The influence of advance information on the response complexity effect in manual aiming movements

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Abstract

The relation between reaction time and the number of elements in a response has been shown to depend on whether simple or choice RT paradigms are employed. The purpose of the present study was to investigate whether advance information about the number of elements is the critical factor mediating the influence between reaction time and response elements. Participants performed aiming movements that varied in terms of the number of elements and movement amplitude. Prior to the stimulus, advance information was given about the number of elements and movement amplitude, movement amplitude only, number of elements only, or no information about the response. Reaction time and movement time to the first target increased as a function of number of elements only when the full response or the number of elements was specified in advance of the stimulus. The implication of these results for current models of motor programming and sequential control of aiming movements are discussed.

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1. Introduction

Since the work of Henry and Rogers (1960), it has generally been accepted that the time required to program a response increases as a function of response complexity. However, the question of what aspect of response complexity is responsible for increases in programming time is still a matter of much debate. In this regard, researchers have investigated the effect of factors such as the number of elements (Fischman, 1984; Sternberg, Monsell, Knoll, & Wright, 1978), response duration (Klapp & Erwin, 1976) and movement accuracy (Lajoie & Franks, 1997; Sidaway, 1991) on reaction time. A second issue that has received much attention concerns the varying effects of response complexity on simple versus choice RT (Henry, 1980; Klapp, Abbott, Coffman, Snider, & Young, 1979; Klapp, Wyatt, & Lingo, 1974). It has become increasingly evident that gaining a clear grasp of these issues is critical to enhancing our understanding of the processes involved in movement preparation and programming.

In simple RT tasks, participants are informed which response to produce prior to the presentation of the stimulus. In contrast, the required response is not known until stimulus presentation in choice RT tasks. Hence, choice RT is longer than simple RT since response selection processes must occur during the RT interval in choice but not simple RT tasks. Also, it is possible that response programming can occur prior to the RT interval in simple RT tasks since participants are informed of the required response in advance of the stimulus. In choice RT, programming must take place after the response is specified by the stimulus.
Assuming that more complex responses take longer to program, choice RT would be expected to increase as a function of response complexity whereas there should be no effect on simple RT. However, while there are clear differences between choice and simple RT (i.e., choice RT > simple RT), the influence of response complexity on reaction times has not been straightforward.

In a series of experiments using Morse code responses, Klapp (1995) showed that the duration of single element responses influenced choice but not simple RT. Alternatively, while simple RT increased as the number of elements in a response increased, there was no effect of number of elements on choice RT. Klapp accounted for these results by proposing a two process model of response programming in which he referred to INT as the programming of internal features (e.g., duration) of individual elements and SEQ as the ordering of elements. In simple RT, INT could be performed prior to the presentation of the stimulus whereas SEQ occurs during the RT interval. Therefore, simple RT is influenced by the number of elements in a response since it takes longer to perform SEQ as the number of elements increases. In choice RT, pre-programming is not possible and therefore both INT and SEQ must occur during RT. Based on the assumption that both processes occur in parallel and that INT takes longer than SEQ, the duration of individual elements influences choice RT but not the number of elements in a response (also see Immink & Wright, 2001).

The results obtained for Morse code responses have been extended to speech articulation (Klapp, 2003). Specifically, Klapp showed that when the syllables of a word can be easily integrated into a chunk, simple RT was not influenced by the number of syllables but choice RT increased as the number of syllables increased. In contrast, in conditions that discouraged integration of syllables, simple RT increased as a function of the number of syllables but not choice RT. Hence, similar to the conclusions based on Morse code responses, choice RT was influenced by the internal features or complexity of a chunk, whereas simple RT increased as a function of the number of elements in a response.

