-target movements were administered in separate blocks of trials and hence participants had advance knowledge of the number of targets. Consistent with past research, both the OTA:RT and the OTA:MT emerged. However, past research has shown that RT and MT to the first target did not differ between one- and two-target movements when advance information about the number of targets was not available (i.e., one- and two-target trials are presented randomly). In Experiment 2, we investigated whether the OTA:RT and OTA:MT would emerge under randomised target conditions when longer foreperiods are afforded to participants, thus providing more time to prepare multiple target sequences.

Table 2. Experiment 2 means (standard deviations) of RT (ms), MT1 (ms), TPKV1 (ms), TAPKV1 (ms), PKV1 (ms), EV1 (mm^3), EA1 (mm^2), PT (ms), MT2 (ms), TPKV2 (ms), TAPKV2 (ms), PKV2 (ms), EV2 (mm^3), and EA2 (mm^2).

	One target					Two targets				
	0	500	1,000	1,500	2,000	0	500	1,000	1,500	2,000
RT	394 (49)	293 (29)	283 (26)	280 (28)	283 (31)	391 (46)	304 (29)	295 (27)	293 (27)	291 (31)
MT1	249 (51)	250 (54)	254 (58)	249 (52)	249 (52)	253 (49)	256 (48)	260 (51)	261 (50)	261 (53)
TPKV1	72 (17)	69 (18)	68 (16)	68 (17)	68 (17)	70 (16)	69 (16)	69 (16)	69 (15)	68 (15)
TAPK1	178 (40)	181 (43)	186 (48)	181 (40)	181 (41)	183 (40)	187 (40)	191 (44)	191 (42)	193 (45)
PKV1	481 (85)	478 (84)	467 (83)	466 (80)	464 (76)	477 (76)	474 (79)	467 (78)	459 (69)	458 (72)
EV1	87 (56)	87 (70)	87 (70)	96 (89)	103 (115)	85 (59)	74 (62)	91 (100)	92 (63)	89 (63)
EA1	12 (4)	12 (5)	12 (5)	13 (8)	15 (7)	11 (4)	12 (4)	11 (5)	12 (4)	13 (5)
PT						71 (28)	71 (26)	72 (26)	77 (26)	77 (25)
MT2						239 (40)	238 (43)	240 (45)	240 (43)	242 (45)
TPKV2						99 (18)	96 (19)	97 (19)	100 (17)	99 (19)
TAPKV2						140 (32)	141 (34)	143 (33)	140 (33)	143 (35)
PKV2						407 (66)	412 (68)	404 (67)	405 (60)	402 (63)
EV2						133 (83)	186 (331)	136 (105)	123 (74)	119 (69)
EA2						17 (7)	19 (8)	16 (7)	15 (5)	16 (8)

RT: reaction time; MT1: movement time to the first target; TPKV1: time to peak velocity to the first target; TAPKV1: time after peak velocity to the first target; PKV1: peak velocity to the first target; EV1: variability ellipsoid volume at peak velocity to the first target; EA1: variability ellipse areas at the first target; PT: pause time; MT2: movement time to the second target; TPKV2: time to peak velocity to the second target; TAPKV2: time after peak velocity to the second target; PKV2: peak velocity to the second target; EV2: variability ellipsoid volume at peak velocity to the second target; EA2: variability ellipse areas at the second target.

Methods

Participants. A total of 30 students from the University of Windsor volunteered to participate in the study (male = 12; female = 18; range = 18–25 years). None of the participants in Experiment 2 participated in Experiment 1. All participants self-declared as being right-hand dominant and had normal to corrected-to-normal vision. The study was approved by the Research Ethics Board at the University of Windsor (Approval Number: 35433; Clearance Date: 17 December 2018). All participants provided written informed consent prior to enrolment in the study.

Apparatus. The experimental set-up was the same as in Experiment 1.

Task and procedure. The task and procedure were similar to Experiment 1 except that one- and two-target trials were randomised from trial to trial.

Results

Means and standard deviations of each dependent measure are reported in Table 2.

