

Pause time alters the preparation of two-component movements

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Abstract Targeted reciprocal aiming movements are pervasive in everyday life, but it is unclear how the timing parameters between task elements affect the preparation of these movements. This study used a loud (124 dB) startling acoustic stimulus (SAS) to probe how changes in the pause time between the outward and return components of a reciprocal aiming task affected the preparatory state of the motor system. Participants performed a visually guided wrist extension–flexion task to a target located at 20° from the start position and were instructed to pause the movement within the wrist extension target zone for either 50, 200, or 500 ms. A SAS was presented during 25 % of trials before either the onset of the wrist extension (out) or flexion (return) components of the task to determine how motor preparation was affected by task requirements. Results showed that the presentation of a SAS prior to the initial outward movement led to significantly earlier onsets of both the outward and return components ($p < .05$), indicating that the pause time in the planned action was

pre-planned. For the longer (200, 500 ms) pause-time conditions, a SAS delivered prior to returning from the target region triggered the return portion of the movement early. These findings suggest that the shortest pause-time movement (50 ms) was preplanned as a single action, whereas for reciprocal movements with longer pause times at least the initial part of the movement and the timing of the pause were preplanned and integrated, while the return portion was more independent.

Keywords Movement planning · Aiming · Startle · Complexity · Pause time

Introduction

Movements involving back and forth components that are reciprocal in nature are often used in everyday life, and frequently involve a targeting or accuracy requirement (e.g., playing video games and operating machinery). It has been suggested that reciprocal movements of this type may be more “complex” than single-direction ballistic movements in terms of the processing requirements because increases in reaction time (RT) are observed along with increases in response complexity (Henry and Rogers 1960). For example, when participants performed tasks with a different number of movement components within a simple RT paradigm, it was shown that RT increased with increasing movement parts (see also Fischman 1984; Kasai and Seki 1992; Ketelaars et al. 1997; van Donkelaar and Franks 1991). Henry and Rogers (1960) suggested that the response programming processes were lengthened for the more complex movements resulting in the longer RTs. Nevertheless, it has been shown that while some movements of varying complexity can be pre-programmed (i.e., response programming

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is completed in advance of the “go” signal), the ability to pre-program a response may depend on how “complexity” is defined (Klapp 1995, 2003). Specifically, while it may be possible to program a more complex single-component action in advance, multiple component actions may be more constrained (Klapp 2003).

One way in which humans cope with multiple component movements is to simply program the first component and then program subsequent components “online” while the first movement is underway. This has been evidenced by a “one-target advantage” whereby movement time (MT) to a single target is shorter than the MT to the first of 2 consecutive targets (Adam et al. 2000; Chamberlin and Magill 1989; Fischman 1984). Chamberlin and Magill (1989) suggested that this 2 (or more)-target disadvantage reflects the online programming of the second movement during the execution of the first. It has been proposed that the online integration of two separate movement elements may lead to these movement-time costs (Adam et al. 2000).

The RT and MT costs of executing multiple movement components can be mitigated with practice (termed “chunking,” see Klapp 1995), suggesting that the individual elements can be integrated into a single component that is fully programmed in advance. Nevertheless, for some movement types, it remains unclear whether this is an efficient and flexible strategy. For example, it has been argued that with increased accuracy requirements in reciprocal targeting, the movement components are planned as separate discrete elements (Buchanan et al. 2006). Khan et al. (2008) argued that when a reversal movement was signaled in advance, it was planned as a whole, whereas when a second target was presented after movement onset, this resulted in low degree of integration between the actions. Franks et al. (1998) further showed that when participants were asked to pause at a movement reversal target for 260 ms, RT did not increase compared to a single-target movement. This finding suggests that the pause time between reciprocal actions affects the planning of the movement. To date, no study has examined how alterations in pause time affect the early programming of the outward and return components of this type of task.

A relatively novel method of probing the state of preparation of a movement is the use of a startling acoustic stimulus (SAS). For example, when a 124 dB SAS is presented simultaneously with or immediately prior to the “go” signal in a simple RT task, the prepared and intended movement is reliably evoked at a short latency following the SAS (Carlsen et al. 2004b; Valls-Solé et al. 1999). Response onset latencies are so short (often <70 ms) that it has been proposed that the SAS acts to involuntarily initiate the planned response via startle-related neural circuits (Alibiglou and MacKinnon 2012; Carlsen et al. 2012). Importantly, this technique allows one to probe not only what has

been prepared in advance (Carlsen et al. 2004a; Maslovat et al. 2008), but also when the program is ready to be executed (Carlsen and MacKinnon 2010). Timing of cue presentation has been shown to be a critical variable that influences the state of movement preparation. For example, in an anticipation-timing task, the action was rarely triggered by the SAS when presented 500 ms before the imperative “go” cue, but was almost always triggered when presented 150 ms prior to the “go”, suggesting that programming was delayed until just prior to the time of required movement execution (Carlsen and MacKinnon 2010; Drummond et al. 2013).

The purpose of the present experiment was to investigate how changes in the time interval between the outward and return components of a reciprocal targeted movement task affect movement preparation. For instance, the task could be planned either as a single outward-and-return movement or as two separate movements (outward then return). A SAS was used to investigate the state of preparation at a time point prior to initiation of either the outward or return components of the task. The extent of preparation was expected to depend on the required pause time at the first of two targets. In particular, it was hypothesized that for short (50 ms) pause requirements, the entire outward-and-return action would be programmed in advance and would be produced at short latency following the SAS. In contrast, for longer (e.g., 500 ms) pause-time requirements, it was expected that only the first component would be pre-planned, whereby a SAS would trigger the outward movement early, but the return movement would be made at the correct time.