Interestingly, Klapp (2003) also showed that when the number of syllables but not the actual content of the syllables was precued prior to stimulus presentation, RT increased as a function of the number of elements. Klapp reasoned that since the content of the syllables was not known in advance of the stimulus, both INT and SEQ must have occurred during the RT interval. Hence, the finding that RT depended on the number of syllables was inconsistent with his original idea that INT and SEQ occurred in parallel and that INT determined RT because it took longer than SEQ. Klapp therefore modified his theory by proposing that SEQ involved the scanning of an abstract time frame rather than the sequencing of the actual elements or chunks. This time frame specifies the time of initiation of each chunk without specific reference to the content of the chunks. In simple RT, the time frame is loaded into a buffer prior to the presentation of the stimulus. During the RT interval, the time frame is activated and scanned to locate the starting point. This scanning process takes longer as the number of elements increases and hence simple RT increases for responses involving more elements. Similarly, the abstract time frame can be loaded into a buffer prior to the stimulus when the number of elements but not the nature of the elements is precued. Hence, RT increases as the number of elements and the time to perform the scanning process increases. In choice RT situations in which the number of elements is not precued, the time frame is retrieved immediately prior to responding and therefore does not have to be scanned. Hence, choice RT does not increase as a function of number of elements in a sequence.

In a recent study, Khan, Lawrence, Buckolz, and Franks (2006) considered an alternative explanation as to why choice RT may not depend on the number of elements in a response. Khan et al. suggested that in choice RT conditions, participants do not have the opportunity to load response elements into a buffer prior to the stimulus since the response is not known until stimulus presentation. Therefore, in order to minimize RT, participants may adopt a strategy in which they program the first element during RT but then delay the programming of other elements until during movement execution (i.e., online programming) (also see Chamberlin & Magill, 1989; Ketelaars, Garry, & Franks, 1997; Smiley-Oyen & Worthingham, 1996; Van Donkelaar & Franks, 1991). In simple RT, participants have more opportunity to load elements in a buffer during the foreperiod since the required response is known before the stimulus. Khan et al. tested this online programming hypothesis using a simple manual aiming task consisting of movements to one or two targets. It was expected that if online programming was occurring in choice but not simple RT tasks, movement times would be longer in choice than simple RT conditions because of the additional processing demand during movement execution. However, movement times were shown to be actually longer in the simple compared to choice RT task. Furthermore, the introduction of a secondary task during movement execution caused a greater deterioration in movement accuracy in the simple compared to choice RT. Khan et al. reasoned that when participants knew in advance that two elements would be required, they adopted a control strategy in which they monitored the first element to enhance the integration between elements (Adam et al., 2000; Helsen, Adam, Elliott, & Beukers, 2001; Ricker et al., 1999). This integration strategy was not adopted in the choice RT condition since participants did not know whether or not they would have to produce one or two elements until stimulus presentation.

In the present study, we investigated how the relation between reaction time and response complexity is influenced by providing advance information about the features of the required response. Participants performed aiming movements that consisted of either a single movement to
a target or a reversal movement in which they moved to one target and then reversed direction to stop at a second target. We also varied the required amplitude of the aiming movements. Prior to the stimulus, participants were either informed about both the required number of elements and the amplitude of the movement, only the number of elements but not the movement amplitude, the required movement amplitude but not the number of elements, or no information about the required response.

The aim of this experiment was twofold. First, we were interested in examining whether the results obtained by Klapp (2003) using speech articulation could be extended to manual aiming movements. More specifically, Klapp showed that reaction time increased as the number of syllables increased when the number of syllables was known in advance of the stimulus irrespective of whether the content of the syllables was specified. When the number of syllables was not known in advance, RT did not increase as a function of response elements. Therefore, we expected that RT would increase as a function of number of elements when both the number of elements and movement amplitude were precued prior to the stimulus or when only the number of elements but not movement amplitude was known in advance.

Our second interest was to investigate whether apriori knowledge of the number of elements was a necessary condition for enhancing integration between elements during movement execution. If this was the case, we expected that when the number of elements was known in advance, movement times to the first target would be lengthened relative to when the number of elements was not specified until stimulus presentation. According to the movement integration hypothesis (Adam et al., 2000), the control processes associated with the production of the second element are implemented during execution of the first element and this increased executive control leads to longer movement times.