Reaction time. The analysis of RT revealed significant main effects of Target Condition, $F(1, 29) = 21.40$, $p < .001$, $\eta_p^2 = .42$, and Foreperiod, $F(4, 116) = 168.95$, $p < .001$, $\eta_p^2 = .85$, as well as a significant Target Condition × Foreperiod interaction, $F(4, 116) = 5.52$, $p < .05$, $\eta_p^2 = .16$. Breakdown of the interaction revealed that there

was no difference in RT between target conditions when the foreperiod was 0 ms. However, RTs were significantly greater in the two- compared to one-target condition at all other foreperiods (see Figure 6).

MTs and PT. Similar to RT, the analysis of MT1 revealed significant main effects of Target Condition, $F(1, 29) = 18.46$, $p < .001$, $\eta_p^2 = .39$, and Foreperiod, $F(4, 116) = 3.07$, $p < .05$, $\eta_p^2 = .09$, as well as a significant Target Condition × Foreperiod interaction, $F(4, 116) = 3.29$, $p < .05$, $\eta_p^2 = .10$. Breakdown of the interaction revealed that MT1 did not differ between target conditions when the foreperiod was 0 ms. However, for all other foreperiods, MT1 was significantly greater in the two- compared to one-target condition (see Figure 7). Furthermore, similar to Experiment 1, MT1 significantly increased as foreperiod increased in the two- but not in the one-target condition. Specifically, MT1 in the two-target condition increased from the 0 to 1,000 ms foreperiods, while MTs at the 1,000, 1,500, and 2,000 ms foreperiods were greater than at the 0 and 500 ms foreperiods.

A main effect of foreperiod duration revealed that PTs at the first target were shorter in the 0, 500, and 1,000 ms conditions compared to 1,500 and 2,000 conditions, $F(4, 116) = 7.94$, $p < .01$, $\eta_p^2 = .22$. The main effect of Foreperiod on MT2 was not significant, $F(4, 116) = 1.50$, $p > .05$, $\eta_p^2 = .05$.

Time to peak velocity, time after peak velocity, and peak velocity. The analysis of TPKV1 revealed only a significant main effect of Foreperiod, $F(4, 116) = 4.18$, $p < .05$, $\eta_p^2 = .13$, with TPKV1 being significantly longer at 0 ms
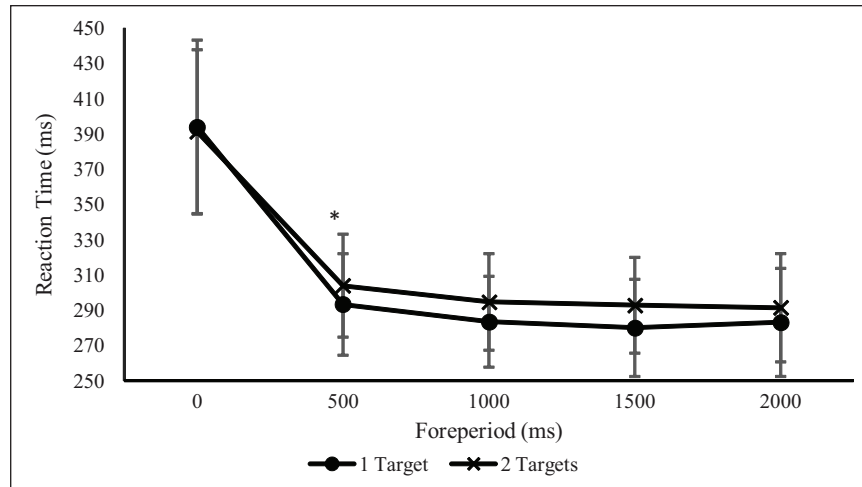
Figure 6. Mean reaction time as a function of foreperiod for both the one- and two-target conditions. Error bars represent standard deviation.
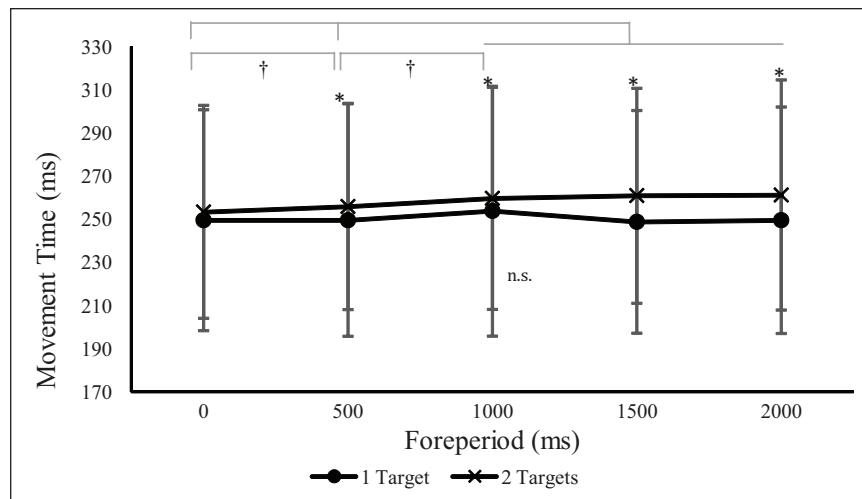*Significant target condition difference in reaction time at each foreperiod.

