

MOTOR PREPARATION AND THE AUDITORY STARTLE RESPONSE

by

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A THESIS SUBMITTED IN PARTIAL FULFILMENT OF
THE REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

in

THE FACULTY OF GRADUATE STUDIES

(Human Kinetics)

THE UNIVERSITY OF BRITISH COLUMBIA

February 2008

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Abstract

Studies investigating human information processing have provided evidence that in some cases, movements can be prepared in advance. Although evidence for motor preparation has been shown at cortical and spinal levels, motor preparation at a subcortical level is not well described. One line of inquiry has involved the use of a startling acoustic stimulus (115-124 dB) that can act as an early trigger for pre-programmed actions in reaction time (RT) tasks. In light of this new research paradigm, the startle reflex may be used as a tool to investigate motor preparation. Here, six experiments were conducted that work towards the goals of understanding the mechanism of RT shortening due to startle, and motor preparation at a subcortical level.

The first section (2 experiments) of this dissertation provides evidence that when a motor action can be prepared in advance, it is pre-programmed and stored subcortically awaiting the normal cortical “go” signal. A startle appears to activate structures directly that are involved with the voluntary response channel leading to early triggering of the pre-programmed response, and dramatically reduced RT. In the current dissertation we investigated alternative mechanisms to explain startle RT facilitation, including the stimulus intensity effect, and a fast transcortical route, with results supporting the original subcortical storage hypothesis.

The second section (4 experiments) presents data which together provide insight into motor programming processes, and the circumstances under which a response is pre-programmed. For example, when the possibility of not having to make the response existed, a known response was not pre-programmed. Similarly, no pre-programming occurred when certainty existed regarding when to respond. However, while a previous

experiment showed that having to make a choice between several response alternatives precluded pre-programming, this dissertation shows that if possible response alternatives are not in conflict with one another, multiple responses can be prepared in parallel. Finally, the complexity of a response such as one involving multiple sequenced sub-components may limit the ability to pre-program in a simple RT task. Taken together, these results suggest that pre-programming is dependent on the task characteristics and appears to involve implementation of strategies to increase programming efficiency.

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Acknowledgements

I would like to thank all of those who have helped me along the way through their guidance, support, technical expertise, challenges, discussions, and friendship. Without all of you this accomplishment would not have been possible.

First and foremost, I would like to acknowledge the contributions of my graduate supervisor, Dr. Ian M. Franks. Dr Franks supported me and developed me from a rough undergraduate into a capable scientist, through his constant challenging, guidance and advice. I cannot imagine having a better graduate supervisor.

The contributions of my graduate committee members, Drs. Romeo Chua, Tim Inglis, and Dave Sanderson have similarly influenced my development. Their contributions to my intellectual growth will stay with me for good. Furthermore, I would like to thank all of them for their open-door policies and approachability.

I would like to thank all of the graduate students and staff that have become great friends throughout my time here. Without such great people, I would never have had the motivation to continue. Although the large number of people makes it impossible to list names, you all know who you are and I thank you for your support and friendship (especially Dana Maslovat, Erin Cressman, Mel Lam, Brendan Cameron, Nikki Hodges, Mike Garry, Mike Kahn, Katie Pauh, Julia Wilkes, Mel Roskell, Brynne Elliott, Karine Duval, and Paul Kennedy).

To my friends and family outside of school, thanks for putting up with me during this time. It will not be forgotten.

Finally I would like to thank some of the sources of my funding including: The University of British Columbia, The School of Human Kinetics, The Faculty of Graduate studies, The Faculty of Education, The Natural Sciences and Engineering Research Council of Canada (NSERC), and The Michael Smith Foundation for Health Research.

Co-Authorship Statement

The research program and experimental design for all of the included experiments was primarily the responsibility of me, Anthony N. Carlsen, with input and oversight by my thesis committee, consisting of Drs. Romeo Chua, David J. Sanderson, J. Timothy Inglis, and Ian M. Franks.

Data collection, and data analysis including experimental set-up, programming, participant debriefing, data reduction and statistical analysis was primarily completed by myself, Anthony N. Carlsen, with assistance from Chris J. Dakin (Experiments 1 & 3) and Ryu Ishimoto (Experiments 4, 5 & 6) in participant recruitment, carrying out the experimental protocol, and EMG marking.

Manuscript preparation for all of the included experiments was completed by me, Anthony N. Carlsen, with input and editorial contributions from my thesis committee, consisting of Drs. Romeo Chua, David J. Sanderson, J. Timothy Inglis, and Ian M. Franks.

1. General Introduction

The speed with which humans can react to external stimuli is remarkable from a lay-person's point of view. For example, in the 100m sprint at the Olympic Games, athletes regularly record reaction times (time between the stimulus and the response) of less than 0.2 seconds. However, it is precisely this delay in reacting that is of interest to researchers. Questions arise as to the nature of the processes occurring between the onset of a stimulus and the onset of a response. Donders (1868 / 1969) was one of the first to investigate these processes by using the "subtractive method." Three different tasks were devised to determine their effect on the duration of the reaction time (RT) processes. First was a simple reaction (Reaction A): the time between the onset of a single light until the pressing of a single button was determined. Secondly, a separate stimulus-response set was added requiring a choice between responses (Reaction B): one button was to be pressed with the left hand in response to a blue light and another button was to be pressed with the right hand in response to a red light. The third task was a go/no-go task (Reaction C), in which a single response was required (key press) but still involved two stimuli (blue light = press key, red light = do not press key). Donders (1868 / 1969) believed that the information processing stages were independent and serial. Using subtractive logic, he determined the time course of each process (e.g. Reaction B – Reaction A = time required to make a choice). In this way he argued that differences in RT between these tasks reflected differences in processing during various stages of the information processor. Through this research, Donders demonstrated that it was possible to manipulate tasks in such a way that the time taken by each of the information processing stages could be measured. These stages are commonly referred to as 1)

Stimulus Identification / Recognition; 2) Response Selection; and 3) Response Programming (Schmidt and Lee 2005).

Several lines of evidence have shown an effect on RT by manipulating the response programming stage of processing. For example, RT increases as the accuracy requirements of a task increase (Fitts and Peterson 1964; Sidaway et al. 1995). That is, in a manual aiming task, as the target size is decreased, RT increases. Similarly, as demonstrated by Henry and Rogers (1960), RT also varies as a function of the complexity of the movement, where movements of a higher complexity (more movement parts) required more time before the participant was able to react (see also Kasai and Seki 1992; Ketelaars et al. 1997). More recently, Ketelaars et al. (1997) have demonstrated that RTs for an elbow extension movement are shorter than RTs for an elbow extension-flexion movement. Similarly, Klapp (1996, 2003) found that a single button tap led to shorter RTs in a simple RT task than multiple taps.

Although initially it was thought that the information processing stages were serial in nature (e.g. Donders 1868/1969), several lines of experimentation have provided evidence that in some cases, the response programming stage (stage 3 above) can be partially or fully completed in advance of the experimental imperative stimulus (i.e. the “go” signal). For example, Klapp (1996, 2003) found that when the required response was known in advance (e.g. simple RT task), increasing the complexity of the action (e.g. the number of syllables in a word, or the duration of a keypress) without increasing the number of response components had no effect on simple RT. Klapp argued that when the response was known in advance, response programming could occur before stimulus onset, and thus the complexity of the response would have no effect on the RT. This was

in contrast to choice RT where these “more complex,” longer duration responses led to longer RTs. In this case, Klapp (2003) argued that because the appropriate response was not known until after the imperative stimulus (IS), programming had to occur during the RT interval, and therefore these effects of increased complexity were only revealed in a choice RT task.

Studies in which only *partial* advance information regarding the appropriate response was given during the RT task foreperiod provided further evidence that response programming can occur in advance. These studies make use of a paradigm called “the precue method” (Rosenbaum 1980), that has been used to try to determine the amount and nature of pre-programming that might occur during a special case of a choice RT (CRT) task: The precue method involves multiple potential stimuli and responses oriented along several movement dimensions (e.g. (A)rm , (D)irection, and/or (E)xtent). In this paradigm, no information, partial information, or full information regarding the upcoming response is provided by the warning signal. This is referred to as a “precue,” that provides information that renders one or more of these response dimensions (A, D, and/or E) certain. For example, the experimenter could have indicated that the upcoming movement would require the left arm. In this case, since the required arm was known, it was assumed that the participant could prepare “arm” in advance. Rosenbaum (1980) found that as more information was provided by the precue, RT became shorter. However, the RT benefit from each precue was not the same. Based on these findings, it was argued that the three parameters tended to be specified, or programmed, individually and in advance when possible (Rosenbaum 1980).

Further evidence that precues did allow advance programming comes from the Lateralized Readiness Potential literature. The Bereitschaftspotential or Readiness Potential (RP) is a measure of cortical activity derived from the electroencephalogram (EEG) that precedes voluntary movements. Similar cortical activity, called the contingent negative variation (CNV), is thought to reflect motor preparation in warned RT tasks. The amplitudes of both the RP and the CNV change as a function of the amount of advance information provided about the upcoming movement (Leuthold et al. 2004; MacKay and Bonnet 1990; Vidal et al. 1995). It was reasoned that measuring lateralized differences in the RP, known as the Lateralized Readiness Potential (LRP) during a precuing task might provide support for the parameter specification model as proposed by Rosenbaum (1980). As such, it was suggested that the temporal locus of the dimensional precue effects could be determined using the LRP onset (Osman et al. 1995). Because a foreperiod LRP can be elicited when hand is precued, it was inferred that the information was used in advance of the stimulus to activate the corresponding motor cortex, indicating advance preparation of the response hand (Osman et al. 1995, 2003). More evidence that precues allow advance programming came from measuring the time from LRP onset until response production when the response side was not precued. Specifically, it was found that the LRP-response interval was shorter when one-parameter (e.g. direction) was precued compared to zero-parameters precued, indicating that the processes occurring during this time (likely motor programming operations) were shortened. Since less motor programming time was required in the one-parameter precued conditions than the zero-parameters precued conditions, it was suggested that the

precue enabled partial advance preparation of the response (Osman et al. 1995; for a review see Leuthold et al. 2004).

Since responses *can* be programmed in advance of a IS, it was suggested that a loud startling stimulus could be used to directly elicit a pre-programmed response without the usual voluntary command. Using a reaction time paradigm, it was reported that premotor reaction time (time from stimulus presentation to EMG onset) was significantly reduced when participants were startled by an unexpected loud acoustic stimulus (130 dB) presented in conjunction with a visual “go” signal (Valls-Solé et al. 1999). Based on these findings, Valls-Solé et al. suggested that “the whole motor programme [could] be triggered [by the startle] without the typical command from the cerebral cortex” (1999 p.937). This conclusion was based on two results from the startle condition: First, premotor reaction time (PMT) observed was very short compared to a control (no startle) condition, and second, EMG activity was unmodified from this control condition. In the fastest reactions observed by Valls-Solé et al., PMT was 65 ms. In a typical RT paradigm, RTs of 180 ms are commonly observed in response to visual stimuli, while RTs of 140 ms or more are commonly observed in response to auditory stimuli (Brebner and Welford 1980). It was argued by Valls-Solé et al. (1999) that movements initiated in less than 65 ms (i.e. $PMT < 65$ ms) were unlikely to involve the cortex due to the fixed amounts of time needed for both transducing the auditory stimulus and for neural transmission. Thus they suggested that sufficient details of a prepared movement may have been stored in the brainstem and spinal centres so that it could be, in some cases, initiated subcortically and released early.

Since the EMG activity for wrist movements (flexion or extension) retained their characteristic triphasic profile through both control (no startle) and experimental (startle) trials, the prepared movement appeared to be elicited unaltered. Specifically, since the observed EMG patterns were unchanged, Valls-Solé et al. (1999) believed the observed response was not produced by an early startle reflex adding on to a later voluntary response. More evidence for this viewpoint was provided by Carlsen et al. (2004b), who showed that neither EMG patterns nor response kinematics were changed in startle-speeded responses compared to their control counterparts. In particular, although an accuracy component was required in a RT task involving an arm extension to fixed targets located at 20, 40, or 60 deg. of angular extension, no differences existed between the Startle and Control conditions in any of the measured kinematic variables. Furthermore, EMG analysis revealed that although the duration of the initial agonist burst and the timings between the bursts were different for all three target distances, there were no observed differences in these variables between the Startle and Control conditions. Thus, although the observed RT was significantly shorter in the presence of a startle, no modifications to the response kinematics or EMG patterns for any of the target distances were evident (Carlsen et al. 2004b). These data confirmed the argument that the response elicited by the startle at short latencies was the response that was prepared.

A simple RT task theoretically allows an individual to complete the response selection and response programming stages in advance of the IS. In contrast, response selection and response programming must occur *during* the RT interval in a choice RT paradigm. In order to confirm that only responses that are prepared in advance of the IS can be speeded by a startling stimulus, Carlsen et al. (2004a) presented a startle was

presented in both a simple and a choice RT task. Results showed that during a simple RT task, PMT was dramatically shortened when a startle was present. This result was consistent with previous studies that showed the response was likely pre-programmed in a simple RT task (e.g. Valls-Solé et al. 1999; Carlsen et al. 2004b). In contrast, however, a startle did not advance RT in situations in which the correct response had to be selected during the RT interval (choice RT). These results showed that the facilitatory effect of the startle during simple RT was not due to faster response propagation, and was more likely due to the involuntary triggering of a prepared response (Carlsen et al. 2004a).

It can be deduced from the Simple / Choice RT + Startle study described above (Carlsen et al. 2004a) that experiments using the startle paradigm can not only enable the investigation of the stream of information processing, but can also concurrently enable investigation into the nature of the observed “startle effect.” One explanation for the drastic RT decreases observed in response to a startle involves the triggering of a subcortically stored motor program (Valls-Solé et al. 1999; Carlsen et al. 2003b; Carlsen et al. 2004a, b). Alternative explanations, however, still exist. For example, one critique (see Carlsen et al. 2004b) of the current explanation involves the well documented “stimulus intensity effect” (Kohfeld 1969; Luce 1986; Woodworth 1938) which holds that RT decreases as the intensity of stimulus increases. It may be that startle speeding of RT is simply an extreme case of the stimulus intensity effect. This is the first of several questions that this dissertation aims to investigate (see Experiment 1).

This dissertation will elaborate on neuromotor preparation and response programming processes in various motor tasks in order to gain a better understanding of how humans prepare the motor system for upcoming actions. The startle method was

used to accomplish this goal and to further the empirical evidence concerning the use of a startle in motor tasks. Experiments 1 and 2 investigated whether the startle was in fact triggering a subcortically stored motor program, or if the observed results could be better explained through alternative means. Experiments 3 through 6 used the startle as a tool to investigate motor preparatory processes within an information processing framework. The six experiments contained in this dissertation are outlined below, while specific hypotheses are contained within each section.