2. Method

2.1. Participants

Sixteen self declared right-handed undergraduate students (11 males and 5 females) between the ages of 18 and 30 yrs volunteered to participate in the experiment. They gave their informed consent prior to taking part and the experiments were carried out according to the ethical guidelines laid down by the Ethics committee of the School of Sport, Health and Exercise Sciences, University of Wales, Bangor, for research involving human participants.

2.2. Apparatus

Participants held a pen with their right hand and made movements on a SummaSketch III Professional digitizing tablet (size = 45 cm x 31 cm, sample rate = 120 Hz, accuracy = ±.02 mm) positioned horizontally in front of them. The tip of the pen was fitted onto a track-way that constrained movements in the left to right direction. The track-way prevented movements in the forward and backward directions. The position of the pen was represented by a round cursor (0.4 cm in diameter with a dot 0.1 cm wide in the middle) on a 19 in. Dell Trinitron computer monitor situated 40 cm in front of the participant and raised 30 cm from the tablet surface. Visual displays of the start position, target lines, and a cursor representing pen position appeared on the monitor screen (see Fig. 1). The start position was located to the left of the monitor and consisted of a vertical line 0.4 cm wide and 4 cm long. Directly above the start position was a 2 cm x 1.5 cm rectangle where the stimulus appeared. Three vertical target lines 0.1 cm wide and 4 cm long were situated 2, 4 and 8 cm to the right of the start position. To minimise head movements participants placed their chin on a chin rest that was adjusted so that the start and target boxes were at eye level. The participants’ arm was occluded by an opaque shield throughout the experiment.

2.3. Task and procedure

At the beginning of each trial, the start position, target lines, and the cursor representing limb position appeared on the monitor. Participants were required to move the cursor to the centre of the start position. Once the cursor was steadily aligned, a precue that consisted of a combination of letters and/or numbers was presented in the stimulus display box for 2000 ms. Following the precue, an audio tone was presented signalling the start of the variable foreperiod (1500–2500 ms). This was followed by the presentation of the stimulus that also consisted of a combination of letter and numbers. Participants were instructed to move the cursor to the targets indicated by the stimulus as quickly and as accurately as possible in a continuous manner. The stimulus remained visible throughout the trial.

There were four possible stimuli: 1S, 2S, 1L, and 2L. A “1S” represented a single element response in which participants were required to move the cursor to the 4 cm target line. A “2S” represented a two element response, in which
participants were required to move to the 4 cm line and then back to the 2 cm line. For the “1L” stimulus, participants were required to move to the 8 cm line, while for the “2L” stimulus they had to move to the 8 cm line and then reverse direction ending their movement on the 4 cm line.

The precues varied with respect to the amount of information they provided about the required response. This information was always valid. In the Full Precue condition, the precue consisted of both a number and a letter (i.e., 1S, 2S, 1L, 2L) and hence participants were informed with 100% certainty of the identity of the stimulus. This condition is similar to the simple RT condition used by Klapp (1995, 2003) and Khan et al. (2006). In the Elements Precue condition, “1” or “2” was presented and hence, participants knew whether or not the stimulus would require a 1 or 2 element response. However, they did not know the required movement amplitude until stimulus presentation. In the Amplitude Precue condition, the precue was an “S” or “L” denoting short and long amplitude movements, respectively. Hence, participants knew the amplitude of the required movement but not the number of elements. Finally, in the Neutral Precue condition, an “X” was presented and participants had no prior information about which response would be required. This condition is similar to choice RT in previous experiments.