Figure 7. Mean movement time to the first target as a function of foreperiod for both the one- and two-target conditions. Error bars represent standard deviation.
*Significant target condition difference in movement time at each foreperiod.
†Significant movement time differences between foreperiod conditions in the two-target condition. Note the no significant differences between foreperiods for the one-target condition (•).

compared to 1,000 ms foreperiod. The analysis of TAPKV1 revealed significant main effects of Target Condition, $F(1, 29) = 18.02$, $p < .001$, $\eta_p^2 = .38$, and Foreperiod, $F(4, 116) = 6.39$, $p < .05$, $\eta_p^2 = .18$, as well as a significant interaction between Target Condition × Foreperiod, $F(4, 116) = 3.15$, $p < .05$, $\eta_p^2 = .10$. Breakdown of the interaction revealed that TAPKV1 increased as foreperiod increased in the two- but not in the one-target condition.

The analysis of PKV1 revealed only a main effect for Foreperiod, $F(4, 116) = 12.47$, $p < .001$, $\eta_p^2 = .30$, with PKV1 decreasing as foreperiod increases.

The analysis of TPKV2, TAPKV2, and PKV2 revealed no significant effects of Foreperiod ($p > .05$).

Variability. The analysis of variability ellipsoid volume at peak velocity of the first movement segment (EV1) did not reveal any significant effects ($p > .05$). The analysis of variability ellipses at the first target (EA1) revealed only a significant main effect of Foreperiod, $F(4, 116) = 2.91$, $p < .05$, $\eta_p^2 = .09$, with EA1 being greater for the 2,000 ms compared to all other foreperiods. Similarly, while the analysis of EV2 did not reveal any significant effects ($p > .05$), the analysis of EA2 did reveal a significant effect of Foreperiod, $F(4, 116) = 3.93$, $p < .05$, $\eta_p^2 = .12$, with EA2 being greater when the foreperiod was 500 ms compared to 1,500 ms.

In addition, to compare variability between the two movement segments in the two-target condition, we
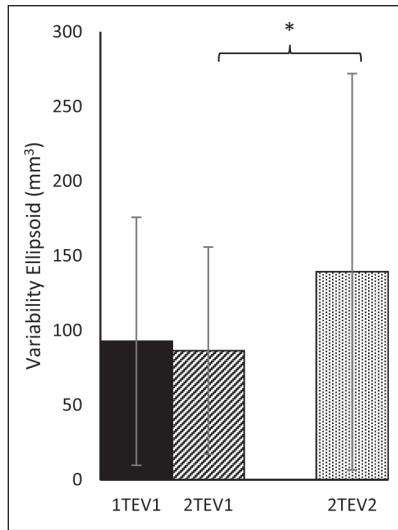
Figure 8. Mean variability ellipsoid volume at peak velocity to the first target for both the one- (1TEV1) and two-target conditions (2TEV1), and at peak velocity to the second target for the two-target condition (2TEV2). Error bars represent standard deviation.
*Significant movement segment difference; variability ellipsoid volume at peak velocity was significantly greater for the second compared to first segment.