Methods

Participants

Seventeen neurologically healthy volunteers participated in the study after giving informed consent. Data from 6 participants was not used due to an insufficient startle response (details below); therefore, final analysis was based on data from 11 participants (7F/4 M, age range 20–38, 8 right-handed by self-report). Testing of each participant took place in a single session. The study was conducted in accordance with the ethical approval of Institutional Review Board at Northwestern University and the Research Ethics Board at the University of Ottawa and conformed to the most recent version of the Declaration of Helsinki.

Participant position

The participants sat facing a 17 inch. computer monitor (resolution 1,024 × 768 pixels) with their right forearm

resting semi-prone in a brace attached to a custom-made wrist manipulandum that allowed measurement of wrist angular displacement. The participant's hand slid inside a u-shaped bracket at the knuckles and was held in place using Velcro straps. The shoulder was flexed and abducted 15° . The forearm was secured to the brace using Velcro straps placed proximal to the wrist joint and distal to the elbow. Wrist motion was free along the flexion–extension axis and constrained in all other directions. A speaker for delivering acoustic stimuli was located 50 cm behind the ears of the participant (for an overhead schematic of the participant position see Carlsen and MacKinnon 2010).

Task and feedback

Participants performed a reciprocal aiming movement with the right wrist. A custom program written in LabView (National Instruments Inc.) provided real-time visual feedback on a computer screen during the task. The participant's wrist angle controlled the horizontal movement of a small white cursor that was vertically fixed near the bottom of the 27.7×19.8 cm (820×590 pixel) feedback screen. Vertical green bars scrolled down the screen that provided target regions for the cursor to be in. Target position was alternated between the left and right side of the screen and participants were instructed to keep the cursor within the target region for as long as possible and to move the cursor between the home (left) and extension (right) targets as quickly and accurately as possible. An illustration depicting the feedback program is shown in Fig. 1.

The target regions moved downwards on the screen at a constant speed and each trial included a break in the home target with a corresponding extension target appearing on the right of the screen. To successfully complete the task, the participant began the trial with the cursor inside the home target, and when the break appeared, moved the cursor rightward to the extension target for the specified duration, and then returned to the home target and waited for the next trial to begin. The home target was given a vertical length such that the cursor could stay in it for 3 s to allow adequate time between movement trials. The extension target consisted of three different lengths, and since it moved at a constant downward speed of 10 cm/s, these lengths corresponded to instructed pause times at the extension target of 50 ms (0.5 cm), 200 ms (2 cm), and 500 ms (5 cm). The width of each target spanned 5° of wrist angular displacement: from -12.5° to -17.5° from neutral (for wrist flexion, and from $+12.5^\circ$ to $+17.5^\circ$ from neutral for wrist extension). Thus, the movement amplitude from target center to center was 30° and this configuration results in an index of difficulty of 2.58 (Fitts 1954). When the cursor

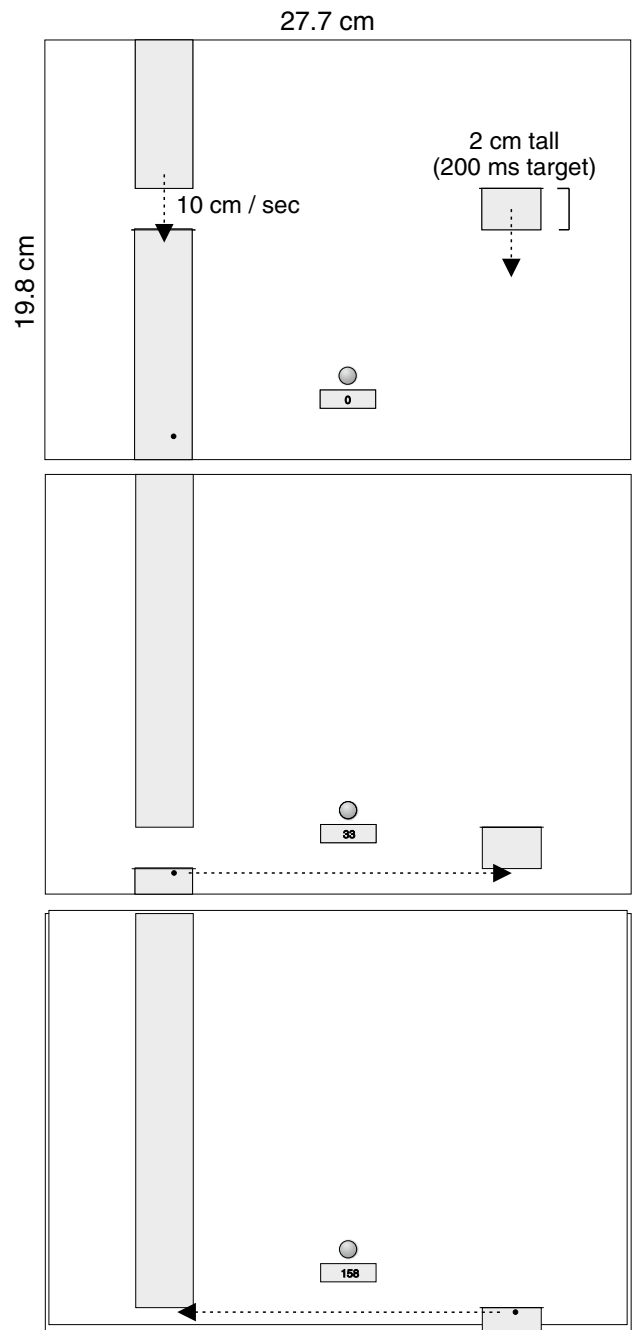


Fig. 1 Visual feedback. Targets (gray boxes) moved vertically down the screen at 10 cm/s while participants tried to keep the cursor (small black circle) inside them using wrist flexion/extension to move the cursor horizontally on the screen. Points were awarded while the cursor was within the target boundaries. *Top panel* shows 200 ms (2 cm long) extension or “out” target approaching and cursor in left “home” target region. *Middle panel* shows the transition where participants were to move the cursor rightward into the extension target. *Bottom panel* depicts the second transition where participants were to move the cursor leftwards back to the home target. Arrows and text (other than score) are presented for context here and did not appear on the actual screen. In addition, the actual feedback screen was black, lines were green, and the cursor was white