1. Experiment 1 investigated the distinction between stimulus intensity-facilitated response time and startle-facilitated response time, thereby addressing one of the main critiques of the startle method (see above).
2. Experiment 2 was used to investigate whether movements that are thought to be cortically controlled via the corticospinal tract can be elicited by a startle. Specifically, can a finger-abduction movement be elicited directly by a startle?
3. Following on from the use of startle in a simple RT task and a choice RT task, Experiment 3 continued exploration of motor programming in a third type of RT task: the go / no-go task. This task is similar to choice RT, except that different stimuli specify whether or not to make a single predefined response.
4. Experiment 4 was designed to use the startle to help determine the extent and the nature of response pre-programming that occurs in a precuing RT paradigm, where a choice must be made between response alternatives but some part of the response is known and may be programmed in advance.

5. Experiment 5 used a startling stimulus to examine at what point in advance of a target a response was programmed within the framework of an anticipation-timing task (see Slater-Hammel 1960).
6. Finally, Experiment 6 investigated how response complexity affects motor programming. Specifically, it has been suggested in certain instances a response can be preprogrammed, while in others it cannot (e.g. Klapp, 1996, 2003). Thus, Experiment 6 looked at whether a more complex response (single component vs. multiple components) could be triggered early by startle in a similar way to a less complex response.

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2. Experiment 1

Startle Produces Early Response Latencies that are Distinct from Stimulus Intensity Effects

A version of this chapter has been published in Experimental Brain Research:

Carlsen AN, Dakin CJ Chua R Franks IM (2007) Startle produces early response latencies that are distinct from stimulus intensity effects. Exp Brain Res 176:199 – 205.

Introduction

The startle response is characterized by a stereotypical pattern of muscle activity and can be elicited by a loud acoustic stimulus (Davis 1984). Recently, a startling stimulus has been used as the “go” signal in reaction time experiments. An interesting effect of this method has been that when participants were startled, the intended movement was initiated significantly earlier in comparison to voluntary initiation (Carlsen et al. 2004b; Valls-Solé et al. 1999). Because of the extremely short response latencies reported, it was argued that the startle acted as an early trigger for the prepared response. Two lines of evidence support the notion of a startle-elicited response. First, the response-related electromyographic (EMG) activation pattern (e.g. Wadman et al. 1979) was similar in both burst duration and timing whether or not participants performed the task in the presence of the startling stimulus (Carlsen et al. 2004b; Valls-Solé et al. 1999). Second, task accuracy was maintained during the startle-elicited response (Carlsen et al. 2004b). These observations indicated that the intended prepared response had been triggered and that it was not simply a later voluntary response superimposed upon an early startle reflex (Seigmund et al. 2001). For this to occur, it was suggested that the prepared response might be held in readiness in subcortical structures that mediate the startle response (Carlsen et al. 2004b; Valls-Solé et al. 1999).

However, there have been varied reports on the loudness required for a stimulus to elicit a startle response, and there exists a point of contention over what actually constitutes a “startle response.” The most widely used response indicator of startle is EMG activity in the orbicularis oculi (OOc) muscle (blink response, Blumenthal et al. 2005; Davis 1984). However, the physiologically separate (non-startle) auditory blink

response can still be elicited following startle habituation, making OOc an ambiguous indicator of startle (Brown et al. 1991). Although a startle blink response has been reported to occur due to acoustic stimuli as low as 85 dB, many studies have utilized stimuli between 90 dB and 130 dB (Blumenthal 1996; Brown et al. 1991). Yet, most of these studies have not attempted to distinguish between startle and non-startle blinks. Thus it was suggested that activity in the sternocleidomastoid (SCM) muscle may be a better indicator of startle as it is among the last indicators to become habituated after repeated exposure to the startling stimulus, and it is less equivocal in nature (Brown et al. 1991; Carlsen et al. 2004a).

The purpose of the current investigation was to determine the effect of stimulus intensity on: 1. The presence or absence of startle response indicators, and 2. Voluntary reaction time (RT). Since increases in stimulus intensity have also been associated with decreased RTs for over a century (see Woodworth 1938, p. 318), it has been suggested that the observed startle-associated decrease in RT may be due to stimulus intensity effects, not subcortical triggering (Carlsen et al. 2004b). We designed this experiment to determine if RT simply declined in a linear fashion with increasing stimulus intensity, or if there was a point at which a more dramatic decrease in RT was associated with a startle response. In other words, is the RT shortening observed in the presence of a startle more than an intensity effect alone?

Method

Participants

Ten participants (7F, 3M; mean age 26 +/- 8 years) with no obvious upper body abnormalities, or sensory or motor dysfunctions volunteered to participate in the study.

All participants reported normal hearing. All participants gave written informed consent, and the study was conducted in accordance with the ethical guidelines set by the University of British Columbia (see Appendix A).

Apparatus and Task

The participants sat in a height-adjustable chair outfitted with an automobile racing harness (Racer Components Inc.) in order to constrain any movement to the wrist joint. The right arm was secured, in a semi-prone position with the palm facing inward, to a custom-made aluminium wrist manipulandum that moved in the transverse plane with an axis of rotation at the wrist joint. The hand was secured in the hand support portion of the manipulandum to restrict any unwanted movement with the wrist joint directly in line with the axis of rotation and the manipulandum arm. The manipulandum was oriented at an angle of 15 degrees to the right of the body midline, as this has been found to be a more comfortable position than orienting the manipulandum parallel to the body midline. The starting position (20 degrees of flexion from neutral) was indicated by a mechanical stop. Prior to testing, the arm / manipulandum unit was obscured from view so that direct visual feedback was not available.

The task was to perform a 20 deg right wrist extension movement to a fixed target as quickly and as accurately as possible following an auditory stimulus. Participants were offered a monetary bonus for fast reactions consisting of 1 cent per ms faster than either their previous best RT or 120 ms.

Instrumentation and Stimuli

The warning tone consisted of three short beeps (100 ms, 1000 Hz, 80 dB each, separated by 500ms) generated by the computer using a 16 bit sound card (Creative SoundBlaster 16®) and standard computer speakers (Juster® sp-691n). A fixed foreperiod of 2.5 sec. spanned the time between the end of the warning tone and the imperative stimulus. A computer program generated the trial imperative stimuli consisting of a narrow band noise pulse (1 kHz, 40ms duration). The signal was amplified and presented via a loudspeaker (<1 ms rise time) placed directly behind the head of the participant. The intensity of the auditory “go” signal (imperative stimulus) ranged from 83 dB to 123 dB in 10 dB increments (resulting in 5 stimulus intensity levels) measured using a sound level meter (Cirrus Research model CR:252B) at a distance of 30 cm from the loudspeaker (approximately the distance to the ears of the participant).

Each participant performed 30 trials at 83 dB (control) and 5 trials at each of the other four stimulus intensities which were randomized between trials. Four catch trials (no imperative stimulus) were also included to discourage anticipation.

Surface Electromyographic (EMG) data were collected from the muscle belly of the following superficial muscles: right flexor carpi radialis (FCR), right extensor carpi radialis longus (ECR), left orbicularis oculi (OOc), and left sternocleidomastiod (SCM) muscles using bipolar preamplified Ag/AgCl surface electrodes (Therapeutics Unlimited). 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 radial styloid process. EMG data were amplified onsite and the electrodes were

connected via shielded cabling to an external amplifier system (Therapeutics Unlimited Inc. Model 544). Wrist angular displacement data were collected using a potentiometer attached to the pivot point of the manipulandum. All data were digitally sampled at 1 kHz (National Instruments® PCI-6023E) using a customized program written with LabVIEW® software (National Instruments Inc.).

Target and Feedback

The target was a fixed point in space located at 20 degrees of angular displacement into extension with respect to the right wrist's starting position. A computer screen placed directly in front of the participant provided real time position feedback during trials by representing the position of the manipulandum with a vertical marker line (1 cm tall) on the screen. The marker's movement corresponded directly to movement of the manipulandum and only moved in the horizontal plane. The starting position of the marker corresponded to it being stationary 5 cm from the left edge of the computer screen. The target was represented by a blue target line (1 cm tall), 10 cm from the right edge of the screen. After each trial, feedback information including displacement error at the end of the initial impulse (deg), and reaction time (ms) were displayed on the same computer monitor display.

Training

Participants were allowed to practice the task prior to testing to familiarize themselves with the task and equipment. The participants were instructed that they would first hear a warning tone, followed by a fixed foreperiod (2500 ms, duration unknown to the participants), and finally a “go” tone (imperative stimulus). Instructions emphasised

fast reaction times and fast movement times, as well as minimising target error.

Participants were also instructed that the loudness of the stimulus would be variable.

Participants received blocks of 10 practice trials, and were deemed to have reached an adequate level of task competence to start the testing trials when they could successfully hit the target (± 5 deg) 4 out of the last 5 practice trials in a block. No participants performed more than two practice blocks.

Data reduction and Analysis

Movement onset was defined as the first point of a change of more than 0.2 deg of angular displacement from the starting position following the stimulus. Peak displacement was determined by identifying the point at which velocity returned to zero following movement onset. The final position of the movement was defined as the first point at which angular velocity remained below 8 deg/sec for at least 150 ms. Movement time was defined as the time (in ms) between movement onset and final position.

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 activity increased to more than 2 standard deviations above baseline (mean of 50 ms of EMG activity preceding onset). Onset was then verified by visually locating and manually adjusting the onset mark to the point at which the activity first increased. This method allowed for correction of errors due to the strictness of the algorithm. Premotor RT (PMT) was defined as EMG onset in the ECR muscle. EMG offsets were marked in a similar fashion, with the activity between EMG onset and EMG offset being defined as a distinct burst. PMTs greater than 1000 ms and less than 40 ms

were discarded if observed in the lowest intensity (83 dB) condition. These comprised less than 1% of trials. In all other conditions, no trials were discarded, however, none fell outside these ranges.

Peak EMG amplitudes in the startle response indicators were defined as the largest EMG amplitude, rectified and filtered with a 25 Hz lowpass elliptic filter, recorded within an interval of 100 ms following EMG burst onset. To normalise the EMG for comparison between participants, EMG burst amplitudes were expressed as a percentage of the mean peak EMG amplitude for each respective muscle in the 124 dB condition for each participant.

Trials were separated by stimulus dB intensity, as well as by whether or not an EMG burst was present in startle response indicators (No response indicator, OOc only, or SCM+OOc). Since SCM did not occur without accompanying OOc activity, this grouping is called SCM. Startle response indicators were classified as startle if onsets occurred in less than 120 ms following stimulus onset.

Integrated EMG values for OOc were computed by numerically integrating the normalized and rectified EMG for each participant. First the EMG was rectified, amplitude and baseline normalized, and onset normalized (aligned to a common onset). These values were numerically integrated (ms time base) over a period of 160 ms from the common onset (0 ms). Subsets were taken consisting of 0-60 ms (to capture the entirety of the first burst observed in OOc only conditions) and 60-160 ms (to quantify any further activity).

Statistical Analyses

Dependent measures were analyzed where appropriate using 5(dB level) x 3(indicator) repeated measures analysis of variance (ANOVA), to determine if differences existed between trials. Differences with a probability of less than .05 were considered to be significant. Tukey's Honestly Significant Difference (HSD) post-hoc tests as well as simple effects tests were administered to determine the locus of the differences.

Results

Voluntary Response

All participants were accurate in performing the required 20 deg movement. One-way ANOVAs showed no significant differences in either final position, $F(4,36) = 1.53$, $p = .347$, or movement time, $F(4,36) = .861$, $p = .497$, across all stimulus intensities.

Premotor RT (PMT) was compared between stimulus dB intensities as well as between startle response indicators using a two-factor ANOVA. Because for some participants, no responses were observed in certain conditions (e.g. OOc only at 113 dB), for statistical analysis, missing cells were filled with mean values for that condition. Thus because true variability is decreased increasing the possibility of Type 1 error, main effects were only considered significant if $p < .01$. Results are presented in Figure 2.1. Significant main effects on PMT were found for both indicator, $F(2,18) = 54.82$, $p < .001$, and dB level, $F(4,36) = 4.81$, $p = .003$, and a significant interaction was found, $F(8,72) = 8.51$, $p < .001$. Post-hoc tests revealed that when SCM was present, PMT was significantly shorter than if no response indicator (NRI) was present regardless of dB

level ($p < .05$). Furthermore, when SCM was present, PMT was significantly shorter than if *only* OOc was present at both 93 dB and 103 dB ($p < .05$). Finally, when only OOc was present RT was significantly shorter than if NRI was observed only at the two highest dB levels ($p < .05$).

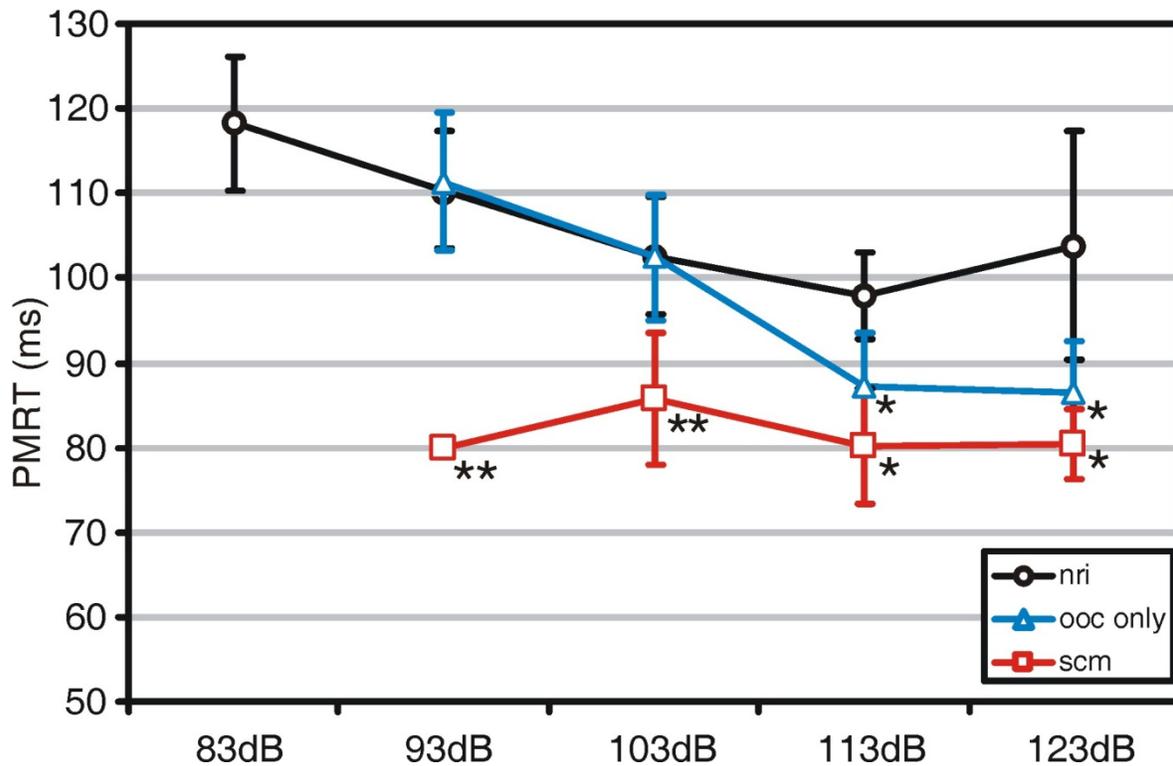


Figure 2.1 Mean (\pm SD) premotor reaction time (PMT) from stimulus to EMG onset as a function of stimulus intensity in decibels (dB) and the presence of startle response indicators. Black circles are means of PMTs for trials in which neither orbicularis oculi (OOc) nor sternocleidomastoid (SCM) were observed (no response indicator, nri). Blue triangles are PMTs for trials in which OOc was observed but SCM was not observed. Red squares are trials in which SCM was observed. * = significant difference from nri. ** = significant difference from nri and OOc only.