Figure 9. Mean variability ellipse area at the first target for both the one- (1TEA1) and two-target conditions (2TEA1), and at the second target for the two-target condition (2TEA2). Error bars represent standard deviation.
*Significant movement segment difference; variability ellipse area was significantly greater for the second compared to first segment.

performed separate 2 Movement Segment (first target and second target) × 5 Foreperiod (0, 500, 1,000, 1,500, and 2,000 ms) repeated measures ANOVAs on variability ellipsoids at peak velocity and variability ellipses at the targets. As shown in Figure 8, the analysis of variability ellipsoids indicated that variability at peak velocity was significantly greater for the second compared to first segment, $F(1, 29) = 6.85$, $p < .05$, $\eta_p^2 = .19$. A main effect of Movement Segment indicated that variability ellipses at the end of the movement segments were significantly greater at the second compared to first target, $F(1, 29) = 33.99$, $p < .001$, $\eta_p^2 = .54$ (see Figure 9). Also, a significant interaction between Movement Segment and Foreperiod, $F(4, 116) = 4.11$, $p < .05$, $\eta_p^2 = .12$, indicated that while variability at the first target was not affected by foreperiod, variability at the second target significantly decreased as foreperiod duration increased.

Discussion

In previous research, RT was not influenced by the number of response segments when the number of segments was not known in advance of the stimulus (Bested et al., 2018; Khan et al., 2006, 2008a; Klapp, 1995, 2003). Consistent with these findings, the results of the current experiment revealed that RT did not differ between target conditions when the foreperiod was 0 ms. However, similar to the results of Experiment 1, RT was significantly longer in the two- compared one-target condition at longer foreperiods.
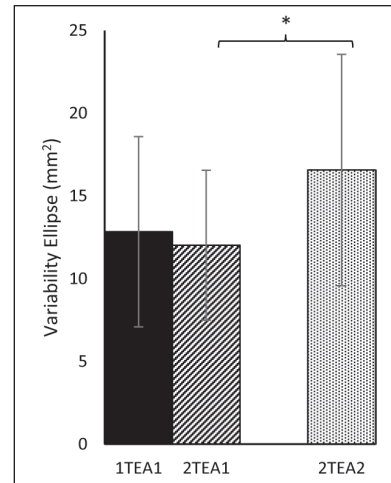
Collectively, the results of both experiments revealed that RT increased as a function of the number of targets when participants were provided with target information ahead of the RT interval, regardless of whether target order was blocked or randomised.

Similar to RT, past research has shown that MTs to the first target did not differ between one- and two-target conditions when the number of targets was not known in advance (Bested et al., 2018). The present results were consistent with this finding at short foreperiods. However, at longer foreperiods, the OTA:MT did emerge between the one- and two-target conditions. It should be noted that in the random condition employed by Bested et al., the trial sequence consisted of a tone as the warning signal, followed by the presentation of the target(s) which served as the imperative stimulus. In the present study, the target(s) were first represented and then a stimulus tone was presented after a variable foreperiod. Hence, similar to the OTA:RT, it appears that when the number of targets is randomised from trial to trial, a period of time between the presentation of the targets and the stimulus is needed for the OTA:MT to emerge. These results add further support to the movement integration hypothesis. Consistent with Experiment 1, MTs to the first target in two-target responses significantly increased as the foreperiod lengthened. Presumably, this reflects the time required to load segments into a buffer that then enables the second segment to be implemented during execution of the first.

The parsing of MTs into time prior to peak velocity and time after peak velocity revealed that there was no difference in the time to peak velocity between one- and two-target conditions. However, the time after peak velocity

showed a similar pattern of results to overall MT. While there was no difference in time after peak velocity between one- and two-target conditions at short foreperiods, there was a significant difference between target conditions at longer foreperiods. Hence, the emergence of the one-target advantage at longer foreperiods is due to the time spent after peak velocity.

Under the blocked condition in Experiment 1, movement endpoints at the first target were more variable in the one- compared to two-target condition. Consistent with the results of Bested et al. (2018), this finding did not materialise in Experiment 2 under the randomised trial sequence. Hence, although the time after peak velocity was significantly longer in the two- compared to one-target condition at longer foreperiods, there was not a corresponding significant difference in spatial variability between target conditions. Hence, there was no evidence for the movement constraint hypothesis when target conditions were randomised, regardless of the duration of the foreperiod.