Participants performed a total of 240 trials. The 16 combinations of precue and stimulus were randomized in a pseudo random manner with each combination appearing before being repeated. The first 80 trials (five repetitions of each precue-stimulus combination) were regarded as practice while the last 160 trials were analysed. At the end of each trial, a display of the pen’s trajectory versus time was presented on the experimenter’s computer monitor. Participants received feedback about their RT (ms) and constant error (mm) at each target in numeric form on their monitor. It was explained to participants that error was calculated from the centre of the cursor and the centre of the target. A positive error indicated that the target was overshoot, while a negative error indicated that the target was undershot. All trials in which participants made the wrong response (i.e., incorrect number of elements or amplitude) or in which RTs were less than 100 ms or greater than 800 ms were rejected and repeated within the sequence of trials.1 This amounted to less than 5% of the trials.

2.4. Data reduction, dependent measures and analyses

The displacement data for each trial were filtered using a second-order dual-pass Butterworth filter with a low-pass cut-off frequency of 10 Hz. Instantaneous velocity data were obtained by differentiating the displacement data using a two-point central finite difference algorithm. In order to locate the beginning of the movement, peak velocity was first obtained. The velocity profile was then traversed backwards in time until the velocity fell below 2 cm/s. The end of the movement to the first target was defined as the first point in time following peak velocity in which the absolute angular velocity of the pen fell below 2 cm/s. If the movement consisted of two elements, the beginning of movement to the second target was determined by first locating peak velocity in the reversal direction. The velocity profile was then traversed backwards in time until the absolute velocity fell below 2 cm/s. The end of the movement was then defined as the point in time following peak velocity at which the absolute velocity fell below 2 cm/s. If the absolute velocity between the end of the first element and the beginning of the second element remained below 2 cm/s, the movement was said to contain a pause. Pause time was then calculated as the interval between the end of the first element and the start of the second element.

Our dependent measures consisted of reaction time (RT), movement time to the first target (MT1), movement time from the first to second target (MT2), pause time at the first target (PT), Variable Error at target 1 (VE1) and target 2 (VE2). Variable error was the within participant standard deviation of the position of the centre of the cursor at the end of each movement segment. Also, based on the assumption that the kinematics of limb trajectories up to peak velocity represent the programmed phase of movement whereas online processes take effect after peak velocity (see Elliott, Helsen, & Chua, 2001), we partitioned MT1 into time to peak velocity (TPKV) and time after peak velocity (TAPKV).

RT, MT1, TPKV, TAPKV and VE1 were analyzed using separate 4 precue condition (Full precue, Elements precue, Amplitude precue, Neutral precue) × 2 number of elements (1, 2) × 2 movement amplitude (short, long) repeated measures ANOVAs. Since PT, MT2 and VE2 were recorded only for movements with two elements, these data were analyzed using separate 4 precue condition (Full precue, Elements precue, Amplitude precue, Neutral precue) × 2 movement amplitude (small, large) repeated measures ANOVAs. All post hoc analyses were performed using Tukey’s HSD (p < .05) tests.

3. Results

The means and standard deviations of all dependent variables are reported in Table 1. The analysis of reaction time revealed a significant main effect for precue condition, \( F(3,45) = 175.9, p < .001 \). Reactions times were shortest for the full precue condition (239 ms) and longest for the neutral precue condition (390 ms). There was no difference between the element (346 ms) and amplitude precue (321 ms) conditions. The main effect for number of elements was significant, \( F(1,15) = 14.2, p < .01 \), as well as the interaction between precue condition and number of elements, \( F(3,45) = 7.6, p < .01 \). Breakdown of this

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1 An error in movement amplitude occurred when the position of the pen at the end of a movement segment was closer to the incorrect target.
interaction revealed that reaction time increased as a function of number of elements in the full and element precue conditions, whereas there was no influence of number of elements in the amplitude and neutral precue conditions (see Fig. 2). There was also a significant interaction between precue condition and movement amplitude, \( F(3,45) = 10.6, p < .001 \). Breakdown of this interaction revealed that reaction time was greater for the long compared to short amplitude movements only in the full precue condition.