Blink Response

We sought to assess whether differences existed in the profile of the OOc EMG based on the presence or absence of SCM activity. This was due to the stronger apparent association between short RTs and SCM activity, as compared to OOc activity. An example of the ensemble average of rectified, baseline and amplitude normalized OOc EMG activity from a single participant is presented in Figure 2.2a. When SCM was present, OOc activity included a larger, longer secondary component that was absent when SCM was also absent. This pattern was analyzed across participants by comparing numerically integrated amplitude-normalized OOc EMG from onset for 160 ms (Figure 2.2b). The integral values were collapsed across stimulus intensity since no main effect was observed ($p = .224$). A one-way ANOVA analyzing Integrated EMG (IEMG) between “OOc only” and “SCM present” groups indicated that IEMG was significantly larger across participants, $F(1,7) = 19.231$, $p = 0.003$, when SCM was present ($29.64 \pm 17.70 \% \cdot \text{ms}$) compared to when SCM was absent ($7.68 \pm 7.66 \% \cdot \text{ms}$). Furthermore, the proportion of the integrated value contributed by the time period from 60–160 ms following onset (representing the second component) was much smaller when SCM was absent (27.2 %) than when SCM was present (53.2%) (Figure 2.2b).

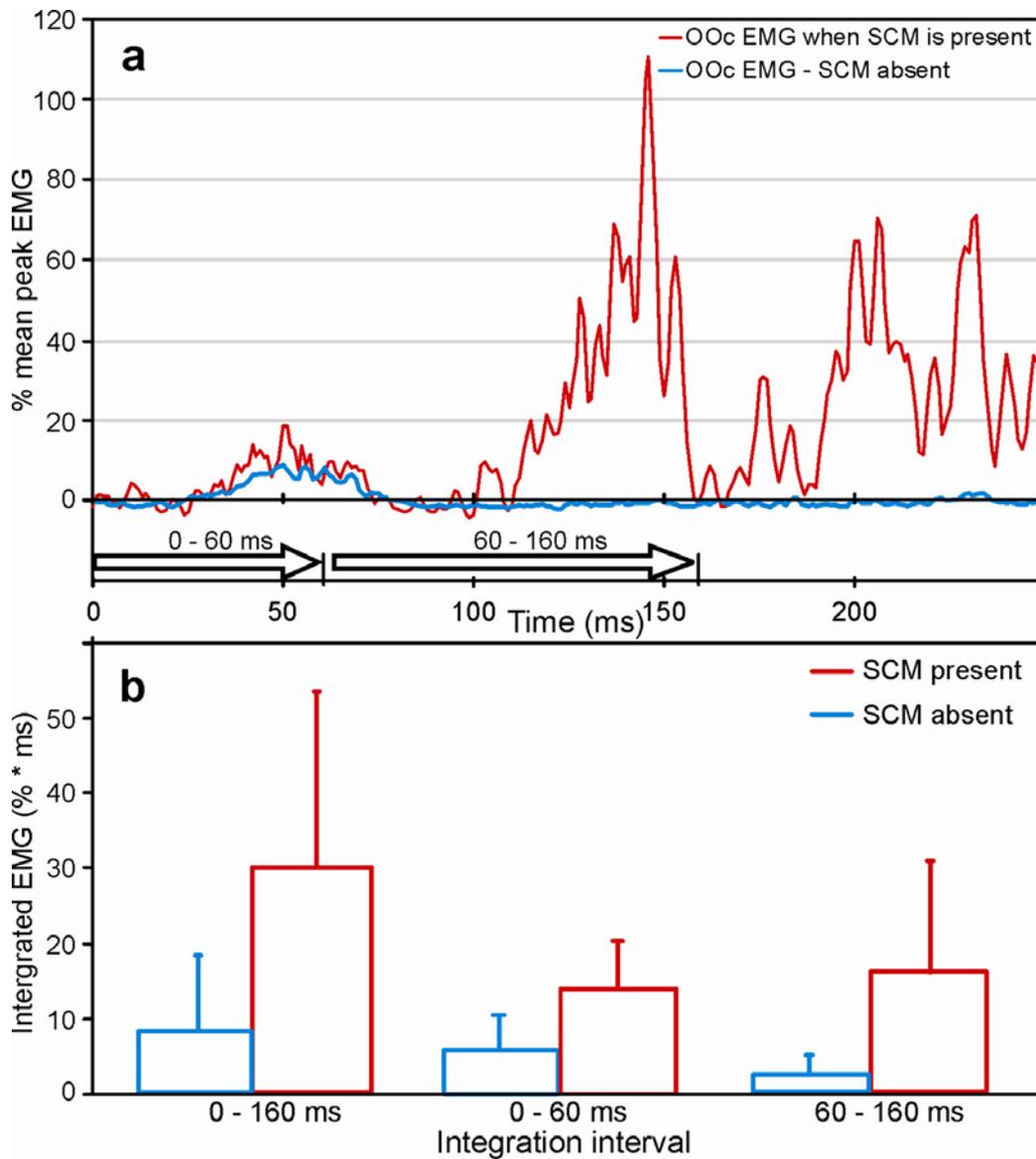


Figure 2.2 Individual (a) and group (b) Orbicularis Oculi (OOc) EMG data expressed by whether sternocleidomastoid (SCM) activity was either detected (red) or not (blue). (a): Examples are baseline and onset normalized ensemble average of rectified OOc activity from a single participant expressed as a percentage of the participant's mean peak EMG. (b): Mean integrated EMG (IEMG) values from OOc by time over which the integration was performed. Group IEMG values (\pm SD) for the time period of 0 – 160 ms, 0 – 60 ms, and 60 – 160 ms following OOc onset.

Probability of Observing Startle Indicators

A significant interaction was found using a two way ANOVA between stimulus intensity and the percentage of trials exhibiting startle indicators, $F(8,72) = 19.857$, $p < .001$ (Figure 2.3). Specifically, at 83 dB no activity was observed in either OOc or SCM (i.e. NRI). However, SCM activity (which was always accompanied by OOc activity) was detected in 2% of trials at 93 dB and increased with increasing dB level, whereas trials in which neither OOc nor SCM were detected decreased with increasing stimulus intensity. Post hoc analysis of the interaction showed that the only significant difference in the percentage of trials in which *only* OOc activity was detected was between 83 dB and 103 dB ($p < .05$), indicating that at 103 dB the probability of observing OOc without SCM was greatest.

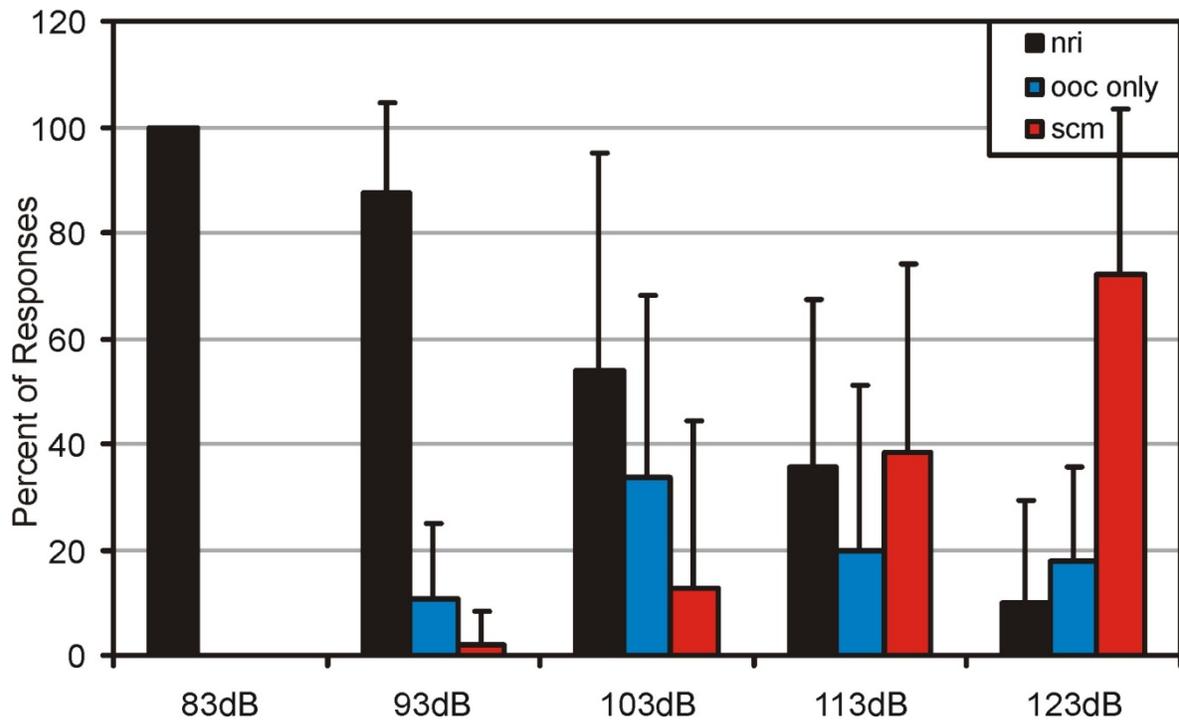


Figure 2.3 Percentage (+/- SD) of trials in which the startle indicators were observed.

Black bars represent percentage of trials in which neither sternocleidomastoid (SCM) nor orbicularis oculi (OOc) activity was observed (nri). Blue bars represent the percentage of trials in which OOc activity was observed but *not* SCM. Red bars represent the percentage of trials in which SCM activity was observed.

Discussion

Previous investigations have shown that PMT is considerably decreased when a startling acoustic stimulus is used as the “go” signal during a RT task (Carlsen et al. 2003, 2004a,b; Valls-Solé et al. 1999), whereas the characteristics of the movement and the EMG profiles are unaffected (Carlsen et al. 2004b). These results have been explained using a subcortical triggering hypothesis. It has been suggested, however, that the RT decrease is simply an extreme case of the well documented “stimulus-intensity effect” (Kohfeld 1969; Luce 1986; Woodworth 1938). Results were unequivocal: when a SCM (startle) response was detected, RT was significantly shorter than when no startle response was elicited, regardless of the intensity of the imperative stimulus.

Reaction time results are displayed in Figure 2.1. When no startle activity (neither OOc nor SCM) was present, premotor RT decreased steadily with stimulus intensity, and reached asymptote at 113 dB. This finding confirms a “stimulus intensity effect” observed by early researchers (see Woodworth 1938) and is thought to occur because sensory and perceptual processing are substantially faster for more intense physical stimuli (Levick 1973). However, when startle SCM activity was observed, RT was significantly shortened for *all* dB levels above control indicating that the startle facilitated responses are different than stimulus intensity facilitated responses.

Although increases in stimulus intensity (in the absence of a startle response) resulted in reduction in RT (Figure 2.1, black circles), there is no evidence to suggest that the information processing pathways for the stimulus were changed. However, due to the extremely short RT latencies observed under startle conditions (Figure 2.1, red squares), it has been suggested that the startle may act upon a different pathway to trigger the

prepared response directly (Carlsen et al. 2004b; Valls-Solé et al. 1999). Specifically, it was argued that if the required response could be specified in advance, it may be possible to store the response subcortically for later voluntary triggering. This hypothesis was tested previously using a simple / choice RT experiment, with results showing that if a response could be prepared in advance (Simple RT) the response was triggered early by startle. However, no RT differences were seen due to startle in a Choice RT condition, when the response was specified following the stimulus (Carlsen et al. 2004a). Thus it appears that a response was triggered by startle only if it was known (and presumably prepared) in advance.

If a response could be specified in advance it may be possible to alleviate cortical demand by offloading sufficient detail of a motor program to a holding area. Thus the only information processing requirement would be detection of the imperative stimulus and subsequent triggering of the response. One possible candidate for such motor program storage is the midbrain reticular formation. This is because it plays an important role in both the involuntary startle response (Yeomans and Frankland 1996) as well as mediating many types of motor output (Rothwell et al. 2002). If this were the case, it may be possible to trigger the motor program in the absence of the normal cortical trigger if some event caused adequate activation of these subcortical storage structures. We suggest that when SCM activity was observed, there was adequate activation to trigger a response in the centres that mediate the acoustic startle response, but additionally, it appears to also be adequate to trigger a stored motor program. The data we have provided merely associates the presence of SCM and decreased RTs, and although separate pathways for

the triggering of the action and triggering the startle response cannot be ruled out, it appears likely that they are related.

It should be mentioned that the level of motor preparation may play a role in the triggering of a response by startle. For example, lower levels of preparation appear to result in an inability of the stimulus to trigger the response directly, as well as startle response habituation (see Carlsen et al., 2003). Thus a high level of preparation is a requirement of this paradigm. However, we feel that the level of preparation was adequately controlled by having all participants maximally prepared. This was accomplished by having participants in a stable environment, with specific instructions to prepare the movement in advance, and by offering a monetary bonus.

Detecting a startle response is thus of paramount importance when investigating the effect of stimulus intensity on RT. Many previous studies have employed the blink reflex (evidenced by EMG activity in OOc) as an indication that a startle response occurred (Blumenthal et al. 2005; Davis 1984). However, some evidence suggests that OOc may not be a clear indicator of startle. For example, Brown et al. (1991) noted that following startle habituation, an early blink response was nonetheless elicited by a loud stimulus. It was argued that the early OOc EMG component was not part of the generalized startle reflex, and reflected a physiologically separate (non-startle) auditory blink reflex (Brown et al. 1991). Our data show a similar single / two-component OOc EMG pattern dissociation (Figure 2.2a) when trials were separated based on whether or not EMG activity was also detected in SCM. These results indicate that OOc activity alone was *qualitatively* different than OOc activity when SCM was also evident. Integrated EMG analysis indicates that there was substantially more OOc EMG activity

when SCM was also detected (Figure 2.2b). Together, these data suggest that OOc was both qualitatively and quantitatively different depending on the presence of SCM, and that OOc activity detected in the absence of SCM was different and not necessarily indicative of a startle response. Thus, OOc may not be the best indicator of startle as has been previously suggested (Blumenthal et al. 2005).

In addition to having a different EMG profile, OOc activity alone (SCM absent) was not consistently associated with shorter RTs across the range of intensities as was SCM activity (Figure 2.1, yellow triangles). At lower intensity stimulus levels (93 dB, 103 dB), RT was no different whether or not OOc was detected. However, even at these low levels, if SCM was detected, RT was shortened (Figure 2.1, red squares). At the two highest stimulus intensities RT was significantly shorter when OOc alone was detected compared to no startle activity, however, the proportion of trials in which OOc alone was detected was very low at the two highest stimulus intensities (Figure 2.3).