General discussion

While the relationship between the number of segments and RT has been extensively investigated (e.g., Henry & Rogers, 1960; Klapp, 1995, 2003; Klapp & Maslovat, 2020), other researchers have focused on the time it takes to execute multiple segment movements (Adam et al., 2000). The requirement to aim to a second target, as well as the properties of the second target (e.g., target size), has been shown to influence movement to the first target (Rand et al., 1997; Rand & Stelmach, 2000; Sidaway et al., 1995). Hence, individual segments are not planned and controlled independently. Khan and colleagues (Bested et al., 2018; Khan et al., 2006, 2008a) have shown that not only does an interdependency exist between movement segments, but there is a systematic relation between the processes occurring during RT and during movement execution. In the current study, we go one step further by considering how the preparation and execution of sequential aiming movements are influenced by the time available prior to the RT interval (i.e., foreperiod duration). One might expect that longer foreperiods would provide the time necessary to programme responses in advance of the stimulus and hence RT and MT would not depend on the complexity of the response (see Ariani & Diedrichsen, 2019; Klapp & Maslovat, 2020). However, the present results demonstrate the opposite for sequential aiming movements as RT and MT differences between one- and two-target movements increased as foreperiod length increased.

Consistent with past research (Bested et al., 2018; Khan et al., 2006, 2008a; Klapp, 1995, 2003), RT was directly related to the number of segments when the number of segments was known in advance (i.e., blocked trials). Also, RT was not influenced by the number of segments when the number of targets was randomised. However,

this was the case only when the targets were presented simultaneously with the warning tone (i.e., 0 ms foreperiod). At longer foreperiods, RT was greater in the two- compared to one-target condition. Collectively, these RT results are consistent with the theoretical framework of Klapp (1995, 2003). Klapp proposed that when the number of elements is known in advance, response information is stored in a buffer prior to the RT interval. According to Maslovat et al. (2014, 2016), while the ordering of response segments can occur during the foreperiod, the preparation of the timing of segment initiation occurs during simple RT. The present results showed that for RT to be influenced by the number of segments, sufficient time was needed from when participants gain knowledge of the number of targets and the presentation of the stimulus. This was the case regardless of whether the number of targets is presented in a blocked or randomised fashion.

The difference in RT between one- and two-target conditions when participants have advance information about the number of targets indicates that participants prepared responses based on available target information. When participants were not given sufficient time to process target information prior to the stimulus (i.e., 0 ms foreperiod under the random sequence), it is possible they prepared intermediate movements that are refined as target information is processed (see Alhussein & Smith, 2021; Ghez et al., 1997). Alternatively, participants may have adopted a strategy whereby they prepared for either a one- or two-target response in advance and then modified their response if the number of targets was different to what was prepared. When foreperiods were 0 ms, MT1 in the two-target condition under the blocked trial sequence (i.e., 247 ms) was similar to the one- and two-target conditions when the number of targets was randomised (249 and 253 ms, respectively). Hence, participants may have prepared for the more complex two-target response (see Elliott et al., 2017). However, it should be noted that Khan et al. (2008b) have shown that participants had difficulty adding or inhibiting a second segment when the task requirements were changed at movement onset. Therefore, preparing for the inappropriate number of targets in advance may be costly in terms of time and errors due to the high level of integration between movement segments.

While Klapp (2003) has referred to the motor representation that is loaded into a working memory buffer as an "abstract time frame," others have referred to a "response primitive" that provides temporal excitation information to neural networks (Ghez et al., 1997). According to Wong, Haith, and Krakauer (2015), full response preparation involves the translation of an abstract representation to the specific end-effector motor commands needed to achieve the task goal. While the boundary between response programming and initiation is not always clearly defined, for the purposes of the current discussion, response initiation (or implementation) will be referred to as the retrieval of

motor-related information from working memory and the translation to the relevant neuromotor centres (see Adam et al., 2000). Haith et al. (2016) have provided evidence that the timing of response initiation is independent of the timing of response preparation. The results of the current study revealed that RT was greater in the two- compared to one-target condition when participants had advance information about the number of targets. Assuming that certain features of the response are planned prior to the RT interval, these results suggest that the lengthening of RT in the two-target condition was due to processes associated with response initiation. However, Klapp and Maslovat (2020) have proposed that programming the timing of response segments must occur during RT immediately before response initiation. This was based on evidence that simple RT increased as a function of the number of keypresses and the timing complexity of the sequence regardless of the duration and predictability of the foreperiod (see Maslovat et al., 2016, 2019).