The analysis of movement time to the first target (MT1) revealed significant main effects for precue condition, \( F(3,45) = 12.9, p < .001 \), number of elements, \( F(1,15) = 10.9, p < .01 \), and amplitude, \( F(1,15) = 215.1, p < .001 \). Overall, movement times were shortest in the full precue condition (207 ms) and longest in the neutral precue condition (226 ms), while there was no difference between the amplitude (217 ms) and element precue conditions (222 ms). A significant interaction between precue condition and number of elements, \( F(3,45) = 8.2, p < .01 \), revealed that movement time to the first target was greater in the two compared to single element condition for the full and element precue conditions but not in the amplitude and neutral precue conditions (see Fig. 3).

The analysis of time to peak velocity revealed a similar pattern to MT1. There were significant main effects for precue condition, \( F(3,45) = 24.6, p < .001 \), number of elements, \( F(1,15) = 48.9, p < .001 \), and amplitude,

| Table 1 | Means and standard deviations (italics) of reaction time (RT), movement time to the first target (MT1), time to peak velocity (Tpkv), time after peak velocity (Tapkv), variable error at target 1 (VE1), pause time (PT), movement time from the first to second target (MT2), and variable error at target 2 (VE2) as a function of precue condition, number of elements and movement amplitude |
|---|---|---|---|---|---|---|---|
| | Amplitude precue | Element precue | Full precue | Neutral precue |
| | 1s | 1l | 2s | 2l | 1s | 1l | 2s | 2l | 1s | 1l | 2s | 2l | 1s | 1l | 2s | 2l |
| RT (ms) | 318 | 332 | 319 | 317 | 340 | 338 | 354 | 354 | 219 | 241 | 242 | 255 | 395 | 380 | 394 | 392 |
| MT1 (ms) | 186 | 246 | 188 | 247 | 187 | 248 | 197 | 255 | 169 | 229 | 186 | 244 | 192 | 258 | 196 | 257 |
| Tpkv (ms) | 80 | 106 | 81 | 109 | 81 | 103 | 87 | 112 | 63 | 90 | 72 | 101 | 82 | 106 | 90 | 112 |
| Tapkv (ms) | 106 | 140 | 106 | 138 | 106 | 145 | 109 | 143 | 106 | 138 | 113 | 143 | 109 | 151 | 106 | 145 |
| Pkv (mm/s) | 421 | 605 | 445 | 613 | 414 | 614 | 425 | 621 | 451 | 642 | 442 | 615 | 404 | 607 | 425 | 621 |
| VE1 (mm) | 6.9 | 7.6 | 5.5 | 7.4 | 5.8 | 7.4 | 5.4 | 7.7 | 5.5 | 7.9 | 5.1 | 6.8 | 5.3 | 7.9 | 5.7 | 7.3 |
| PT (ms) | 1.3 | 1.3 | 1.4 | 1.6 | 1.4 | 1.3 | 1.1 | 1.1 | 1.5 | 1.5 | 1.1 | 1.6 | 1.3 | 1.5 | 1.3 | 1.5 |
| MT2 (ms) | 37 | 49 | 33 | 28 | 37 | 49 | 33 | 28 | 27 | 44 | 33 | 34 |
| VE2 (mm) | 3.9 | 5.2 | 3.7 | 5.1 | 3.7 | 5.1 | 4.1 | 5.2 | 4.1 | 4.7 |
| (mm) | 0.8 | 1.2 | 0.8 | 1.2 | 0.8 | 1.2 | 1.2 | 1.2 |