was within the target a small green circle on the screen illuminated and a score displayed on the screen increased. When the cursor was outside the targets, the green circle darkened and the score did not increase. This served to increase the participants' motivation to stay within the targets as long as possible and to move between them quickly. Participants completed two blocks of 144 reciprocal movements, where each block involved 48 movements for each instructed pause time. The first block of 144 trials was a practice block for participants to become familiar with the task and for performance to stabilize and was not analyzed. An anticipation-timing task was used since it has been previously shown that participants delay preparation of the movement until shortly prior to its execution in this type of paradigm (Carlsen and MacKinnon 2010). This served to ensure that extensive preparation was unlikely to occur during the rest interval at the home position. However, this may have also led to a decreased preparation level and perhaps a decreased robustness of the response speeding effect of the SAS (see "Discussion" section).

Startling acoustic stimulus (SAS)

During the second (testing) block of 144 trials, a loud acoustic stimulus (124 dB) was presented in 25 % of trials, but the participants were told it was irrelevant to the task. The acoustic stimulus (1 kHz, 40 ms) was created by amplifying a signal created by a tone generator (Grass model S10CTCMA). The stimulus was presented via a loudspeaker (MG Electronics, MG58H) centered 50 cm behind the head of the participant with an intensity of 124 dB. Stimulus intensity at the seated participant distance was confirmed using a precision sound level meter (Brüel and Kjær Impulse Precision Sound Level Meter 2204, A-weighted scale, impulse setting).

The SAS was pseudorandomly presented (the SAS was not delivered in the first 3 trials or in 2 consecutive trials) prior to the outward movement (SAS-o) in 6 trials, and prior to the return movement (SAS-r) in 6 trials, for each instructed pause times. This resulted in a total of 36 SAS presentations during the 144 reciprocal movement trials. The SAS was timed such that its onset occurred 150 ms prior to the estimated average electromyography (EMG) onset in advance of the target. This was determined from the data collected during the last half of the practice block. For instance, if EMG average onset occurred 100 ms prior to the outward target then the SAS was set to have an onset 250 ms prior to the targets.

Recording equipment

Surface electromyography was collected from the following muscles: right extensor carpi radialis longus (ECR),

right flexor carpi radialis (FCR), and left sternocleidomastoid (SCM)—using bipolar pre-amplified (gain = 10) surface electrodes (Delsys Bagnoli DE-2.1) connected via shielded cable to an external amplifier system (Delsys Bagnoli 16, gain = 1,000). The recording sites were prepared and cleansed in order to decrease electrical impedance. The electrodes were oriented parallel to the muscle fibers and then attached using double-sided adhesive strips. A grounding electrode was placed on the participant's left lateral epicondyle. Wrist angular position was collected using a potentiometer (Alpha 10 k Ω) attached to the central axis of the manipulandum. The potentiometer signal was smoothed with a low-pass analog filter with a cut-off frequency of 40 Hz (NeuroLog NL126). Position data, target location, startle trigger pulses, and EMG were digitally sampled at 1 kHz for 3 s and stored for offline analysis (LabView, National Instruments Inc.). On each trial data collection was initiated 1 s prior to arrival of the extension target to the level of the cursor on the screen.

Data reduction

Kinematic data was analyzed by identifying 4 time points in each 3 s trial. These time points corresponded to outward movement onset, outward movement endpoint, return movement onset, and return movement endpoint. Outward movement onset was defined as the first point with a change of more than 0.5° from baseline (calculated from a mean of 200 ms of data from trial onset). Outward movement endpoint was defined as peak angular displacement achieved in the ballistic portion of the movement (i.e., ignoring subsequent corrections). Return movement onset was defined at the first point with a change of more than 0.5° from the right side "extension" target (calculated from a mean of 25 ms of data from outward movement end). Return movement endpoint was defined as peak angular displacement achieved in the ballistic portion of the return movement. The above points were visually confirmed and adjusted if necessary due to the strictness of the criteria. Outward and return movement durations were defined as the time from movement onsets to movement endpoint. Dwell time was defined as the time between outward movement end and return movement onset.