The largest proportion of trials in which SCM activity was observed was, unsurprisingly, at the highest stimulus intensity. This result agrees well with previous startle studies that have shown larger startle response amplitudes in response to higher intensity stimuli (Blumenthal 1996; Yeomans and Frankland 1996). Additionally, the proportion of trials in which SCM activity was observed decreased along with dB level (Figure 2.3). Conversely, the proportion of trials in which no startle response was observed decreased steadily up to the highest intensity. The proportion of trials in which blink (OOc) activity was observed alone, however, exhibited a somewhat different pattern. It appears that the middle intensities were sufficient to elicit a greater proportion of non-startle blinks, while at the higher intensities a greater proportion of trials resulted

in a SCM response. Thus, in order to have the highest probability of eliciting a SCM (startle) response in experiments in which the effect of a startle is being examined, the highest stimulus intensity should be used. However, great care should be taken to select an intensity that elicits a startle without risk of damage to the auditory system (see NIOSH 1998).

In summary, several conclusions can be drawn from the preceding study: First, the facilitation of voluntary reactions by startle is different than that brought about by increasing stimulus intensity. This is because when SCM startle activity was observed, PMT was significantly shortened to approximately 80 ms irrespective of stimulus intensity. Secondly, the probability of observing SCM activity increased with stimulus intensity, leading to an increased number of observations of consistently short PMT's with increasing dB level. Third, when OOc was observed without the presence of SCM, PMT observed were not different from simple intensity effects except at the highest intensities (when OOc alone was rarely observed, Figure 2.3). Fourth, the EMG of OOc when observed alone was both qualitatively and quantitatively different compared to when it was paired with SCM indicating the presence of a distinct response. Thus it appears that the stronger the startle response that is evoked (i.e. SCM vs. OOc only), the greater will be the shortening of RT. As such, OOc EMG, currently the most employed startle indicator (Blumenthal et al. 2005; Brown et al. 1991), may not always be the best indicator of a strong startle response. EMG from SCM may be a more appropriate indicator of startle than OOc, due to its association with a separate RT distribution, and its less ambiguous nature.

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3. Experiment 2

Movements Controlled Through Corticospinal Connections are not Elicited Early by Startle

A version of this chapter has been submitted for publication:

Carlsen AN, Chua R, Inglis JT, Sanderson DJ, Franks IM (in review) Movements controlled through corticospinal connections are not elicited early by startle.

Introduction

Recent studies employing a reaction time (RT) paradigm, have reported that premotor RT (time from stimulus presentation to EMG onset) in voluntary aiming tasks was substantially shortened when an unexpected loud acoustic stimulus (130 dB) was presented along with the usual “go” signal (Valls-Solé et al. 1995, 1999). Based on these findings, it was suggested that a loud startling stimulus could be used to directly elicit a pre-programmed response without the usual voluntary command. Specifically, Valls-Solé et al. stated that “the whole motor programme [could] be triggered [by the startle] without the typical command from the cerebral cortex” (1999 p.937). This statement was mainly supported by the drastic nature of the RT decrease observed. That is, premotor RT (PMT) was very short compared to a control (no startle) condition. In the fastest reactions, PMT was 65 ms (Valls-Solé et al. 1999). In contrast, RTs of 180 ms are normally observed in response to visual stimuli, while RTs of 140 ms or more are commonly observed in response to acoustic stimuli (Brebner and Welford 1980). Valls-Solé et al. (1999) argued that because of the fixed amounts of time needed both to convert the acoustic stimulus to neural signals and for neural transmission, it was unlikely that cortical loops were involved in the initiation of movements in which PMT was less than 65 ms. Thus they suggested that sufficient details of a prepared movement may have been stored subcortically, possibly in the brainstem and spinal centres that were accessible to the startle volley, so that in some cases it could be triggered early. Several later experiments replicated and extended these findings (e.g. Carlsen et al. 2003a, b, 2007; Castellote et al. 2007; Cressman et al. 2006; MacKinnon et al. 2007; Seigmund et al. 2001). For example, it was found that response kinematics and EMG patterns are unchanged between control

and startle elicited movements (Carlsen et al. 2004b), and that the paradigm can be extended to different effectors and movement types such as saccades (Castellote et al. 2007) and anticipatory postural adjustments (MacKinnon et al. 2007).

The defining requirement for a response to be elicited by a startle appears to be pre-programming. That is, in order for a startle to elicit a movement at short latencies it must have been prepared in advance. When a startle was presented in a choice RT paradigm, it was found that PMT was unaffected by the startle. This indicated that the RT shortening effect of startle was not simply due to increased neural excitability allowing for faster response transmission, since a similar speeding effect would be observed whether or not a response could be pre-programmed. The response was speeded by a startle only when the required action was certain beforehand (i.e. a simple RT task, see Carlsen et al. 2004a). Although this result supports the suggestion that a stored program is triggered early by a startle, it does not necessitate subcortical program storage (e.g. Carlsen et al. 2004b; Valls-Solé et al. 1999) since it cannot rule out an undescribed, fast transcortical route.

While it has been traditionally thought that corticospinal connections are extremely important in the control of individual finger movements, recent studies indicate that some reticulospinal connections with distal finger muscles exist, and modulate their activity with movements of the finger (Baker and Riddle 2007; Soteropoulos et al. 2007). These reticulospinal connections, however, are seen less frequently than corticospinal connections (Baker and Riddle 2007), and thus may be less functionally effective. This is evidenced by earlier studies showing that following permanent lesions of the corticospinal tract, monkeys were unable to produce individual finger movements for

tasks such as eating and grooming, although they recovered the ability to use more proximal muscles for climbing and walking (Lawrence and Kuypers 1968). A similar albeit more variable, level of fine finger control deficit has been observed in humans following stroke (e.g. Carroll 1965; Wade et al. 1983). More recently, deficits in fine finger control have also been shown in monkeys through reversible chemical inactivation of primary motor cortex (Brochier et al. 1999).

The aim of the current experiment was to determine if a startle acts to shorten RT in a finger movement (abduction of the index finger) that is thought to be strongly mediated by corticospinal connections. It was hypothesised that if this finger movement were speeded by a startle, then the startle effect likely includes a transcortical component. If, however, the movement was not speeded by startle, then it would support the suggestion that for other types of movements (e.g. arm extension, see Carlsen et al. 2004b), motor programs can be stored subcortically, and that the startle can act to trigger pre-programmed movements without the involvement of the cortex.

Method

Participants

Ten participants (7M, 3F; age 23 +/- 5 years) with no obvious upper body abnormalities, or sensory or motor dysfunctions volunteered to participate in the study. All participants gave written informed consent, and the study was conducted in accordance with the ethical guidelines set by the University of British Columbia (see Appendix A).

Apparatus and Task

Participants performed two tasks on separate days. These will be referred to as the *finger task* and the *arm task*.

For the finger movement task, participants sat in a height-adjustable chair with their right arm secured to a table pointing forward and in a semi-pronated position. The arm was positioned so that the shoulder was both flexed and abducted approximately 30 deg with the elbow flexed at 30 deg. The hand was also secured to the table using a Velcro strip attached to a clip and passing around fingers 3-5 which were bent 90 deg at the proximal interphalangeal joint leaving the index finger (digitus II) free to move. A simple contact switch requiring 0.04 N to close (i.e. simply resting the finger in the switch was sufficient to close it) was placed under the end of the outstretched index finger on the medial surface so that upwards movement (abduction) of the index finger opened the switch (see Figure 3.1). The finger movement task was a rapid finger abduction which was just sufficient to open the switch using only the finger muscles, following an acoustic stimulus.

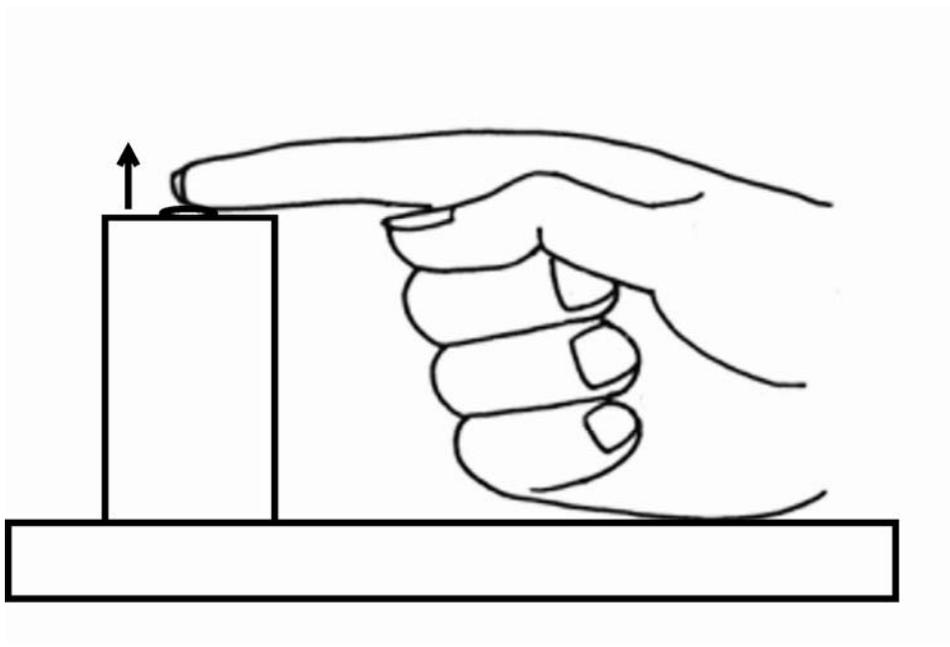


Figure 3.1 Illustration of the finger movement task. The right hand was placed with the index finger extended and relaxed, resting on a switch. Participants were instructed to make a rapid finger abduction movement in the upward direction (indicated by the arrow) following the acoustic stimulus.

For the arm task, participants sat in a height-adjustable chair outfitted with an automobile racing harness (Racer Components Inc.) in order to constrain any movement to the right elbow joint. The right arm was secured, in a pronated position with the palm down, to a custom-made aluminium manipulandum that moved in the transverse plane with an axis of rotation at the elbow. The starting position (90 degrees of flexion at the elbow with the shoulder flexed 30 degrees) was indicated by a mechanical stop. Participants were instructed to perform a 20 deg arm extension movement to a fixed target as quickly and as accurately as possible following an acoustic stimulus. For both tasks participants were offered a monetary bonus for fast reactions.

Instrumentation and Stimuli

Trials started with a warning consisting of a short acoustic tone (100 ms, 300 Hz, 80 dB) generated by the computer using a 16 bit sound card (Creative SoundBlaster 16®) and standard computer speakers (Juster® sp-691n). A variable foreperiod of 2 - 3 sec. spanned the time between the end of the warning tone and the imperative stimulus. A computer program then generated the imperative stimulus consisting of a narrow band noise pulse (1 kHz, 40ms duration). The signal was amplified and presented via a loudspeaker (<1 ms rise time) placed directly behind the head of the participant. The intensity of the acoustic “go” signal (imperative stimulus) was either 82 dB (control trials) or 115 dB (startle trials), and was measured using a sound level meter (Cirrus Research, model CR: 252B) at a distance of 30 cm from the loudspeaker (approximately the distance to the ears of the participant).

It was previously shown that 124 dB was the most effective intensity for eliciting a startle response (i.e. EMG activity in the sternocleidomastiod muscle) and startle RT

facilitation in the greatest proportion of trials. In contrast, lower intensities resulted in a higher proportion of trials in which a startle response was not observed. Although RT was decreased in non startle trials, it was shown that when a startle response was observed, there was an associated further dramatic decrease in premotor RT to 80 ms irrespective of stimulus intensity (Carlsen et al. 2007). Here we used 115 dB so that several startled (SCM activity present) and non-startled (no SCM activity) loud (115 dB stimulus) trials would be achieved from each participant. This was done in order to control for stimulus intensity facilitation (e.g. Woodworth 1938, p.318) where increases in intensity are associated with decreases in RT.

Each participant performed 75 trials in each of the 2 tasks, comprised of 57 control, 12 startle, and 6 catch (no acoustic imperative stimulus) trials. Catch trials were included to discourage false starts. Startle trials and catch trials occurred randomly amongst the control trials with the stipulation that no 2 consecutive trials were startle trials, and no startles occurred within the first 5 trials. The approximate trial to trial interval was 10s, although this varied due to the random foreperiod (see above).

For the arm movement task, surface Electromyographic (EMG) data were collected from the right elbow prime movers: the long head of the biceps brachii (BIC), and the lateral head of triceps brachii (TRI), as well as from the startle response indicator sternocleidomastoid (SCM). For the finger task, EMG data were collected from the first dorsal interosseous (FDI, primary index finger abductor), as well as from SCM. The recording sites were prepared and cleansed in order to decrease electrical impedance and then bipolar preamplified Ag/AgCl surface EMG electrodes were attached in the middle of the muscle bellies parallel to the line of force of the muscles. These electrodes were

connected via shielded cabling to an external amplifier system (Therapeutics Unlimited Inc., model 544). A grounding electrode was placed on the participant's left radial styloid process. Arm angular displacement data in the arm task was collected using a potentiometer attached to the pivot point of the manipulandum. Time of initiation of finger displacement in the finger task was monitored using the contact switch described above. All raw data were digitally sampled for 2 sec at 1 kHz (National Instruments® PCI-6023E) using a personal computer running a customized program written with LabVIEW® software (National Instruments Inc.). Data collection was automatically initiated 500 ms prior to the imperative stimulus.

Target and Feedback

The target for the arm task was a fixed point in space located at 20 degrees of angular displacement into extension with respect to the right arm's starting position. A computer screen placed directly in front of the participant provided real time position feedback. The position of the manipulandum was represented with a yellow marker line (1 cm tall) whose movement in the horizontal plane corresponded directly to movement of the manipulandum. The starting position of the marker was approximately in the centre of the computer screen. The target was represented by a stationary blue target line (1 cm tall), located 10 cm from the right edge of the screen. After each trial, feedback information including target error (deg), and RT (ms) was displayed on the same computer monitor display. For the finger task, RT (ms) was displayed following each trial.

Training

Participants were allowed to practice the task prior to testing to familiarize themselves with the task and equipment. The participants were instructed that they would first hear a warning tone, followed by a variable foreperiod, and finally a “go” tone (imperative stimulus). Instructions emphasised fast reaction times and fast movement times. Participants were also instructed that the loudness of the stimulus would be variable. For each task, participants received a single block of 10 practice trials in which no startle tone occurred.

Data Reduction and Analysis

For the arm task, movement onset (Displacement RT) was defined as the first point of a change of more than 0.2 deg of angular displacement from the starting position following the stimulus. For the finger task, movement onset was the moment that the finger switch registered a positive voltage greater than 1V. Additional variables were calculated for the arm task. The final position of the movement was defined as the first point at which angular velocity remained below 8 deg/sec for at least 150 ms. Movement time was defined as the time (in ms) between movement onset and final position.