Fig. 2. Mean reaction time and standard errors as a function of number of elements for the amplitude (AP), element (EP), full (FP) and neutral (NP) precue conditions.
\( F(1, 15) = 189.8, \ p < .001, \) as well as a significant interaction between precue condition and number of elements, \( F(3, 45) = 4.2, \ p < .05. \) Similar to the MT1 analysis, time to peak velocity increased as a function of number of elements for the full (1 element = 76 ms; 2 elements = 87 ms) and element (1 element = 92 ms; 2 elements = 100 ms) precue conditions but not the amplitude (1 element = 93 ms; 2 elements = 95 ms) and neutral (1 element = 95 ms; 2 elements = 101 ms) precue conditions. The analysis of time after peak velocity also revealed a significant interaction between precue condition and element, \( F(4, 45) = 4.4, \ p < .05. \) Time after peak velocity increased as a function of number of elements for the full (1 element = 122 ms; 2 elements = 129 ms) but not the amplitude (1 element = 123 ms; 2 elements = 122 ms), element (1 element = 126 ms; 2 elements = 126 ms) and neutral (1 element = 130 ms; 2 elements = 125 ms) precue conditions. The analysis of peak velocity revealed significant main effects of precue condition, \( F(3, 45) = 3.8, \ p < .05, \) and amplitude, \( F(3, 45) = 276.5, \ p < .001. \) There was also a significant interaction between precue condition and number of elements, \( F(3, 45) = 5.2, \ p < .01. \) Breakdown of this interaction revealed that peak velocity tended to decrease as a function of elements for the full precue condition (1 element = 546 mm/s; 2 elements = 528 mm/s) while there was a tendency for peak velocity to increase as a function of elements in the amplitude (1 element = 513 mm/s; 2 elements = 529 mm/s) and neutral precue conditions (1 element = 505 mm/s; 2 elements = 523 mm/s).

The analysis of pause time at the first target revealed no significant effects (mean = 37 ms) (\( p < .05 \)), while the analysis of MT2 revealed only a significant main effect of movement amplitude, \( F(1, 15) = 109.3, \ p < .001. \) As would be expected, movement times to the second target were greater for the long (281 ms) compared to short amplitude movements (221 ms). Similarly, the analysis of variable error revealed that movement endpoints at both the first, \( F(1, 15) = 151.9, \ p < .001, \) and second targets, \( F(1, 15) = 38.9, \ p < .001, \) were more variable for long (VE1 = 7.5 mm; VE2 = 5.0 mm) compared to short movements (VE1 = 5.5 mm, VE2 = 3.9 mm). No other effects were significant (\( p < .05 \)).

4. Discussion

Previous research has revealed that simple RT increased as a function of the number of elements in a response, whereas there was no influence of the number of elements on choice RT (Khan et al., 2006; Klapp, 1995, 2003). The results of the present experiment were consistent with these findings. When participants knew which response would be required prior to the stimulus (i.e., full precue condition), reaction time was longer for the two compared to single element responses. However, when no information was available in advance of the stimulus (i.e., neutral precue condition), the number of response elements did not influence reaction time.

Klapp (2003) has accounted for this pattern of reaction time results by suggesting that when the number of elements is known in advance, an abstract time frame is loaded into a buffer during the foreperiod. Upon stimulus presentation, the abstract time frame must be searched to locate the first element. This search process takes longer for responses with more elements and hence reaction time increases as a function of number of elements. In cases in which the number of elements is not known in advance, the abstract time frame is loaded just prior to response initiation and therefore does not have to be searched to locate the starting point. Hence, reaction time is not influenced by the number of response elements.

An important feature of the abstract time frame proposed by Klapp (2003) is that it does not contain information about the actual content of the elements. This proposal was based on the finding that reaction time
increased as a function of the number of times a syllable was to be repeated when the number of syllables was specified in advance, but the actual syllable was not known until stimulus presentation. The present study extends these results to manual aiming movements. When the number of elements but not the amplitude of the movement was specified prior to the stimulus, reaction time increased as a function of the number of response elements. Therefore, it appears that a necessary condition for reaction time to increase as a function of response elements is that the number of elements is known prior to the reaction time interval. Reaction time is directly related to the number of response elements when the entire response is known in advance of the stimulus or when the number of elements is specified, but other features of the response remain unknown until stimulus presentation. There is no influence of response elements on reaction time when the number of response elements is not known until stimulus presentation. It is also worth noting that in the study of Klapp, utterances consisted of the same syllable being repeated a required number of times. The two element aiming movements employed in the present study consisted of components that were fundamentally different in both extent and direction. Therefore, the implementation of an abstract time frame is not limited to repetitions of the same element.