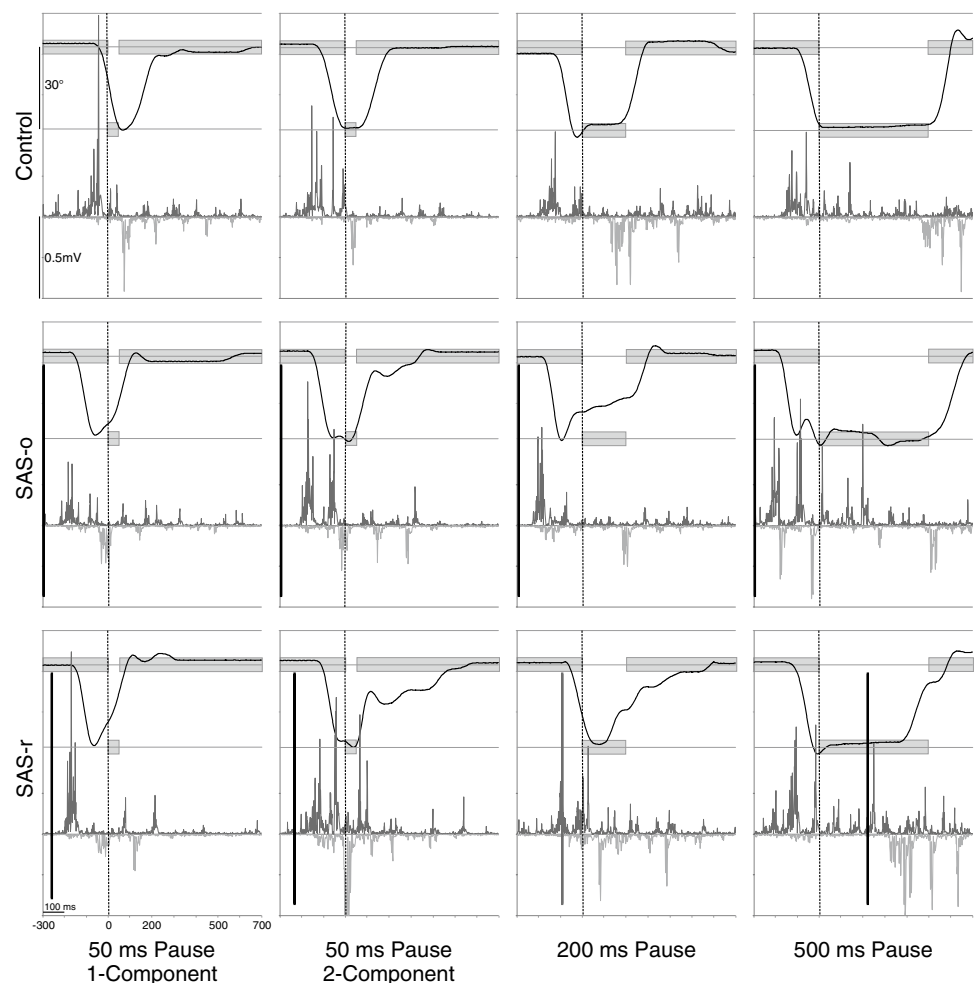
During data collection and inspection, it was noted that many participants performed the required task using two distinct strategies in the 50-ms instructed pause condition. That is, participants were often unable to pause at the target for only 50 ms and either: 1) simply made continuous out-return movements without any discernible pause, or 2) paused on the target, often for durations longer than the required 50 ms. Thus, during initial kinematic and EMG data analysis, movements were sub-classified based on whether or not a subject actually paused at the outward

(extension) target. “Dwell time” was defined as the period of low angular velocity (<20 deg/s) and/or multiple zero line crossings in the velocity profile. Movement trials where no pause was detected were categorized as “1-component” whereas trials where a pause was noted were categorized as “2-component” (see Fig. 2 for example raw displacement and EMG data for 1- vs. 2-component movements in the 50-ms instructed pause-time condition). Thus, for the kinematic variables in the 50-ms 1-component movement, the outward component was defined as movement onset to peak displacement, while the return component began at peak displacement and ended at return peak displacement—there was no dwell time by definition.

Prior to analysis, raw EMG signals were DC offset corrected and band-pass filtered from 20 to 400 Hz using a fourth order digital Butterworth filter. EMG burst onsets for the typical triphasic (three-burst) pattern commonly observed in targeted ballistic movements (Berardelli et al. 1996) were identified for both the outward and return movements. For the 50-ms 1-component movements there was no pattern associated with a return movement

component, simply a single triphasic pattern associated with a movement reversal. Internal timing parameters of the triphasic pattern were analyzed by calculating the time from initial agonist (Ag1) onset to antagonist (ANT) onset, as well as the time from initial agonist onset to the second agonist burst (Ag2). Surface EMG burst onsets were defined as the point at which the EMG first began a sustained rise above baseline levels. The location of this point was determined by first displaying the EMG pattern on a computer monitor with a superimposed line, indicating the point at which rectified, filtered EMG activity increased to more than 2 standard deviations above baseline (mean of 100 ms of EMG activity 500 ms prior to the onset of the outward target). Onset was then verified by visually locating and manually adjusting the onset mark to the point at which the activity first increased on the raw EMG trace. This method allows for correction of errors due to the strictness of the algorithm (Hodges and Bui 1996). Triphasic EMG timing patterns were quantified by calculating the time between burst onsets (inter-onset times): time from initial agonist onset to antagonist onset was calculated as

Fig. 2 Single trial raw data from a representative participant in each of the target conditions and stimulus conditions. In each panel, displacement (black), wrist extensor EMG (dark gray), and wrist flexor EMG (light gray) are shown and aligned to outward target onset (time zero). Targets are shown as gray bars. Thick black vertical lines show the time at which the startling acoustic stimulus (SAS) was presented



well as time from initial agonist to secondary agonist onset for each movement portion.

SAS trials where no EMG was detected in SCM (indicative of a startle response, see Carlsen et al. 2011) were removed from analysis. Thus, the SAS trials were restricted to those that fit within the definition of a startle-evoked release of the planned movement. If any participant had more than 3/6 SAS trials removed from any condition, the entire data set was removed from analysis. This procedure led to the removal of six of the original 17 participants. Of the remaining SAS trials, 29/396 (7.32 %) were discarded due to a lack of SCM startle response.

Statistical analysis

Dependent variables (movement onsets, outward/return movement durations, dwell times, EMG onsets, and timing patterns) were analyzed using repeated measures analysis of variance (ANOVA) tests described below to determine if differences between SAS and control trials or between instructed pause times existed. Partial eta squared (η_p^2) is reported to provide an estimate of the proportion of the variance that can be attributed to the tested factor. Prior to analysis, proportion variables were corrected for normality using an arcsine square root transformation. Greenhouse–Geisser corrected degrees of freedom were used to correct for violations of the assumption of sphericity. Differences with a probability of $<.05$ were considered significant. Main effects were decomposed using Holm–Bonferroni corrected multiple paired samples t tests to investigate global effects of the manipulated variables where no interactions existed. Significant interaction effects were tested using paired samples t tests to investigate pre-planned contrasts between SAS and control conditions at each instructed pause time to determine if hypothesized differences in preparation due to instructed pause would be revealed by differential effects of a SAS on dependent measures.