For both tasks, 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 preceding onset). 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. Premotor RT (PMT) was defined as EMG onset in the TRI muscle for the arm task and EMG onset in the FDI for the finger task. PMT was the main measure of RT for the current study as it represents an estimate of the total central processing time. EMG offsets were marked in a similar fashion, using a mean of EMG activity following the end of movement as a baseline level to account for any residual activity time between bursts. These were also verified and manually adjusted, with the activity between EMG onset and EMG offset being defined as a distinct burst. PMTs greater than 1000 ms and less than 40 ms were discarded if observed in the control (82 dB) condition

Startle trials in which SCM activity was not present prior to 120 ms following the stimulus were treated separately from startle trials in which SCM activity was observed as this distinction can be used to control for the effect of stimulus intensity vs. the effect of startle (Carlsen et al. 2007). This led to the designation of a third stimulus category for analysis (see Results section).

Statistical Analyses

Dependent measures were analyzed using 2 factor (task), or 3 factor (stimulus) repeated measures analysis of variance (ANOVA), where appropriate, to determine if differences existed between tasks and/or conditions. EMG and kinematic measures were not analyzed between tasks as the mechanical features of the tasks differed greatly. Several dependent measures were available for the arm task only, (e.g. final position) and were analyzed using a 3 factor (stimulus) repeated measures ANOVA. Proportion variables were subjected to an arcine square root transform prior to analysis. Greenhouse-Geisser corrected degrees of freedom were used to correct for violations of the

assumption of sphericity. Differences with a probability of less than .05 were considered to be significant. Tukey's Honestly Significant Difference (HSD) post-hoc tests were administered to determine the locus of the differences.

Results

Raw data from a single participant is shown in Figure 3.2 exemplifying the differences observed between the conditions in both the arm task (left panels) and the finger task (right panels). The presence of startle-related EMG activity in sternocleidomastoid (SCM) was used to categorize startle trials into trials in which SCM activity was present (SCM+) vs. absent (SCM-). The dashed line allows comparison of PMT observed in SCM+ trials with PMT observed in the control and SCM- conditions. Although the 115 dB stimulus led to shorter PMT in both movement tasks, only in the arm task did the presence of a startle response (SCM+) lead to a further reduction in PMT.

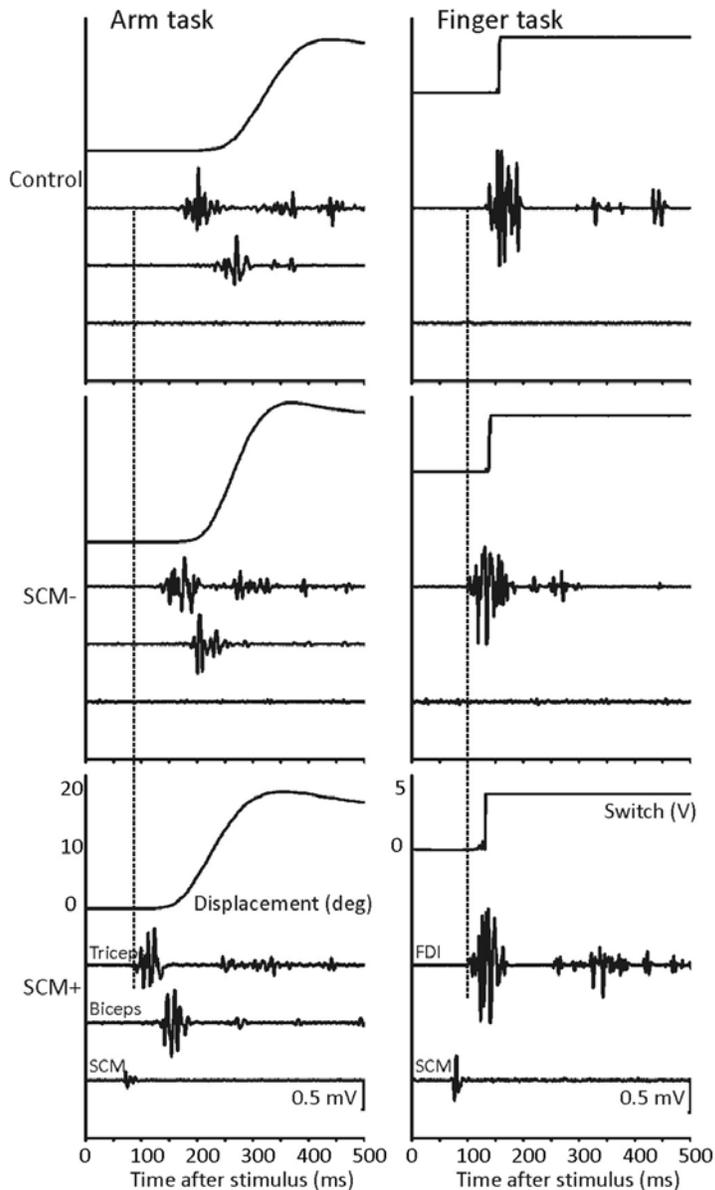


Figure 3.2 Example raw data from a single representative participant. Left panels contain data from the arm task, right panels from the finger task. Top two panels = control trials (82 dB); middle panels = startle trials (115 dB) no SCM activity (SCM-); bottom panels = startle trials with SCM activity (SCM+); Arm task panels show displacement, raw Triceps, Biceps and SCM EMG activity. Finger task panels show displacement onset, and raw FDI and SCM EMG activity. Dashed line shows prime mover EMG onset in the SCM+ condition allowing for comparison to the other conditions.

Startle Response

In both the finger task and arm task EMG activity in SCM was observed in startle trials for all participants. There was no significant difference in SCM onset latency between the arm task (76.5 +/- 17.1 ms) and the finger task (82.6 +/- 19.9 ms), $F(1,9) = 1.378$, $p = .271$. Calculations showed that effect size was low, partial eta squared (η_p^2) = .133, indicating that only 13.3% of any difference observed was attributable to the difference between tasks. Although SCM activity was not observed in *all* 115 dB (startle) trials, the proportion of trials in which SCM activity was present (SCM+) vs. absent (SCM-) did not differ between tasks, $F(1,9) = .369$, $p = .558$, $\eta_p^2 = .039$, with a SCM response being observed in 59.2 +/- 28.7% of startle trials in the arm task and in 62.5 +/- 25.2% of startle trials in the finger task. Thus dependent measures were analyzed between three stimulus conditions: Control trials, SCM+ trials, and SCM- trials. This made it possible to investigate the effect of stimulus intensity separately from the effect of a startle response as both SCM+ and SCM- trials involved the same stimulus (115 dB).

Premotor Reaction Time

Since participants were not always startled by the 115 dB stimulus, as defined by EMG activity in SCM (Carlsen et al. 2007), premotor RT (i.e. time from stimulus to prime mover EMG onset) was analyzed between control trials, SCM+ trials, and SCM- trials for each task. Results are presented in Figure 3.3 & Figure 3.4. For the arm task, a significant main effect for stimulus was found, $F(2,18) = 36.646$, $p < .001$, $\eta_p^2 = .803$. Post-hoc tests revealed that PMT was shortest for SCM+ trials ($p < .05$), with PMT for SCM- trials being both significantly longer than for SCM+ trials and shorter than control trials ($p < .05$, see Figure 3.3A). This difference is further illustrated in Figure 3.4, where

it can be seen that the SCM+ and SCM- PMT distributions are separated. For the finger task, a significant main effect for stimulus was also found, $F(2,18) = 28.879$, $p < .001$, $\eta_p^2 = .878$. However, while post-hoc tests revealed that control trial PMT was significantly longer than both 115 dB conditions ($p < .05$), post-hoc tests showed no difference ($p > .05$) in PMT between SCM+ and SCM- trials (see Figure 3.3B). In fact, Tukey's post-hoc calculations showed that a PMT difference of 13.6 ms between conditions was required to reach significance at $\alpha = .05$. Secondary analysis also showed that there was no significant difference, $F(1,9) = .393$, $p = .546$, $\eta_p^2 = .042$, between the two 115 dB stimulus conditions for the finger task. This can also be seen in Figure 3.4, where there is considerable overlap between the SCM+ and SCM- PMT distributions for the finger task. No catch trial false starts were observed and all were discarded from analysis.

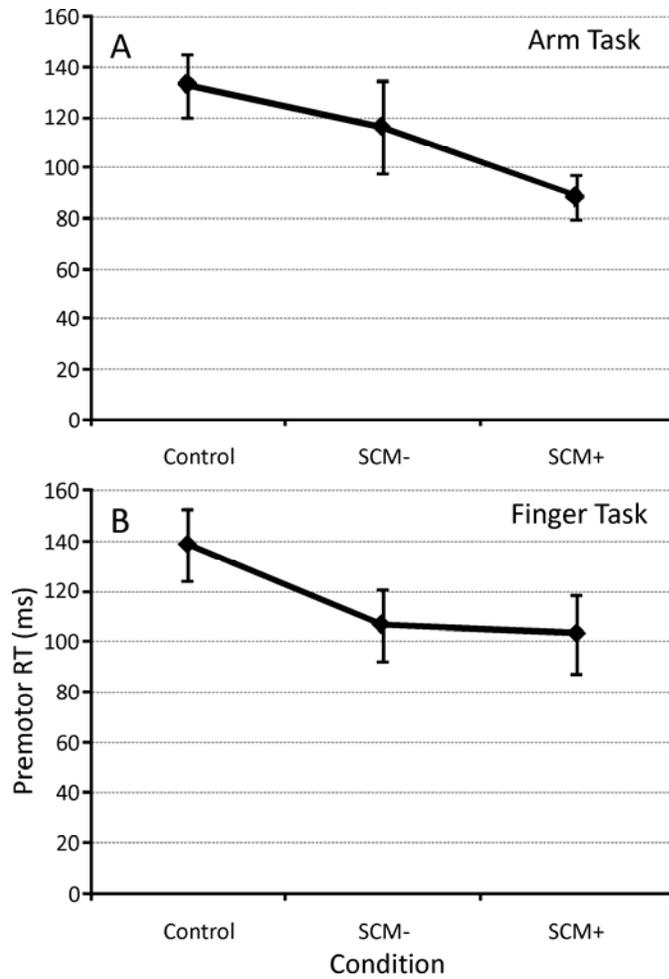


Figure 3.3 Mean premotor reaction time (\pm 1 SE) in the arm extension task (A) and the finger abduction task (B) for each stimulus condition: Control (82 dB), SCM- (115 dB, no sternocleidomastiod activity observed), SCM+ (115 dB, sternocleidomastiod activity observed)

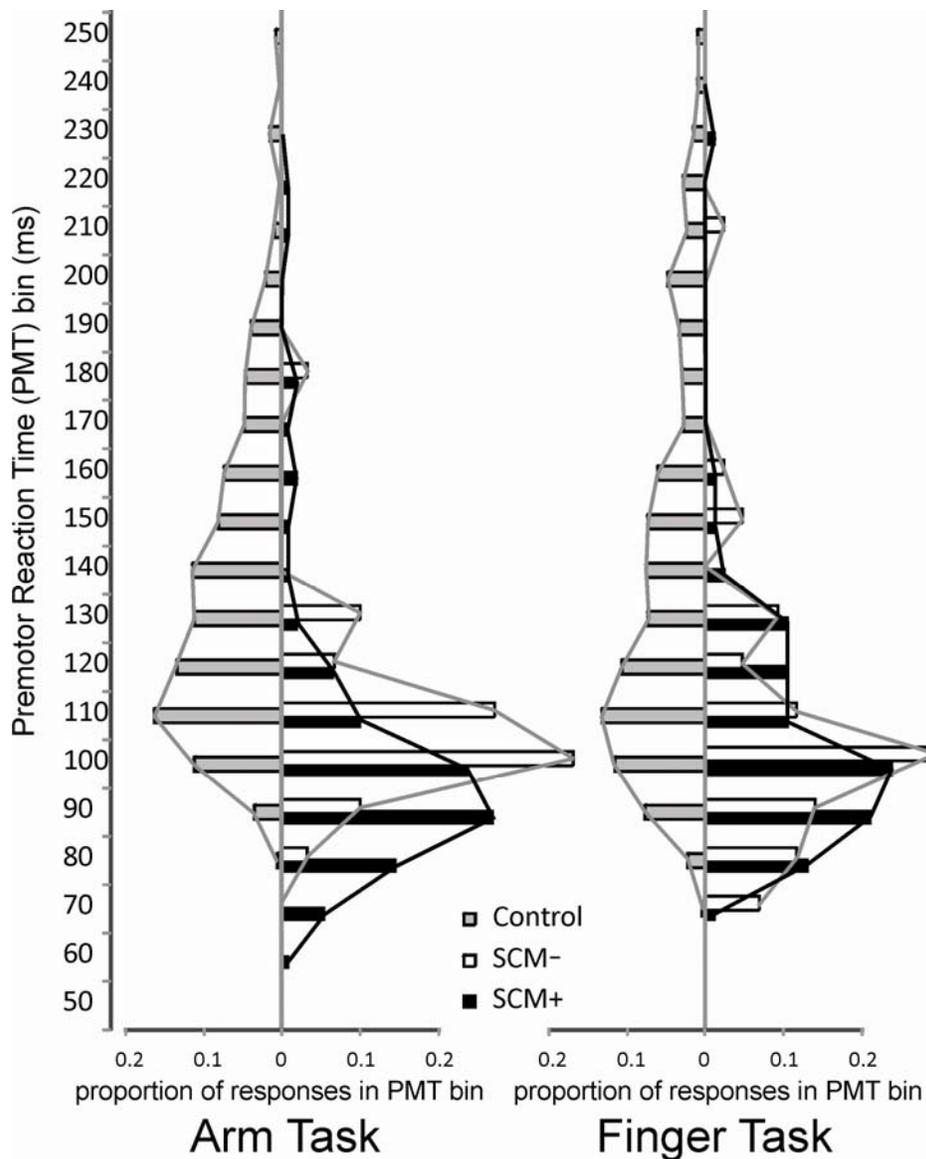


Figure 3.4 Premotor reaction time (PMT) distributions in the arm extension task and the finger abduction task. Data are proportions of the total number of trials observed across all participants in 10 ms PMT bins for each stimulus condition: Control (82 dB), SCM- (115 dB, no sternocleidomastiod activity observed), SCM+ (115 dB, sternocleidomastiod activity observed). PMT bin values are upper limits for that bin.

Kinematic and EMG Measures

For the arm task, displacement RT, movement final position and movement time (time from displacement onset to final position) were analyzed between stimulus conditions. Displacement RT was also calculated and analyzed for the finger task. Results are presented in Table 3.1. None of the kinematic measures were significantly different between stimulus conditions except displacement RT for both the arm task, $F(2,18) = 51.038$, $p < .001$, $\eta_p^2 = .850$, and for the finger task, $F(2,18) = 16.607$, $p < .001$, $\eta_p^2 = .649$. Post hoc tests showed the same pattern as observed for premotor RT: that is displacement RT was significantly different between SCM+ and SCM- in the arm task ($p < .05$), but not different in the finger task.