For the aiming movements employed in the present study, it is possible that participants pre-program the general pattern of muscle activity when the number of elements is known prior to the stimulus. The control of reversal movements is unique in that the antagonist muscle activity that decelerates the limb at the end of the first element also acts as the agonist to accelerate the limb on the reversal component. Khan et al. (2006) have suggested that participants may be able to program this general pattern of muscle activity regardless of whether or not the required movement amplitude is known. Because the pattern of muscle activity is more complex for these reversal movements and a high degree of integration between elements is involved, it may take longer to activate or “run off” the motor program for dual element movements than single element movements.

Although the general pattern of muscle activity may have been programmed prior to response initiation, it appears that additional control processes were involved when advance information was provided about the number of elements. Movement times to the first target were longer in two compared to one element responses when the number of elements or the full response was precued. It is well documented that the control of movements to a target is influenced by the presence and characteristics of other movement segments (Adam & Paas, 1996; Adam et al., 1995; Aivar, Brenner, & Smets, 2005; Lavrysen et al., 2003; Rand, Alberts, Stelmach, & Bloedel, 1997; Rand & Stelmach, 2000). According to the movement integration hypothesis (Adam et al., 2000), the one-target movement time advantage is due to increased executive control during execution of the first element that mediates the integration between the response elements. In this regard, Adam et al. (2000) have distinguished between the online programming hypothesis and the movement integration hypothesis. Online programming involves both the construction of a motor program and implementation of the program during movement execution. According to the movement integration hypothesis, program construction is performed prior to response initiation but the implementation of the second element is performed online concurrent with execution of the first element. This implementation process causes interference and hence the one-target advantage.

It is important to note however that previous research has shown that the one-target movement time advantage is usually absent for aiming movements involving a reversal in direction. In reversal movements, the one-target movement time advantage is either absent (Adam et al., 2000; Helsen et al., 2001) or a two-target movement time advantage emerges whereby movement times to the first target are faster in two compared to single target responses (Adam, van der Bruggen, & Bekkering, 1993) (for an exception see Rand et al., 1997). This two-target movement time advantage is due to integration at a more mechanical level since the transition of antagonist activity on the first element to agonist forces on the second element is energy efficient as there is no need to dampen mechanical oscillations at the end of the first element.

In a previous study, Khan et al. (2006) showed that the two-target movement time advantage was reduced when participants knew in advance that a two element response was required. It was proposed that when participants knew that a two element response was required, they programmed the first movement with a longer duration so that execution of the first element could be monitored online to enhance the integration between elements. In other words, increased executive control that mediated the transition between elements reduced the movement time benefits that were due to mechanical factors. Although a two-target movement time advantage was not revealed in the present study, it appears that similar executive control processes were operating during the integration of response elements. Movement times to the first target were longer in the two compared to single element responses in both the full and element precue conditions. Hence, similar to Khan et al., there was a move towards a one-target advantage when the number of elements was known in advance. Evidence that participants programmed movements to adopt a movement integration strategy was provided by the finding that time to peak velocity was greater in the two compared

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2 While this explanation is appropriate for the aiming movements employed in the present study, it is difficult to extend this interpretation to other response types. For example, in the study of Klapp (2003), reaction time was shown to increase as a function of number of syllables when responses consisted of the same syllable being repeated a required number of times. The degree of integration between syllables in such a response would be low and hence would likely not involve the specification of a complex motor program prior to stimulus presentation.
to single element responses when the number of elements was specified in advance. In the full precue condition, participants actually lowered peak velocities in the two compared to single target responses. Programming movements with slower durations may have provided sufficient time for participants to use visual feedback during execution of the first element to time the implementation of the reversal component (also see Ricker et al., 1999). Timing the reversal component is critical when there is a transition from antagonist to agonist activity as accuracy at the first target is determined by when the reversal component is implemented (Ketelaars, Khan, & Franks, 1999). As demonstrated by Khan et al., withdrawing attention away from this process disrupts integration between elements and results in reduced spatial accuracy at the end of the first element.