Results

To determine whether instructed pause time led to a difference in the movement strategy used, the percentage of times that movements that were classified as 1-component (see above) were analyzed using a 3 (instructed pause: 50, 200, 500 ms) \times 3 (stimulus: Control, SAS-o, SAS-r) repeated measures ANOVA. This analysis revealed a significant main effect for instructed pause time, $F(2,20) = 17.918$, $p < .001$, $\eta_p^2 = .642$, but no main effect for stimulus ($p = .063$) and no interaction between the variables ($p = .066$). Post hoc tests showed that the percentage of movements where no measurable pause was detected

was significantly higher for the 50-ms pause (50.1 %) compared to 200 ms (8.9 %) or 500 ms (0.5 %).

Based on the above result, the 50-ms pause-time condition data were separated based on classification for subsequent analyses. Since all participants did not demonstrate both strategies in all 50-ms pause conditions (Control, SAS-o, SAS-r), certain participant/condition combinations resulted in missing values. These missing cells were filled (total cells filled = 10 of 66) using a linear regression-based multiple imputation process (Howell 2010) in SPSS (IBM Inc.). Similar separation for the 200- and 500-ms instructed pause conditions was not possible since the percentage of trials classified as 1-component was very low, and thus, these trials were removed from analysis. The remaining statistical analyses were conducted using 4 (pause: 50-single, 50-dual, 200, 500 ms) \times 3 (stimulus: Control, SAS-o, SAS-r) repeated measures ANOVAs.

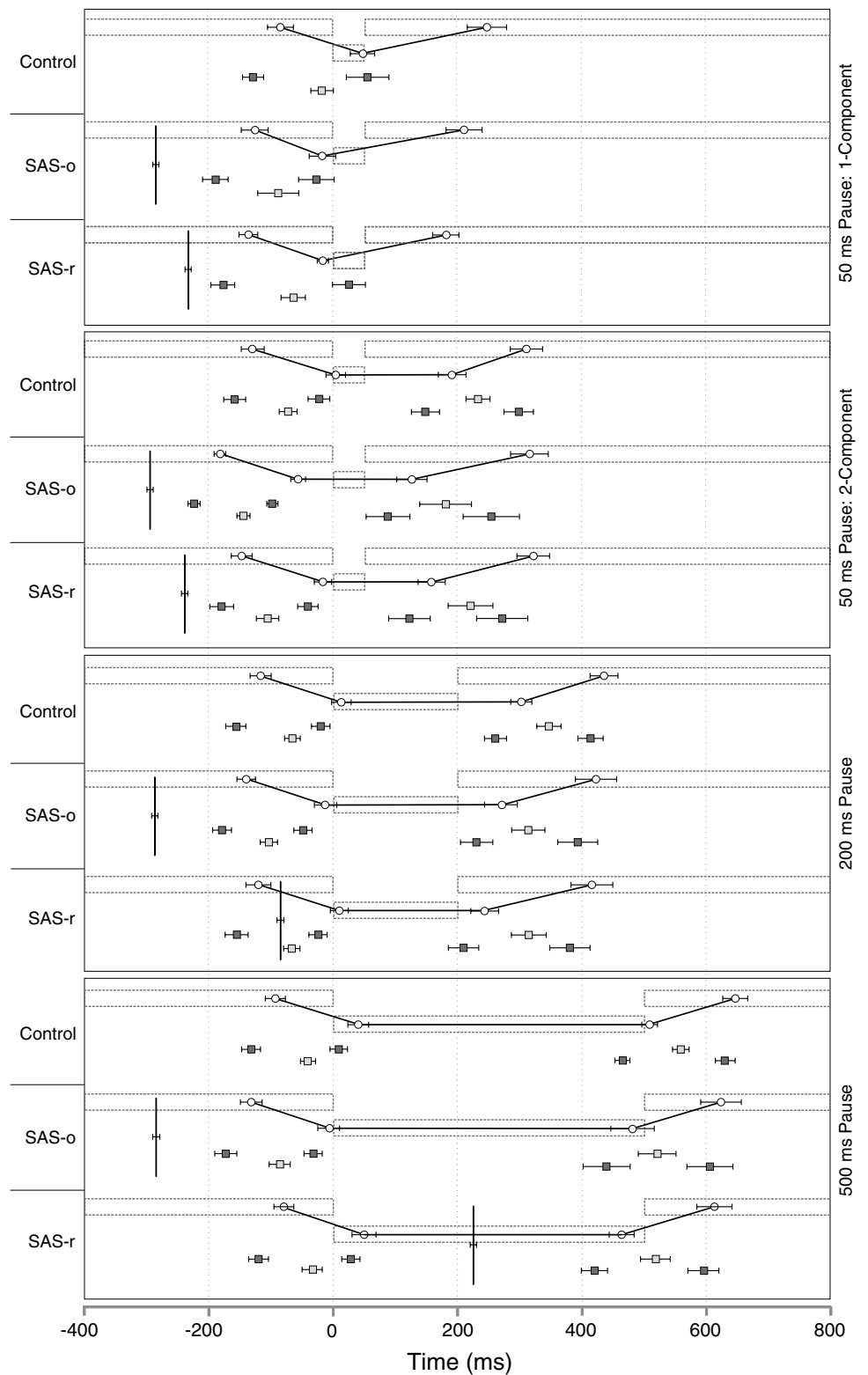
Movement kinematics

Kinematic variables were analyzed to determine if either the instructed pause time or the stimulus condition had an effect on the movement and data are presented in Fig. 3 (black lines).