Accordingly, Maslovat and Klapp (2022) have distinguished between the processes during the foreperiod and RT intervals. They suggest that once a response is precued, selection of an abstract representation of the response that includes a timing structure goal is prepared in advance of the RT interval. However, the compilation of the timing code, which is a component of response initiation (Klapp & Maslovat, 2020), cannot be completed until the RT interval. Maslovat and Klapp suggest that while cortical areas involved in the selection of an abstract representation of the movement can support working memory, subcortical structures including the cerebellum that are responsible for response timing are not able to support the retention of neural coding associated with response timing in working memory. Consistent with this viewpoint, the results of the present study revealed that RT increased as the number of targets increased even when the number of targets was known well in advance of the stimulus.

The movement integration hypothesis (Adam et al., 2000) has certain parallels with these theoretical explanations. According to the movement integration hypothesis, movement segments are prepared and loaded into a buffer prior to response initiation. Adam et al. (2000) proposed that to ensure a smooth transition between movement segments, the second segment is implemented during execution of the first segment. This overlap of processes during the execution of the first segment causes interference and hence the lengthening of MT. If implementing the second segment during execution of the first is contingent on the ability to load segments in a buffer prior to response initiation, advance knowledge of the number of segments would be a requirement for the OTA:MT to emerge. Consistent with this assumption, Bested et al. (2018) have shown that the OTA:MT was present when one- and two-target trials were blocked and alternated but not when trials were randomised. In the present experiment, we tested whether the time available to prepare responses (i.e., foreperiod) influences the magnitude of the OTA:MT. Assuming that loading movement segments into a buffer prior to response initiation takes time, it was expected that the OTA:MT would emerge or be greater at longer foreperiods.

The results of both experiments support the underlying assumptions of the movement integration hypothesis (Adam et al., 2000). When target conditions were blocked, the OTA:MT emerged regardless of foreperiod duration, but the magnitude of the OTA increased as foreperiod duration lengthened. When target conditions were randomised, the OTA was not present at shorter foreperiods but did emerge at longer foreperiods. Hence, consistent with the movement integration hypothesis, it appears that a sufficient amount of time is needed from target presentation to stimulus onset to load segments into a buffer. Taken together with the theoretical framework of Klapp (1995, 2003) and others (Klapp et al., 2019; Klapp & Maslovat, 2020; Maslovat et al., 2019; Maslovat & Klapp, 2022), it appears that when the foreperiod is long enough to enable an abstract representation of the movement to be loaded in short-term memory, RT increases as the timing of response segments is compiled. This determines the initiation of movement to the first target while the second is held back and implemented during execution of the first. The implementation of the second segment during the first causes interference and hence a significant lengthening of MT1.

The present results also add support to the movement constraint hypothesis. Variability at the first target was significantly lower in the two- compared to one-target condition but only when the number of targets was blocked. Bested et al. (2018) demonstrated that the OTA:MT emerged when target conditions were blocked and alternated but not when they were randomised. However, evidence for the movement constraint hypothesis was only revealed in the blocked target sequence. The present study demonstrated that although the OTA:MT emerged at longer foreperiods in the randomised target sequence, there was no significant difference in variability at the first target between the one- and two-target conditions, regardless of foreperiod. Collectively, these results demonstrate evidence for both the movement integration and constraint hypotheses under the blocked trial sequence. However, only the movement integration hypothesis holds when the number of targets is randomised providing foreperiods are long enough to allow segments to be loaded into a buffer before movement execution.

When the number of targets was randomised, there was no difference in peak velocity and the time to peak velocity between the one- and two-target conditions. Hence, the early phases of the limb trajectory that are said to be indicative of the programmed phase of movements and impulse control through comparisons of expected efference and sensory consequences (Elliott et al., 2017) did not differ between target conditions. However, the time spent after

peak velocity was significantly longer in the two- compared to one-target condition at longer foreperiods. While the time after peak velocity is typically associated with feedback-based error corrections, there was no difference in variability at movement endpoints at the first target between the one- and two-target conditions. Similar findings were reported by Bested et al. (2018) when one- and two-target movements were alternated from trial to trial. Therefore, the greater time spent after peak velocity in the two- compared to one-target condition does not appear to reflect processes associated with the movement constraint hypothesis. Rather, it seems that the presence of the OTA:MT under the randomised condition is due to processes underlying the movement integration hypothesis whereby the implementation of the second element caused a lengthening of time after peak velocity.