While the one-target advantage is due to interference at a cognitive level, the two-target advantage arises from the integration of muscular forces whereby the antagonist on the first element serves a dual purpose of also acting as the agonist on the second element. As we suggested, it appears that when participants were informed in advance that a two element response would be required, increased executive control was implemented to enhance the transition between elements. In the present study, the movement time costs associated with additional cognitive processes may have outweighed the movement time benefits associated with the integration of muscular forces for two reasons. First, movement amplitude was varied from trial to trial. In other studies that have revealed a two-target advantage (e.g., Adam et al., 1993), the amplitude of the movement has been fixed within a block of trials. This may have led to more consistency in the timing and amplitude of force pulses and hence a greater stability in the integration between elements on a mechanical level. Second, relatively small targets were employed in the present study. In the study of Khan et al. (2006), a two target movement time advantage was observed for aiming responses to targets sizes of 2 and 4 cm while line targets 0.1 cm in width were used in the present study. Past research has shown that a two target movement time advantage emerges when the accuracy demands at the first target are low but not when a high degree of accuracy is required at the first target (Adam et al., 1993). Supposedly, the transition of antagonist muscle forces to agonist activity is disrupted under high accuracy constraints by processes associated with monitoring accuracy levels at the first target (Adam et al., 1993).

Consistent with Fitt’s Law, movement times to the first target increased as a function of amplitude. Also, similar to other studies that have shown a direct relation between reaction time and index of difficulty (e.g., Lajoie & Franks, 1997; Sidaway, 1991), reaction time increased as a function of amplitude when the full response was precued. Interestingly, however, when the number of elements was not known prior to the stimulus, reaction time was not influenced by the amplitude of the movement. This finding may be a direct reflection of the nature of reversal movements. Since the first and second elements are highly integrated in reversal movements, the control of the first element depends heavily upon whether the response must be terminated at the first target or continued to the second target. Hence, information provided by the amplitude precue was perhaps only useful in programming responses if participants could prepare the pattern of muscle activity associated with either a single element or two element reversal response. This would again suggest that the pattern of muscle activity associated with reversal movements is prepared in advance of movement initiation, and online processes monitor and implement the reversal component during movement execution. It might be that the programming of movement amplitude is tied to the number of elements if the control of the first element depends strongly on whether a second element is required. For other types of sequential aiming movements that do not involve a reversal in direction, the programming of movement amplitude may not depend on whether or not a second element is required since the control of the two elements may be more independent.

In conclusion, the results of the present experiment revealed that reaction time increased as a function of the number of elements in a response when the number of elements was known prior to the stimulus. This was the case when the required response was fully specified prior to the stimulus or when the number of elements was known but other features of the response were not specified until stimulus presentation. These findings are consistent with dual process models of motor programming that account for the greater influence of number of elements on simple compared to choice reaction time (Klapp, 1995, 2003). We have suggested that when the number of elements is known in advance, a more complex pattern of muscle activity is prepared for multiple elements movements. Past research has demonstrated that the execution of early segments is influenced by the presence and properties of later segments (Adam et al., 1995; Aivar et al., 2005; Rand et al., 1997; Rand & Stelmach, 2000). Following from the work of Khan et al. (2006), the present study provides evidence that points to the influence of advance information on movement integration strategies. It appears that when the number of elements is known in advance, participants program movements to optimize the integration between response elements. This increased executive control leads to increases in reaction time and movement durations of the first element. These results add to our understanding of how advance information influences motor programming prior to stimulus presentation, during the reaction time interval and movement execution. Further work will

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3 Rand et al. (1997) also reported a one-target advantage for both extension and reversal movements in a study in which the direction of the second element, the amplitude and target size of the second target were manipulated in blocks of ten trials.
address the time course of preparatory processes during these time intervals.

References