Outward movement component

Analysis of the onset timing of the outward movement component showed significant main effects for both instructed pause-time condition, $F(3,30) = 14.822$, $p < .001$, $\eta_p^2 = .597$, and for stimulus, $F(2,20) = 18.418$, $p < .001$, $\eta_p^2 = .648$, and there was a significant interaction between the variables, $F(6,60) = 2.965$, $p = .013$, $\eta_p^2 = .229$. Pre-planned contrasts showed that the SAS-o, presented on average 287 ± 17 ms prior to the outward target, led to a significantly earlier movement onset for all instructed pause-time conditions compared to control trials (all p values $<.013$). In contrast, presenting a SAS on average 283 ± 15 ms prior to the return target (SAS-r) only led to a significantly early outward movement onset for the 1- ($p = .046$) and 2-component ($p = .038$) 50-ms instructed pause conditions compared to control. This result is not completely unexpected since presenting a SAS prior to the return component for the 50-ms instructed pause still resulted in the SAS being presented well before (e.g., 233 ms) the target for the outward movement. Analysis of time to peak displacement for the outward component showed no main effect for instructed pause time ($p = .292$) or stimulus ($p = .211$), and no interaction between the variables ($p = .091$). Similarly, there were no significant differences in mean peak displacement of the outward movement component (mean = $31.82^\circ \pm 3.44^\circ$) due to instructed pause time or stimulus (all p values $>.2$).

Fig. 3 Mean (\pm SE) values for kinematic and EMG data aligned to time zero (outward target onset) for each of the pause and stimulus conditions. In each pause condition, the *top* group is control, *middle* is where a startling acoustic stimulus (SAS) was presented prior to the outward target (SAS-o), and *bottom* is where a SAS was presented prior to the return target (SAS-r). *Circles* connected by *black lines* represent mean angular displacement onset and end times with respect to the targets (*dashed lines*). *Gray boxes* below targets show mean EMG onsets for first agonist (*dark gray*), antagonist (*light gray*), and second agonist (*dark gray*) bursts for each movement component. *Tall vertical black lines* show mean time when SAS was presented



Dwell component

Analysis of dwell time, or the time actually spent paused at the extension target, revealed main effects for both instructed

pause time, $F(3,30) = 300.373, p < .001, \eta_p^2 = .968$, and for stimulus, $F(2,20) = 9.694, p = .001, \eta_p^2 = .492$, and there was a significant interaction between the variables, $F(6,60) = 2.655, p = .024, \eta_p^2 = .210$. Pre-planned

comparisons showed that SAS-o did not lead to significantly different dwell times compared to control for any of the instructed pause times ($p > .43$). However, SAS-r led to significantly shortened dwell times in both the 200-ms instructed pause ($p = .009$) and 500-ms instructed pause ($p = .005$) conditions, but not in the 50-ms 2-component condition ($p = .514$), or the 50-ms 1-component movement (p value undefined as dwell time was zero by definition in all trials).

Return movement component

Analysis of onset time for the return movement component revealed significant main effects of both instructed pause time, $F(3,30) = 296.802$, $p < .001$, $\eta_p^2 = .967$, and stimulus, $F(2,20) = 12.023$, $p = .001$, $\eta_p^2 = .546$, but no interaction effect between the variables ($p = .343$). Post hoc tests on the instructed pause-time main effect confirmed the expected result that longer instructed pause times led to later return movement onsets for all of the instructed pause-time conditions (all p values $< .001$). Post hoc tests of the stimulus main effect showed that presenting a SAS led to earlier onset of the return component compared to control whether it was presented prior to the outward target (SAS-o, $p = .008$) or return target (SAS-r, $p = .003$).

Analysis of the return MT (time to return target peak displacement) also revealed main effects for both instructed pause time, $F(3,30) = 10.468$, $p < .001$, $\eta_p^2 = .511$, and stimulus, $F(2,20) = 7.697$, $p = .003$, $\eta_p^2 = .435$, but no interaction effect between the variables ($p = .065$). Post hoc tests of the instructed pause-time main effect showed that the duration of the return component was shorter for the 200-ms ($p = .017$) and 500-ms ($p = .004$) instructed pause-time movements compared to the 50-ms 1-component movement. Post hoc testing of the stimulus main effect showed that presenting the SAS prior to the outward movement led to longer duration return movements ($p = .004$). No other comparisons were significant.

Movement-related EMG

Electromyography onset times were analyzed using 4 (pause) \times 3 (stimulus) repeated measures ANOVAs to determine if either the instructed pause time and movement strategy, or stimulus condition had an effect on the timing of the triphasic EMG patterns. As the underlying EMG led to the overt movements, many of the EMG results mirror those of the displacement effects presented above. Mean EMG onset times (\pm SE) for the bursts in the triphasic pattern are shown below each of the kinematic time points in Fig. 3.

First movement component

Analysis of initial agonist onset time revealed main effects for both instructed pause time, $F(3,30) = 11.906$, $p < .001$, $\eta_p^2 = .543$, and for stimulus, $F(2,20) = 27.683$, $p < .001$, $\eta_p^2 = .735$, and there was a significant interaction between the variables, $F(6,60) = 3.602$, $p = .004$, $\eta_p^2 = .265$. Pre-planned contrasts showed that SAS-o led to a significantly earlier agonist onset for all pause conditions compared to control (all p values $< .012$). In addition, SAS-r also led to a significantly early initial EMG onset (outward movement) in both the 1-component ($p = .017$) and 2-component ($p = .049$) 50-ms pause conditions compared to control.

Since the 50-ms 1-component movement was made as a single reversal movement, the EMG timing parameters were compared with the outward movement components for the other three pause-time conditions. No significant main effect or interactions were found for Ag1 to ANT (all p values $> .27$). However, a main effect of instructed pause time was found for Ag1 to Ag2, $F(3,30) = 6.869$, $p = .001$, $\eta_p^2 = .407$, while there was no main effect for stimulus ($p = .152$) and no interaction between the variables ($p = .468$). Post hoc analysis of the instructed pause-time main effect showed that the Ag1 to Ag2 interval was longer in the 50-ms 1-component movement than in all other conditions (all p values $< .041$).