Table 3.1 Mean (+/-1 SD) EMG and kinematic data for each task and stimulus type

Task Stimulus	Arm				Finger			
	Control	SCM+	SCM-		Control	SCM+	SCM-	
EMG Measures								
Premotor RT (ms)	133.0 (12.5)	88.5 (8.4)	116.3 (18.4)	*†	138.7 (14.3)	103.3 (15.6)	106.6 (14.4)	*
Initial agonist burst duration (ms)	97.3 (17.2)	91.7 (16.6)	85.7 (24.1)		92.1 (22.0)	95.9 (29.3)	89.5 (29.7)	
TR1 to BIC inter-onset time (ms)	81.8 (39.1)	73.1 (29.3)	73.1 (22.2)		-	-	-	
TR1 to TR2 inter-onset time (ms)	153.7 (40.3)	160.1 (44.0)	155.6 (32.5)		-	-	-	
Kinematic Measures								
Displacement RT (ms)	191.5 (14.8)	146.8 (12.3)	165.9 (15.8)	*†	176.5 (14.6)	137.3 (12.9)	140.7 (24.5)	*
Final position (deg)	20.4 (1.4)	21.8 (3.8)	21.3 (3.7)		-	-	-	
Movement time (ms)	304.1 (29.1)	339.1 (59.4)	320.2 (45.1)		-	-	-	

Note. Standard deviations in parentheses, * signifies a significant main effect for auditory tone condition, † signifies a significant difference between trials in which sternocleidomastiod activity was present (SCM+) and absent (SCM-). TR1 is initial triceps burst. BIC is biceps burst. TR2 is second triceps burst. Premotor reaction time (RT) is time from stimulus to initial agonist EMG onset. Displacement RT is time from stimulus to onset of displacement.

In addition to premotor RT (see above) EMG measures were analyzed and are presented in Table 3.1. Initial agonist durations (TRI for the arm task; FDI for the finger task) were analyzed for differences between stimulus conditions, however no significant differences were observed for either task, $\eta_p^2 = .042, .143$ for the finger and arm tasks respectively. Secondly, burst onset timing was analyzed for differences between stimulus conditions for the arm task. While a characteristic triphasic pattern of activity (agonist-antagonist-agonist) was observed for the arm task, no significant differences in burst timing were observed between the stimulus conditions.

Discussion

Previous investigations have demonstrated that during a RT task, pre-programmed movements can be elicited early if the “go” signal is accompanied by a startling acoustic stimulus (Carlsen et al. 2004a, b; Castellote et al. 2007; Cressman et al. 2006; Seigmund et al. 2001; Valls-Solé et al. 1999). Although it has been suggested that the startle effect acts by releasing a motor program that was stored subcortically (Carlsen et al. 2004b; Valls-Solé et al. 1999), there have been no direct tests of this hypothesis. In the present study, a 115 dB startling stimulus replaced the usual RT “go” stimulus on several trials of two movement tasks. Here we show that for a finger abduction movement, which appears to be more strongly mediated by corticospinal connections, the loud stimulus led to a reduction in PMT, yet no further PMT difference was observed whether or not a startle response was elicited. For an arm extension movement, however, when a startle reaction was detected in response to the loud stimulus, a further decrease in premotor RT was observed compared to when no startle response was elicited. These data indicate that in

order for early response triggering by startle to occur, the movement must involve more extensive subcortical brainstem connections.

In order to infer any effect of a startle on RT, it is important to measure the presence of a startle response in the participants. Without a startle response, the acoustic stimulus is simply “loud.” It may be suggested that the startle effect is merely an extreme case of stimulus intensity facilitation (e.g. Woodworth 1938, p.318) where increases in intensity are associated with decreases in RT. However, it has been recently shown that when a startle (SCM) reaction was detected, the RT facilitation was different and larger than that brought on by increases in stimulus intensity alone (Carlsen et al. 2007): A startle response can be detected using EMG activity in SCM, as it has been shown to be the electrophysiological indicator of startle in muscle EMG that is the among most reliable and one of the last to habituate to repeated stimuli (Brown et al. 1991). This SCM activity was associated with substantially shorter RTs at all stimulus intensities (93 – 123 dB). Irrespective of the intensity of the stimulus, if SCM activity was observed, PMT was shortened to approximately 80 ms (Carlsen et al. 2007). However, lower intensities were also associated with a lower probability of observing a startle (i.e. SCM) response (see Carlsen et al. 2007). In the present study, a stimulus intensity (115 dB) was chosen that would elicit a startle response in about half of the “loud” trials. Although varying numbers of trials in which a startle response was (SCM+) or was not (SCM-) detected between participants (yet all exhibited some SCM+ and some SCM- trials), the mean proportion of SCM+ 115dB trials was not different between the two tasks (59.2% and 62.5% for the arm task and finger task respectively). Thus by comparing dependent measures between Control trials, 115 dB SCM+ trials, and 115dB SCM- trials, it was

possible to examine the effect of the stimulus intensity on RT separately from the effect of an overt startle response.

Premotor RT (PMT) results for the arm task were similar to those reported in previous studies (Carlsen et al. 2003a, 2004a,b, 2007; Cressman et al. 2006; Seigmund et al. 2001; Valls-Solé et al. 1995, 1999). Specifically, when a startle reaction was detected (EMG activity in SCM) in trials where a loud stimulus (115dB, SCM+) replaced the usual “go” stimulus (82dB, control), mean PMT was dramatically shortened from 133 ms to 88 ms (Figure 3.3A). However, many individual trials with PMT much shorter than this were observed (see Figure 3.4). Previously, to explain a similar dramatic reduction in RT due to startle, it was hypothesised that under certain circumstances the details of the motor program were stored subcortically and triggered directly by the startle (Valls-Solé et al. 1999).

This subcortical storage and triggering hypothesis (Valls-Solé et al. 1999) is based on interconnections between the neural pathways involved in both voluntary reactions and startle. The startle reflex pathway involves connections between the cochlear nucleus and the caudal reticular formation, with the giant neurons of the nucleus reticularis pontis caudalis (NRPc) acting as control neurons for the startle reflex (Yeomans and Frankland 1996; Koch 1999). In addition, voluntary movement preparation-related activity has also been recorded from the NRPC in animal models (Buford and Davidson. 2004; Schepens and Drew. 2004). Thus it was suggested that the startle reflex may interact with the voluntary response at the level of the reticular formation (Carlsen et al. 2004b; Rothwell 2006; Rothwell et al. 2002) leading to early release of the intended movement. This was suggested because of the drastic nature of the RT decrease observed, and because

estimates of stimulus transduction and nerve conduction delays precluded a transcortical pathway for responses with PMTs of less than 65 ms (Valls-Solé et al. 1999). This value was calculated by summing the time between an acoustic stimulus and the first volley of activity arriving at the auditory cortex (35 ms, Erwin and Buchwald 1986), with the time required for neural conduction between the primary motor cortex and the muscles (20-30ms, Jones et al. 1996; Rothwell 1997). This left almost no time for cortico-cortical transmission, let alone any cortical processing for the shortest RTs observed. However, these previous results could not rule out an unknown fast transcortical route. In the present study, the fastest PMT observed in SCM+ trials (arm task) was 58 ms, with many more less than 80 ms, replicating the observed response speeding effect due to startle. Importantly, these fast reactions all belong to the same RT distribution which is significantly different from the control trial distribution (Figure 3.4).

In the arm task, PMT for the SCM- trials (116 ms) was significantly longer than for SCM+ trials, which also agrees well with previous studies that have shown that PMT for startle facilitated responses are different than stimulus intensity facilitated responses (Carlsen et al. 2003a, 2007). It was argued that *only* when SCM activity was observed, there was sufficient activation to directly trigger a response that was stored subcortically (Carlsen et al. 2003a, 2007). Otherwise, PMT was sufficiently long (based on the above calculation) to allow the involvement of a normal cortical route for response initiation. Thus in the current study, it appears that SCM- trials were only affected by the increased intensity of stimulus (Kohfeld 1969; Luce 1986; Woodworth 1938, p.318) and not by a triggering effect due to startle.

Previously it was suggested that the speeding effect due to startle may simply be due to a later voluntary response adding on to an earlier startle reflex, resulting in an apparent decrease in voluntary RT where none truly existed. However, unless somehow seamlessly blended together, this would result in differences in EMG timing characteristics. For example the duration of the initial agonist burst as well as the time from EMG onset until antagonist onset would be lengthened. This was exemplified in an experiment in which participants produced a required arm extension movement to a target located at 20, 40 or 60 deg from the starting position. Although the burst durations were different between the movement distances, when startled, no differences were observed in either the kinematic or EMG characteristics (Carlsen et al. 2004b). This provided evidence that the startle triggered the intended movement and was not simply a movement superimposed on an early startle. In the current experiment, as in previous studies, the movement produced when participants were startled (or simply had a loud stimulus) was indistinguishable from that produced in response to the control stimulus (except for RT differences). That is, no differences in either EMG timing patterns or response kinematics were observed between the conditions for either the finger task or the arm task. Additionally, the small non-significant difference shown in the initial agonist burst duration data (Table 3.1) was opposite to the hypothesised outcome if a startle added onto a later voluntary response. If that were the case, the burst durations observed in response to startle should be longer than control, not shorter as observed here.

In the finger task, however, a somewhat different RT result was observed compared to the arm task. That is, like for the arm task, PMT was significantly shorter for

the 115 dB stimulus compared to control when the primary movement task was index finger abduction. However, while some responses were observed at what would be considered “startle like” latencies in the finger task following the 115 dB stimulus, the PMT distributions were not different whether or not a startle (SCM) response was observed (Figure 3.3B & Figure 3.4). Furthermore, mean PMT in both SCM+ and SCM- trials was sufficiently long to allow for traditional transcortical pathways to be used to initiate the response, and was also similar to mean PMT for SCM- trials in the arm task (Figure 3.3). Thus, the results of the present experiment indicate that unlike the arm task, the finger task was not directly triggered by startle. Indeed, it appears that the response pathway may be different for the finger task compared to the arm task due to the differential effect of a startle reaction on RT between the two tasks. Therefore, it is suggested that the RT advancement observed in the finger task may have been due to stimulus intensity facilitation, which is thought to have a perceptual basis, and is the result of faster cortical perceptual processing (Levick 1973). This is in contrast to the hypothesised subcortical origin for the RT speeding effect of startle.

This result is important in determining the mechanism of the startle effect. As previously stated, there is considerable evidence that the intrinsic muscles of the hand (such as FDI) are strongly mediated by cortico-motoneuronal connections (Brochier et al. 1999; Carroll 1965; Krakauer and Ghez 2000; Lawrence and Kuypers 1968; Wade et al. 1983). Furthermore, although some subcortical connections exist with the distal finger muscles (Baker and Riddle 2007; Soteropoulos et al. 2007), stimulation of reticulospinal tracts does not appear to have much influence on intrinsic hand muscles (Davidson and Buford 2006). If the mechanism of startle advancement is to release a motor program that

is stored in subcortical structures, as has been proposed (Carlsen et al. 2004b; Valls-Solé et al. 1999), a movement involving intrinsic hand muscles, such as the one used in the current experiment, would not be triggered by startle. This is precisely what was observed in the current investigation. On the other hand, reticulospinal pathways and parallel subcortical (e.g. reticulospinal / rubrospinal) connections in the voluntary activation pathway can have strong effects on more proximal limb muscles such as the elbow prime movers (Buford and Davidson 2004; Davidson and Buford 2006; Drew and Rossignol 1990; Schepens and Drew 2004). Furthermore, there appears to be strong projections to the reticular formation from cortical preparatory areas (e.g. Keizer and Kuypers 1989), as well as from cerebellar nuclei with preparatory activity (Allen et al. 1997). Thus, since PMT in the finger task was not facilitated by startle (over and above the effect of stimulus intensity), while PMT in the arm task was facilitated by startle, it appears that the involvement of subcortical (particularly reticulospinal) pathways for voluntary activation are a requirement to elicit a prepared movement via startle.

At least part of the RT advancement observed in startle trials may be due to increased neural activation. In some cases, startle activity may lower the thresholds of spinal circuits, resulting in sub-threshold activation of alpha motor neurons. Thus when the voluntary response is triggered, less time is required for the central command to reach the muscles. Although one experiment involving a choice RT task found no evidence of decreased RTs due to startle (Carlsen et al. 2004a), others have described some RT advancement in a choice RT task (Kumru et al. 2006; Oude Nijhuis et al. 2007; Reynolds and Day 2007). One explanation for a startle-related decrease in RT in a choice task was that the increased neural excitability may have been responsible for at least some of the

response shortening observed. Indeed, an alternative explanation for the differential effect of startle between the two tasks in the current experiment involves the startle response threshold of the hand muscles. Specifically, hand muscles such as FDI may have much higher thresholds required to elicit a startle response, as evidenced by a low probability of eliciting startle activation (Brown et al. 1991). The startle reaction itself provides evidence that startle response pathway differs for the intrinsic hand muscles. It has been observed that the latency to activation of intrinsic hand muscles as part of the generalized startle reaction is disproportionately long (Brown et al. 1991; Rothwell 2006), indicating that a different pathway is used for activation due to startle. This pathway possibly involves caudo-rostral pattern of activation beginning at the NRPC resulting in late corticospinal startle activation of the hand muscles. Therefore, even though a startle response was detected in SCM on some trials, there was not necessarily sufficient activation in the FDI pathway to lead to a further decrease in PMT. The current PMT results could be explained if the only effect of startle was to increase neural excitability; however, it seems unlikely that simply a decrease in neural transmission time could account for the entirety of the 45 ms PMT decrease (larger for the fastest reactions) from 133 to 88 ms observed in the arm task. A similar argument has been made previously (Valls-Solé et al. 1999). Although decreased conduction time may explain some of the observed PMT decrease, we believe that a modified response pathway stemming from the elicitation of a startle response is also partially responsible for the observed PMT decrease.

Finally some consideration must be given to the possibility that the response speeding effect of startle does act via a fast transcortical route. This pathway may

possibly involve ascending projections from the pontine reticular formation to primary motor cortex or even premotor areas. Indeed it has been shown that sensori-motor cortex can be modulated by stimulation to reticular structures (Parma and Zanchetti 1956). Further, it is thought that motor systems may be influenced by the ascending reticular activating system through direct activation of thalamocortical circuits (McDowell et al. 2006; Skinner et al. 2004) or indirect activation through basal ganglia (Takakusaki et al. 2004). In this way, startle may act to automatically trigger a prepared motor program that is stored cortically by simply bypassing the normal voluntary processes of stimulus detection, stimulus identification, and response triggering.

A calculation of the time required for response triggering via direct activation of a reticulo-thalamo-cortical pathway can be estimated based on earlier studies. First, it has been shown that an acoustic stimulus can result in activation of Lateral Lemniscus (LL, at the level of the Pons) at a latency of 5-7 ms (Erwin and Buchwald 1986; Stelmack et al. 2003). Second, using brain stem auditory evoked responses, it was shown that another 5-10 ms are required for conduction between LL and Thalamus (Stockard et al. 1977). Finally, conduction between Thalamus and primary motor cortex (or premotor areas) takes another 2-4 ms. Conservatively adding these values to the 25 ms conduction time to the limb muscles (Rothwell 1997) gives a minimum time of 46 ms for nerve conduction, which is well within the PMT values observed in the current experiment.