It is interesting to note that studies have shown that participants can plan multiple segments of future actions both before and during movement execution. Using a forced-RT paradigm, Ariani and Diedrichsen (2019) demonstrated that response execution times decreased as preparation time increased for up to three to four finger keypresses. Also, for both finger keypress sequences (Ariani et al., 2021) and tracking tasks (Bashford et al., 2022), the ability to process larger windows of advance information increases with practice. These findings would suggest that when advance information was available about the number of targets in the present experiments, participants may have been able to prepare an entire two-target sequence prior to response execution and hence the reliance on online processes would be minimal. However, the present results, along with previous evidence, appear to suggest that this may not apply to sequential aiming movements. For example, Khan et al. (2006) previously hypothesised that when the response could be pre-planned (simple RT), the use of online planning processes would be decreased. However, MTs to the first target were in fact longer in the simple compared to choice RT condition, and this difference was greater in the two- compared to one-target condition. Furthermore, the presence of a dual-task probe caused a significant increase in movement errors in the simple but not in the choice RT condition. Hence, it appeared that online processes were more prevalent when the number of targets was known in advance. To add to these findings, the current study revealed that MTs to the first target increased as foreperiod lengthened in both experiments. Hence, it appears that for sequential aiming movements, the reliance on processes during movement execution is greater when participants have an opportunity to prepare responses prior to response initiation.

Consistent with this interpretation, Vindras and Viviani (2005) have proposed that while preparation of both target segments may occur before movement onset, fine tuning of the movement to the second target is required during movement execution of both segments due to uncertainty and variability associated with the execution of the first segment. This fine tuning may consist of adjusting the parameters of the second segment before its onset as well as corrections during its execution. This would account for the lengthening of MTs and PTs throughout the movement sequence. Khan et al. (2006) have proposed that when participants know the number of targets in advance, two-target movements are programmed with lower velocities to facilitate the implementation of the second segment by visually regulating the execution of the first segment. Consistent with this, the present study revealed that when target conditions were blocked, peak velocity was significantly lower in the two- compared to one-target condition. Also, both time to peak velocity and time after peak velocity were significantly longer in the two- compared to one-target condition. According to Khan et al. (2011), visual regulation plays a dual role in two-target sequential aiming movements. First, along the lines of the movement integration hypothesis, the execution of the first segment is visually monitored to optimally time the implementation of the second segment to facilitate a smooth transition between segments (also see Ketelaars et al., 1999). Visual information from the first segment also serves to adjust the parameters of the second segment. For example, if the first segment is predicted to undershoot the centre of the first target, the amplitude of the second segment can be increased accordingly, and vice versa. These visual regulation processes underlying the implementation of the second segment are attention demanding and hence are subject to dual-task interference resulting in the lengthening of MTs (Ketelaars et al., 1999; Khan et al., 2006). Second, along the lines of the movement constraint hypothesis, visual regulation serves to adjust limb trajectories to minimise variability at the first target. Reducing variability at the first target not only ensures that accuracy demands at the second target are met but also enhances the transition between segments by reducing uncertainty of movement endpoint locations at the first target.

In summary, the presence of both the OTA:RT and OTA:MT is contingent on participants having advance information about the number of targets. This is the case regardless of the order of one- and two-target movements, provided there is sufficient time to process target information prior to the stimulus (i.e., at longer foreperiods). While evidence for the movement integration hypothesis emerged regardless of trial sequence, processes underlying the movement constraint hypothesis appear to operate only when the number of targets is blocked. Hence, when two-target movements are repeated from trial to trial, MTs to the first target are lengthened due to the implementation of the second segment and in reducing variability in limb trajectories during execution of the first segment. When the number of targets changes within a trial sequence, limb trajectory variability is not constrained in two-target movements beyond that which occurs in one-target movements.

Instead, the lengthening of MTs in two-target sequences, provided participants have sufficient time to process target information in advance of the stimulus, is due to processes after peak velocity in regulating the implementation of the second segment.

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Note

1. Vertical velocity was used to determine the start and end of movements since there may have been slight sliding of the tip of the stylus on the tablet.

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