Return movement component

EMG triphasic timing for the return movement component were analyzed using 3 (instructed pause: 50 ms, 200 ms, 500 ms) \times 3 (stimulus) repeated measures ANOVAs. The 50-ms 1-component movement was not included in this analysis since by definition there was no separate return component triphasic EMG pattern. Analysis of onset time for the return movement agonist EMG revealed a significant main effect for pause time, $F(2,20) = 166.455$, $p < .001$, $\eta_p^2 = .943$, and for stimulus, $F(2,20) = 6.511$, $p = .007$, $\eta_p^2 = .394$, but no interaction between the variables ($p = .403$). Post hoc tests on the pause-time main effect confirmed the expected result that longer instructed pause times led to later return EMG onsets (all p values $< .001$). Post hoc tests of the stimulus main effect showed that presenting a SAS led to earlier onset of the return movement-related EMG compared to control whether it was presented prior to the outward target (SAS-o, $p = .025$) or prior to the return target (SAS-r, $p = .003$). No differences were found in Ag1 to ANT timing or in Ag1 to Ag2 timing for the return movement due to any of the manipulated variables.

Discussion

Several previous experiments have shown that RT increases as movements become more complex, particularly if there are multiple movement components in a sequence (Henry and Rogers 1960; Klapp 2003). It has been suggested that this effect is caused by the requirement to program more movement elements prior to movement onset. However, under certain circumstances, some of the action can be programmed “online” while the initial part of the movement is being carried out (Franks et al. 1998; Khan et al. 2008). The present experiment studied how motor pre-programming was affected by changes to the amount of time that participants were required to pause on a target in a movement reversal task by using a SAS to trigger the prepared action. The results indicate that for short (50 ms) pause times, the movement was programmed in its entirety in advance (both the outward and return components). For longer pause times (≥ 200 ms), the outward part of the movement was planned in advance along with a “dwell-time” component. The return component of longer pause-time movements may have been prepared in advance or online, but was sufficiently independent that it could be elicited early by a SAS.

Outward movement startle

Previous studies have shown that when participants are startled by a loud (124 dB) acoustic stimulus in a RT task, the intended action can be initiated at short latency, but only if the response is prepared in advance (for reviews and neural underpinnings of this effect see Alibiglou and MacKinnon 2012; Carlsen et al. 2012; Valls-Solé et al. 2008). For example, when a SAS was presented in a simple RT task, the RT was shortened from 141 to 85 ms, but when the SAS was presented in a choice RT task, RT was unaffected (Carlsen et al. 2004a). Therefore, a SAS can be used to determine if a pre-planned response is prepared and ready to be initiated. Importantly, it has been shown that a SAS can also trigger the early release of an intended movement in an anticipation-timing task, but this only reliably occurs if the SAS is presented in a small time window (estimated at 150–300 ms) preceding the expected timing of movement onset (Carlsen and MacKinnon 2010; Drummond et al. 2013). This suggests that the response is fully prepared shortly before it is to be initiated in this type of situation, thus, a less robust speeding effect of the SAS may be expected. In the present experiment, the presentation of a SAS at an average of 287 ms prior to the outward movement target (SAS-o) reliably led to early outward movement onsets for all three instructed pause times (Fig. 3). This suggests that the initial outward component was programmed and ready for initiation just prior to movement onset in the timing task used here.

While the above result indicates that at least the outward component was prepared, the *entire* reversal movement often appeared to be elicited by the SAS-o, particularly for the 50-ms 1-component movement. Again, this may not be surprising given that these types of immediate reversal movements have been shown to be elicited by SAS in RT tasks (Valls-Solé et al. 1999). In addition, it has been previously shown that for reversal movements with sufficiently large reversal targets (as used in the present experiment), the one-target advantage disappears (Adam et al. 1995), suggesting that the whole movement is programmed as a single unit with the braking force also acting as the acceleration force back to the home target. This movement component integration does not occur for two-component double extension movements, as the braking force may interfere with the accelerative force for the second component (Lavrysen et al. 2002). Thus, while a sufficiently high index of difficulty was used to encourage accurate discrete movements, participants nevertheless often used a single-component reversal strategy. Of particular note was the observation that movements produced with a dwell between them (i.e., two-component movements) also appeared to be elicited in full by the SAS-o, even for the longer instructed pause times. Specifically, for the 50-ms 2-component, 200, and 500 ms, instructed pause conditions, there was no increased dwell duration (i.e., the time actually spent paused at the “extension” target). An increase in dwell duration would be expected if the return portion was executed at the “correct” time, following an early outward movement portion. However, although SAS-o led to outward movement onsets occurring 39 ms earlier on average across the instructed pause times, the duration of the dwell prior to the return movement onset was only increased by 2.3 ms (Fig. 3). In other words, when the SAS-o led to an early onset of the outward component, it also resulted in the return component being executed early, suggesting that the timing of the dwell at the “out” target was part of the initial pre-planned motor program, since no correction for an early outward movement onset was made online. Thus, it appears that at least the outward movement *and* the dwell-time component were executed in a serial open-loop fashion even though real-time visual feedback was available. Previous experiments using a SAS have demonstrated that the timing between two movements could be pre-programmed, but this was limited to bimanual actions (Maslovat et al. 2009). These data therefore suggest that the instructed pause time was treated as an active component of the overall movement plan rather than a passive time gap that was judged online using visual feedback.