However, it remains unclear why no differences were observed in PMT for the finger movement whether or not SCM activity was observed. It may be that startle speeding of RT may depend on two simultaneous effects: First, startle may lead to the bypassing the early information processing stages by directly triggering the action.

Second, startle may also result in increased neural activation leading to a decrease in time required for neural transmission and propagation. Indeed, more recent studies involving startle and a choice RT task have shown some RT benefit although the response could not have been fully prepared in advance (Kumru et al. 2006; Oude Nijhuis et al. 2007; Reynolds and Day 2007). In the current experiment, loud stimuli incapable of producing a startle response may have led to a decrease in PMT in the arm movement by activating the response through a more direct reticulo-cortical route, but because there was insufficient activation to produce a startle the response could not be further speeded as compared to when a startle response was observed. In the case of the finger movement, because the action is mediated primarily by cortico-motoneuronal connections which are not typically activated in a startle response, the only effect would have been due to the direct cortical triggering by startle, leading to the observed results (i.e. the addition of an overt startle response would not have added to the effect). If this were the case, then it remains unclear why the finger task would be triggered in the absence of an observed startle response, irrespective of any startle related activity in the hand muscles. One possibility is that response triggering threshold was somehow smaller for the finger movement. The current experiment cannot, however, distinguish between these alternative hypotheses, and thus further investigation is required to clarify the underlying mechanism behind of the speeding effect on RT produced by startle.

Conclusion

The present experiment investigated the effect of a startling acoustic stimulus on the performance of a finger abduction movement and an arm extension movement within the context of a RT task. Consistent with previous literature, the presence of a startle

response (activity in SCM) during the arm movement task resulted in the early release of the intended response. In contrast, no increased difference was observed in PMT for the finger abduction task when a startle response was observed. Since voluntary activation of the intrinsic muscles of the hand depends largely on corticospinal connections, these results suggest that only movements involving muscles with strong subcortical circuit connections as part of the voluntary response pathway are susceptible to response speeding by startle.

Bridging Summary to the Following Chapters

The experiments described above in the current dissertation were designed to investigate alternative explanations concerning the speeding effect of startle on RT. These experiments provided evidence that the startle effect is a subcortical phenomenon (Experiment 2) acting on a pre-programmed response (Carlsen et al. 2004a). Furthermore, RT facilitation is associated with an overt startle reaction and is not simply due to either increased stimulus intensity (Experiment 1) or increased neural activation (Carlsen et al. 2004a). Thus it appears more likely that the startle acts to shorten RT via the mechanism first proposed by Valls-Solé et al (1999), and less likely that it acts via the alternative mechanisms investigated.

Having supported the hypothesis that a pre-programmed response is triggered by startle, Experiments 1 & 2 were followed by four experiments investigating the preparation of motor acts. Specifically, Experiments 3 - 6 investigated the conditions under which humans pre-program a motor act, using classical motor control paradigms as a starting point. Donders (1868/1969) was among the first to use behavioural methods to investigate the processes governing motor actions. Using an innovative (at the time) “subtractive logic method,” he calculated the time required for response selection (e.g. choice RT – simple RT) and stimulus discrimination (Go / No-go RT – simple RT). Later studies investigated the effect of partial response information on response programming (Rosenbaum 1980), the time required to stop a pre-planned action (e.g. transit reaction, Slater-Hammel 1960), and the effect of response complexity on RT (Henry and Rogers 1960; Klapp 2003). These paradigms were employed in Experiments 3 - 6 to further understand the conditions under which humans engage motor planning processes.

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4. Experiment 3

Startle Reveals an Absence of Advance Motor Programming in a Go / No-Go Task

A version of this chapter has been published in Neuroscience Letters:

Carlsen AN, Chua R, Dakin CJ, Inglis JT, Sanderson DJ, Franks IM (2008) Startle reveals an absence of advance motor programming in a Go / No-go task. *Neurosci Lett*.

doi:10.1016/j.neulet.2008.01.029.

Introduction

In a series of recent experiments, an unexpected, loud acoustic stimulus capable of eliciting a startle response was presented to participants preparing to react to an auditory “go” signal during a simple reaction time (RT) task. It was demonstrated that premotor RT (PMT) could be substantially reduced when participants were startled (Carlsen et al. 2004b, 2007; Valls-Solé et al. 1999). Because the response was produced at latencies too short (e.g. <65 ms) to have involved the cerebral cortex, it was suggested that the prepared response was stored subcortically and triggered directly by the startle (Carlsen et al. 2004b, 2007; Valls-Solé et al. 1999). Two other lines of evidence also support the notion of a startle-elicited response. First, the observed triphasic EMG activation pattern (Wadman et al. 1979) produced in the startle condition was unchanged (in both burst duration and timing) from that produced when participants performed the task in the absence of a startling stimulus (Carlsen et al. 2004b; Valls-Solé et al. 1999). Thus it was argued that effect of a speeded response was not produced simply by a late voluntary response superimposing on to an early startle response (Seigmund et al. 2001). Second, task accuracy was maintained during the startle-elicited response. In particular, an experiment was conducted in which an accuracy component was required in a startled RT task involving an arm extension to fixed targets located at 20, 40, or 60 deg. of angular extension. Results showed that no differences existed between Startle and Control conditions in any of the measured kinematic variables (Carlsen et al. 2004b).

The preceding results were obtained within the framework of a simple reaction time (RT) task. It was suggested that because the response was known in advance, the response could be prepared in advance of the imperative stimulus (IS), and could

therefore be triggered by the startle (Carlsen et al. 2004b; Valls-Solé et al. 1999). However, in a choice RT paradigm, the appropriate response must be selected from several alternatives following the IS, so response selection and response programming (cortical processes, Schluter et al. 1998, 2001) must occur during the RT interval. When participants were startled in conjunction with the IS in a choice RT task, the response was not triggered early (Carlsen et al. 2004a), although some limited RT facilitation in response to a startle was observed (Kumru et al. 2006; Oude Nijhuis et al. 2007). This provided evidence that a startle could only elicit responses that were prepared in advance of the IS, as in a simple RT task (Carlsen et al. 2004a).

In a third type of RT task, often termed a “Go / No-go” RT task, a single response is required (e.g. key press) but only to one of two possible stimuli. For example, Donders (1868/1969) performed an experiment in which the participant was required to press a response key if a blue light appeared; however, if a red light was illuminated the participant was instructed to refrain from making the keypress response. It was suggested that because this task involved the discrimination between stimuli, but required only a single response, the response could be prepared in advance of the IS (Donders 1868/1969). As such, in a Go / No-go task the processes following the IS may simply involve whether or not to trigger the prepared response. If this is the case, any pre-programmed action should be automatically triggered by a startling stimulus in a similar way as in a simple RT task.

Motor preparation may, however, depend partially on the probability of having to make a response. For example, it has been shown that manipulating the probability of receiving a particular stimulus affects the RT (Bernstein et al. 1967). Specifically, more

frequently occurring stimuli (e.g. 80% probability) lead to RT decreases in a choice task. This effect may be due to a perceptual bias, with participants more prepared to receive the more frequent stimulus (Bertelson and Tisseyre 1966; Miller and Pachella 1973). However, it has also been argued that a response bias is responsible for the effects (Bernstein et al. 1967; Low and Miller 1999), meaning that participants may be more likely to prepare the response in advance of the IS when there is a higher probability of a particular response.

Thus the purpose of the current investigation was to further examine the extent of movement pre-programming occurring in a Go / No-go RT task. This was done by introducing a startling acoustic stimulus simultaneously with the imperative stimulus in a task involving different probabilities of Go stimuli. It was hypothesized that if a response is prepared in advance in a Go / No-go task, that a startle would lead to early response triggering. Additionally, if preparation depends on the probability of receiving a Go stimulus, a startle may lead to response triggering when the probability of a Go is high (80%), but not in a low probability (20%) condition.

Method

Participants

Thirty right-handed volunteers (14M, 16F; ages 23 +/- 6 years) with no sensory or motor dysfunctions participated in the study after giving written informed consent. This study was conducted in accordance with the Declaration of Helsinki and in accordance with ethical guidelines established by the University of British Columbia (see Appendix A). Seven participants were excluded from analysis due to the absence of a reliable startle

response (see Results section). Thus the final analysis included data from 23 participants (11M, 12F; ages 24 +/- 6 years).

Participant Set-up and Task

Participants sat in a height adjustable chair, outfitted with an automobile racing harness to constrain movement to the forearm segment. The right arm was secured in a semi-prone position, with the palm facing inward, to a custom-made aluminum manipulandum that moved in the transverse plane with an axis of rotation at the wrist joint. The starting position was defined by a physical stop (20 deg wrist flexion from neutral).

The task was a Go / No-go RT task in which the goal was to perform a 20 deg right wrist extension movement to a fixed target as quickly and as accurately as possible after a green box appeared on a computer screen directly in front of the participant, or to refrain from making the movement when a red box appeared. An auditory stimulus occurred simultaneous with the appearance of the visual stimulus. Participants were offered a monetary bonus for fast reactions.

Instrumentation and Stimuli

Surface EMG data were collected from the muscle bellies of the right flexor carpi radialis (FCR), right extensor carpi radialis longus (ECR) and left sternocleidomastoid (SCM) muscles using bipolar preamplified Ag/AgCl surface electrodes (Therapeutics Unlimited). The recording sites were prepared and cleansed to decrease electrical impedance. EMG data were preamplified onsite and electrodes were connected via shielded cabling to an external amplifier system (model 544, Therapeutics Unlimited).

Wrist angular displacement was monitored using a potentiometer attached to the pivot point of the manipulandum. All data were digitally sampled at 1000 Hz (National Instruments® PCI-6024E) for 2 sec, beginning 500 ms prior to the IS, using a customized program written with LabVIEW® software (National Instruments Inc.).

The target was a fixed point in space located at 20 degrees of angular displacement into extension with respect to the right wrist's starting position. A computer screen placed directly in front of the participant provided real time position feedback during trials by representing the position of the manipulandum with a vertical marker line (1 cm tall) on the screen. The marker's movement corresponded directly to movement of the manipulandum and only moved in the horizontal plane. The starting position of the marker corresponded to it being stationary 5 cm from the left edge of the computer screen. The target was represented by a blue target line (1 cm tall), 10 cm from the right edge of the screen.

A warning tone, preceding a variable (1.5 – 3 sec.) foreperiod, consisted of three short beeps (100 ms, 1000 Hz, 80 dB each, separated by 500ms). The acoustic stimulus, consisting of a narrow band noise pulse (1 kHz, 40ms duration), was amplified and presented via a loudspeaker (<1 ms rise time) placed directly behind the head of the participant with an intensity of either 82 dB for control (C) or 124 dB for startle (S) trials. Intensity was measured using a sound level meter (Cirrus Research model CR:252B) at a distance of 30 cm from the loudspeaker (approximately the distance to the ears of the participant). The acoustic stimulus was presented concurrently with either a 3 x 3 cm square visual imperative stimulus that appeared around the target marker. The square either appeared green, indicating a “go” trial, or red indicating a “No-go” trial. After each

trial, feedback information including displacement error at the end of the initial impulse (deg), and reaction time (ms) were displayed on the same computer monitor display.

Experimental Procedure

Participants were randomly assigned to one of 3 groups prior to the testing session and the groups were balanced. The groups were differentiated by the proportion of trials in which a “go”(G) stimulus occurred compared to a “No-go”(N) stimulus. The group proportions were: 20/80, 50/50, and 80/20%, Go: No-go trials, and for the final analysis the groups included 7, 7, and 9 participants respectively. Within each group, each participant performed 70 control trials and 10 startle trials. All participants received 5 startle-go (SG) and 5 startle-no-go (SN) trials plus the number of control-go (CG) and control-no-go (CN) trials to make up the various proportions (e.g. 20% Go: 11CG, 59CN, 5SG, 5SN) which were distributed pseudo-randomly (no 2 consecutive trials were startle trials). Participants received 2 blocks of 10 practice trials in which no startle stimulus occurred prior to testing to familiarize themselves with the task and equipment.

Data reduction and Analysis

Dependent variables analyzed included EMG onset times, EMG amplitudes, as well as percentage of observed errors. EMG onsets were defined as points at which the EMG first began a sustained rise above baseline levels (see Carlsen et al. 2004a). EMG offsets were marked in a similar fashion, with the activity between EMG onset and EMG offset being defined as a distinct burst. Premotor RT (PMT) was defined as the interval from the IS onset to ECR EMG onset. Peak EMG amplitudes were defined as the largest EMG amplitude, rectified and filtered with a 25 Hz lowpass elliptic filter, recorded

within an interval of 100 ms following EMG burst onset. Integrated EMG values were determined by numerically integrating raw rectified EMG data for the duration of a defined EMG burst. Task errors were recorded when either no displacement was detected in Go trials, or when more than 0.5 deg of angular displacement from the starting position was detected in No-go trials.

Statistical Analyses

Dependent variables were analyzed using Mixed ANOVAs (described in Results section). Proportion variables were subjected to an arcsine square root transform prior to analysis. Differences with a probability of less than .05 were considered to be significant. Tukey's Honestly Significant Differences (HSD) post-hoc tests were administered to determine the locus of any differences.

Results

Startle Response

EMG activity in SCM was used as an indication that a startle response was elicited by the acoustic stimulus (Carlsen et al. 2003, 2007). Since the aim of current experiment was to investigate the effect of a startle on a Go / No-go task, trials in which no EMG burst was detected in SCM were discarded. If 3 or more startle trials were discarded from either the SG or SN conditions for any single participant, the entire dataset from that participant was excluded from the analysis. This procedure led to data being excluded from 7 of the original 30 participants (23%). This level of "low responders" was similar to that reported previously (Abel et al. 1998).

Peak EMG amplitude as well as Integrated EMG in SCM for startle trials were analyzed for differences using a 3 (group: 20, 50, 80 % Go) x 2 (condition: Go vs. No-go) mixed factor ANOVA. For peak SCM amplitude, no significant main effect was found for either condition, $F(1,20) = .141$, $p = .711$, $\eta_p^2 = .007$, or group, $F(2,20) = 1.181$, $p = .327$, $\eta_p^2 = .106$, and no interactions were found between the factors. Similarly, no significant main effects were found for integrated EMG.

Premotor RT

In order to evaluate whether the ratio of Go:No-go trials had an effect on PMT, a one way, 3 (group) ANOVA was performed on the CG condition. A significant main effect was found, $F(2,20) = 5.019$, $p = .017$. Tukey's post-hoc tests indicated that PMT in the CG condition was significantly different ($p = .014$) between the 80% Go (80G) group (298.8 ms), and the 20G group (354.0 ms), while PMT for the 50G group (314.6 ms) fell in the middle and was not significantly different from either (see Figure 4.1, Control).