Many previous experiments have shown that visual feedback cannot typically be consciously processed and used for correcting movement errors in less than 150 ms (e.g., Zelaznik et al. 1983). Therefore, it is not inconceivable,

given that the outward component was executed relatively quickly (132.3 ms), that the timed dwell portion of the movement would be prepared in advance. Nevertheless, some data has suggested that rapid, visually guided targeted limb adjustments can be made (Day and Brown 2001; Reynolds and Day 2007) perhaps via a dorsal visual stream-mediated “automatic pilot” (Cressman et al. 2006; Pisella et al. 2000). Since similarly fast corrections were not made in the current experiment, these data indicate that this more subconscious “vision for action” may only serve to function in the spatial rather than the temporal domain. It should be noted that following SAS-o in the 500-ms instructed pause condition, the observed dwell time was 19.9 ms longer than control and quite variable (SD 85 ms), but this was not statistically reliable. However, it does suggest that for the 500 ms instructed pause condition, the timing component may not have always been fully pre-programmed by all participants, or that sufficient time may have been available in some cases to correct for the early outward movement. Thus, 500 ms may represent the upper limit for the duration of a pre-programmed timing component when online visual feedback is available.

Return movement startle

A SAS delivered prior to the return portion (SAS-r) in the 50-ms instructed pause condition also led to the early initiation of the outward (and entire) action irrespective of whether it was a 1-component or 2-component action. Since the SAS was delivered on average 283 ms prior to the return movement target, this means that for the 50-ms instructed pause-time condition, it nevertheless occurred more than 200 ms prior to the outward movement. Thus, both SAS-o and SAS-r likely led to similar effects in the 50-ms instructed pause condition because of the similar absolute timing of the SAS occurring prior to the outward movement. For the 200- and 500-ms instructed pause conditions, SAS-r led to an early onset of the return movement component. This was evidenced by the significant shortening of dwell time in these conditions by 55 ms on average (see Fig. 3). Even though the presentation of SAS-r still preceded the outward *target* onset, it often did not occur prior to outward movement onset since participants tended to initiate movement early to arrive at the extension target at the correct time (Fig. 3). This result suggests that the return movement component was able to be triggered early and thus was often prepared and ready for execution when SAS-r occurred.

Although the unchanged dwell time in response to the SAS-o (discussed above) suggests that the entire reciprocal movement may have been pre-planned, the return component appears to have been prepared sufficiently independently from the other component(s) to be able to be

triggered by the SAS-r in the 200-ms and 500-ms instructed pause trials. Some previous studies have shown that for targeted reversal movements with pause times of 200 ms or more, the return movement is prepared online during the outward movement and/or dwell since RT did not increase as a function of task requirements (Franks et al. 1998). However, since the task used in the present experiment was an anticipation-timing task, we are not able to know whether the 200- and 500-ms movements would have incurred increased RTs. Thus, the present data cannot unequivocally distinguish whether the return component was pre-planned or planned online, since independent return component triggering may be seen in either case. Nevertheless, some evidence for online programming related to the second component was seen. Presenting the SAS prior to the outward movement (SAS-o), particularly in the 200-ms dwell-time condition, often led to “disrupted” return movements (see Fig. 2 for example data). These movements included shortened or slowed ballistic portions, as well as multiple corrections. It has been previously reported that a startling stimulus often leads to cognitive deficits and errors in processing for a short time following the stimulus (Carlsen et al. 2004a; Thackray et al. 1972; Vlasak 1969). Thus, SAS-o may have affected the return portion of the movement by disrupting processing related to the planning of the return component. Alternatively, the disruption of the return component may have resulted from the SAS-o interfering with other online control processes related to its execution. Since SAS-r did not disrupt the return component’s movement kinematics in the same way, it appears that SAS-r was presented late enough to not to interfere with online programming or execution processes.

EMG patterns

The observed timing of the EMG patterns support and mirror the movements observed in the kinematic data (see Figs. 2, 3). One major difference seen in EMG patterns was for the 50-ms 1-component movement. While the time between agonist onset and antagonist onset was not different between conditions, the time between agonist onset and the second agonist burst was significantly lengthened in the 50-ms 1-component movements compared to all other conditions. This is explained by the observation of the two qualitatively different movements made in the 50-ms instructed pause condition. In the 50-ms 2-component movements (as well as the 20 and 500-ms instructed pause conditions), the limb was stopped at the extension target, whereas no such dwell time was observed for the 50-ms 1-component movement. A lengthened antagonist burst and delayed second agonist burst have been consistently reported for reversal movements compared to targeted single-target movements (Kasai and Seki 1992; Ketelaars

et al. 1997). The different EMG patterns observed for the 1-component reversal actions support the suggestion that the movement was in fact programmed as a different type of movement in these cases.

It should be noted that in most trials, the interval between the SAS and EMG onset is slightly longer than what has been commonly observed in SAS RT experiments (e.g., Carlsen et al. 2004b). In the current experiment, an anticipation-timing-type task was used, which has been previously shown to lead to later motor preparation (Carlsen and MacKinnon 2010). As such, since the SAS was presented with a relatively long latency (mean 285 ms) prior to the anticipated action in some instances, the response may not have been prepared. This may have led to increased SAS-EMG latencies as the prepared actions would have been elicited early, while when the response was unprepared, it would not have been facilitated. One exception is that when the SAS was presented in the 50-ms 2-component condition. In particular, the SAS-o appeared to be slightly more reliable in eliciting the response early compared to the 50-ms 1-component movement (although this was not significant). It is possible that the increased complexity of this action compared to the 50-ms 1-component movement required programming to be completed earlier. In addition, in the SAS-r trials, the SAS occurred 50 ms later and the response would also have been more likely to be prepared at this point. However, this possibility requires further experiments to confirm.

In summary, by using a SAS to elicit the pre-planned portion of the actions, the current results showed that for the 50-ms instructed pause-time task, the movement was prepared in its entirety in advance as a cohesive unit. For longer instructed pause times of 200 and 500 ms, it appears that the initial part of the movement was prepared in advance along with a pre-planned and preset timing component. The return component of longer instructed pause-time movements appears to have been prepared differently since the later presentation of the SAS was able to trigger the actions independently. For longer pause times where feedback-based modification is possible, it appears that the system is able to either prepare a return movement framework that is easily modifiable online, or that the return movement is fully programmed online during the initial part of the movement.

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