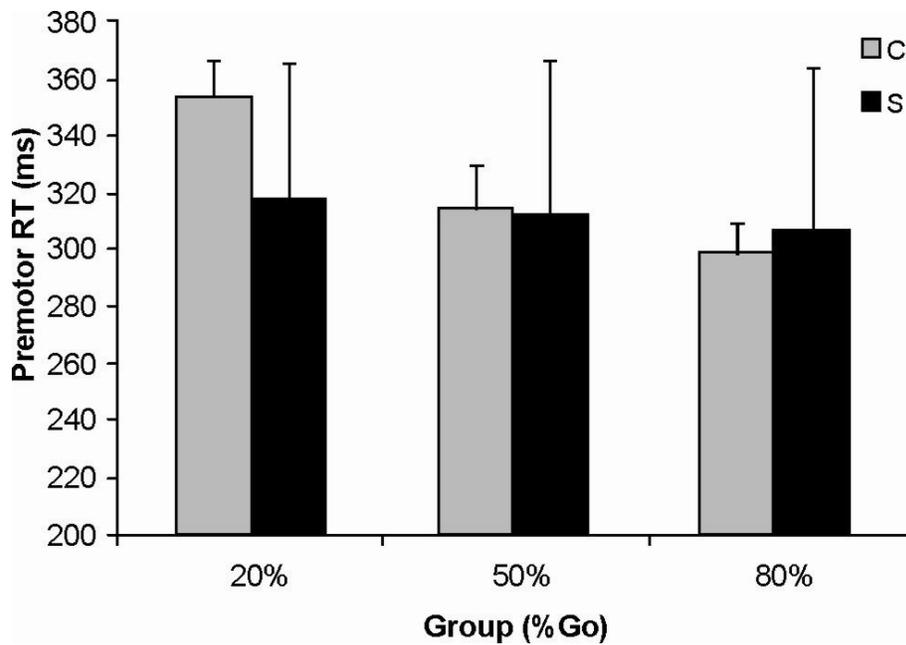


Figure 4.1 Mean premotor reaction time (SE) for Control (C, grey) and Startle (S, black) Go trials for the 20, 50, and 80% Go groups.

However, when PMT was compared between startle and control for the three groups, no significant effects were observed: Using a 3 x 2 mixed factor ANOVA, no main effect was observed for stimulus, $F(1,19) = .013$, $p = .910$, $\eta_p^2 = .001$, (Figure 4.1). Additionally, when PMT was collapsed across stimulus conditions, there was no main effect for group, $F(2,19) = .148$, $p = .864$, $\eta_p^2 = .015$. Finally, there was no significant interaction between the factors.

Errors

Errors were defined as Go trials in which no response was made within 1500 ms, or No-go trials in which a movement of more than .5 deg was recorded (false alarm). Error data are presented in Figure 4.2. The proportion of observed errors (e.g. number of errors as a percentage of the number of trials in each condition for each group) was analyzed using a 3 (group) x 2 (stimulus) x 2 (condition) mixed factor ANOVA. A main effect was found for stimulus, $F(1,20) = 21.264$, $p < .001$, $\eta_p^2 = .515$, indicating that more errors were committed in startle trials compared to control trials (Figure 4.2). In addition, a main effect was found for condition, $F(1,20) = 18.796$, $p < .001$, $\eta_p^2 = .484$, indicating that significantly more errors were made in the No-go trials compared to the Go trials (Figure 4.1). There was no main effect for group, and no significant interaction effects were observed.

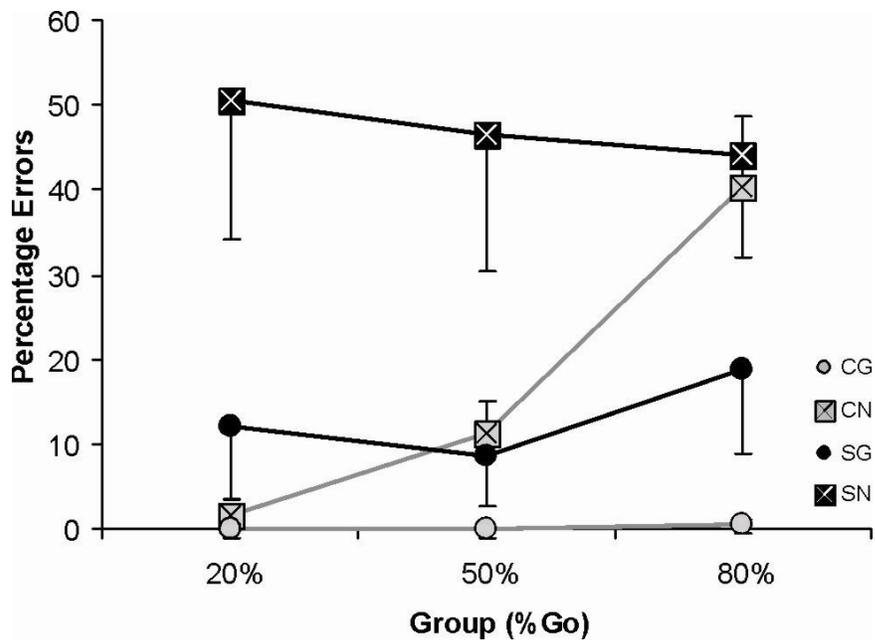


Figure 4.2 Mean percentage of observed errors (\pm SE) in Control Go (CG), Control No-go (CN), Startle Go (SG), and Startle No-go (SN) trials for each Go probability group.

Go data is filled circles, No-go data is crossed squares. Control data is grey, startle data is black. See text for a description of error types.

Since false alarms (errors of commission) were not observed by all participants in all conditions, it was not possible to analyze PMT using ANOVA. Thus PMT data were collapsed (as no differences in PMT were observed between groups when the control data were compared to the startle data for the Go condition) and compared between CN and SN using a T-test. No significant PMT difference was found, $t(30) = 1.056$, $p = .299$, between CN (264.8 +/- 62.8ms) and SN (233.9 +/- 101.5ms) trials.

Discussion

In a Go / No-go task the motor system can be at least partially prepared in advance of the imperative stimulus (Low and Miller 1999). However, the extent of motor preparation depends in part on the probability of having to make the response (i.e. the ratio of Go : No-go trials). The purpose of the present experiment was to utilize the response triggering effect of a startling acoustic stimulus in order to determine if a response was fully pre-programmed in a Go / No-go task, and if that preparation varied with the probability of receiving a Go signal. Here we show that although RT was affected by Go signal probability, a pre-programmed response was not reliably released early by the startle, indicating that complete advance motor programming and storage of the response did not occur.

Previous studies that have used a startling stimulus in place of or in addition to the IS in a simple RT task have shown that the startle may act as an early trigger for a pre-programmed response (Carlsen et al. 2004b; Valls-Solé et al. 1999). This phenomenon has been attributed to the startle volley interacting with the voluntary response pathway at a subcortical level (Carlsen et al. 2004b; Rothwell 2006; Rothwell et al. 2002; Valls-Solé et al. 1999). Specifically, it has been suggested that sufficient details of a known response

could be prepared in advance of the IS and stored in central structures that are common to both the startle response pathway and voluntary response channels. In these experiments, premotor RTs observed when participants were startled were of sufficiently short latencies (eg. <65 ms) that cortical response initiation was ruled out (Valls-Solé et al. 1999). Thus it was hypothesized that a stored motor program could be involuntarily triggered directly by neural burst activity occurring at the level of the pontine reticular formation that is associated with the startle reaction (Valls-Solé et al. 1999).

In the current experiment, there was no evidence of early response triggering observed (Figure 4.1). In particular, there were no significant differences in PMT between CG and SG trials, and mean startle PMT was in excess of 300 ms for all three Go-probability groups. Clearly, the effect of early response triggering by startle was not seen in the current experiment when a Go / No-go task was employed, although it has been observed previously in simple RT tasks (Carlsen et al. 2004b; Seigmund et al. 2001; Valls-Solé et al. 1999). A previous startle experiment involving a choice RT task, where the IS informed the participant of the required response, produced similar results to those seen here. That is, the inclusion of a startling stimulus did not result in the early release of a pre-programmed movement in a choice RT task, and resulted in many execution errors (Carlsen et al. 2004a). It was suggested that because the response was not known in advance in the choice RT task, it could not be pre-programmed, and was thus not available to be triggered early by the startle. Although some non-significant RT shortening was observed in the present experiment (Figure 4.2), and has been observed in previous startled choice RT tasks (Kumru et al. 2006; Oude Nijhuis et al. 2007), the RTs

reported suggest that the shortening is mainly a cortical perceptual effect due to the increased stimulus intensity (Levick 1973).

It appears that in the current experiment, the Go / No-go RT task was treated similar to a choice RT task in that participants waited until after the IS to program the movement. Although it was theoretically possible to pre-program the movement (i.e. prior to the IS), since it was always the same and thus certain, participants did not know if the response was going to be required on any given trial. Interestingly, even when the probability of having to make the response was high (80% Go), the startle did not act to trigger the movement, indicating that the possibility of not making the response on just 20% of trials was sufficient to discourage complete pre-programming of the response. Thus it appears that in a Go / No-go RT task, even though the response is known beforehand, as in a simple RT task, it is not programmed until after the IS, as in a choice RT task.

Substantially more errors were committed for No-go trials compared to Go trials (Figure 4.2). That is, participants performed the action when they received a No-go signal much more often than not performing the action when they received a Go signal. In fact the latter error was almost nonexistent for control trials. This is not entirely surprising, as this type of error would likely simply manifest as slower RTs, whereas a false alarm cannot be withdrawn once initiated. For Control (82 dB) trials, it appears that more false alarms were committed by the high probability (80%) group in No-go trials (see Figure 4.2, CN), as has been observed previously (Low and Miller 1999; Ramautar et al. 2004). To account for this, it has been suggested that in high Go probability conditions, participants tend to sacrifice successful response inhibition for faster RTs (Ramautar et

al. 2004) . However in the current experiment, the difference in false alarms between the groups was not statistically reliable (i.e. there was no main effect for group), likely due to the influence of Startle trial data. Nevertheless, the startle did lead to a large increase in error rate, both for the Go and the No-go trials. The data show two interesting effects. First, in a substantial number of SG trials, no movement was made for at least 1500 ms. This is in stark contrast to the CG trials, where this error type was rarely made (see Figure 4.2). Secondly, in the SN trials, there did not appear to be any difference in the proportion of false alarms observed between any of the groups, and these approximated the error rate observed in the CG condition for the 80% Go group. In the same startle experiment referred to earlier involving a Choice RT task (Carlsen et al. 2004a), a much higher error rate was observed when participants were startled. These errors included movements to the incorrect target as well as “freezing,” characterized by a lack of movement for at least 1 sec (Carlsen et al. 2004a). It was argued that the errors arose because the presence of a startle reaction interfered with cortical processes involved in making a choice between alternatives. A cortical interference phenomenon has also been observed in early experiments involving startle (Woodhead 1959, 1963). Thus the current error data suggest, similarly to the RT data, that the GNG task was treated more like a choice RT task, requiring cortical assessment and triggering. This may have been particularly true when the probability of making a response was high (80%), where the task may be more cognitively demanding, possibly due to increased demand for correctly identifying the rarely occurring No-go signal.

It is possible that the large proportion of false alarms in the startled No-go conditions is indicative of a triggering effect of startle. This interpretation is unlikely,

based on two pieces of evidence. First, for the 80% group, there was little difference between false alarm rates in the control and startle conditions (Figure 4.2). However, this is the condition in which participants would be most likely to prepare a response in advance (Low and Miller 1999). Second, no evidence of shortened PMT was observed between control and startle No-go false alarms. That is, the inclusion of a startle did not result in substantially lower PMT, as would be expected if the pre-programmed response was triggered automatically (Carlsen et al. 2004b; Valls-Solé et al. 1999). Taken together these data suggest that the observed false alarms were not due to involuntary response triggering by startle.

Premotor RT in the control (non-startle) Go condition was found to be shortest for the 80% group, and longest for the 20% group (see Figure 4.1). This result replicates previous studies that found a RT benefit for a higher probability of Go stimuli (Eimer 1993; Low and Miller 1999; Ramautar et al. 2004). There has been some contention regarding which processes in the information processing stream are affected by stimulus probability. For example, it has been suggested that the speed at which a stimulus is perceived depends on its probability (Bertelson and Tisseyre 1966; Miller and Pachella 1973). Conversely, recent work has shown that some advance preparation of the motor system occurs in a Go / No-go task, and this preparation is affected by Go probability. For example, it has been shown that the latency and amplitude of the lateralized readiness potential (LRP), which is derived from the event-related brain potential, is affected by Go probability (Low and Miller 1999; Smid et al. 1992), and can be eliminated in No-go trials if Go probability is low enough (Low and Miller 1999). Similarly, it has also been recently shown that the amplitude of the startle response EMG in SCM is smaller in a Go

/ No-go task compared to a Choice RT task, indicating that the excitability of subcortical motor circuits was affected by the possibility of having to not make a response (Kumru et al. 2006). These studies suggest that at least some partial preparation of motor circuits occurs in a Go / No-go task, particularly when the Go probability is high. Thus in the current experiment, it appears that although readiness to perceive the stimulus and increased motor excitability may have contributed to decreased PMT for the 80% Go group in the current experiment, complete motor programming of the response did not occur until after the IS.

In conclusion, the current data show that participants did not complete full advance motor programming of the response prior to the IS. This conclusion is based on two pieces of evidence: First, PMT was not dramatically shortened when a startle was introduced, as has been observed in a simple RT task. Second, many more errors were observed in the startle trials, suggesting that the startle interfered with ongoing cortical processes. Together these data suggest that in terms of motor programming, a Go / No-go task is treated similarly to a Choice RT task.

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5. Experiment 4

Precues Enable Multiple Response Pre-Programming: Evidence from Startle

A version of this chapter has been submitted for publication:

Carlsen AN, Chua R, Summers JJ, Inglis JT, Sanderson DJ, Franks IM (in revision)

Precues enable response pre-programming: evidence from startle.

Introduction

In the traditional serial model of human information-processing (Donders 1868/1969), response programming necessarily follows response selection. As such, in a choice reaction time (CRT) paradigm, response selection and response programming must both occur following the imperative “go” stimulus, that is, *during* the reaction time (RT) interval (Klapp 1996, 2003). On the other hand, in a simple RT (SRT) paradigm, the required response is known in advance and response programming can occur *prior* to the imperative stimulus (IS). However, if some partial information about the required response is known in advance in a CRT task the question arises whether some response pre-programming can occur (prior to the IS).

A “precue” method (Rosenbaum 1980) has been used to investigate the amount and nature of full or partial pre-programming that might occur during a special case of a CRT task. The required response involves an action that is oriented along several movement dimensions. Rosenbaum employed a button-press task in which eight buttons were arranged in two vertical columns of four in front of the participant. The starting positions for the left and right hands were in the middle locations of the left and right columns of buttons. As such, for each hand, two buttons were located in a forward direction from the starting position, and two in a backward direction. In this way, the required response could be defined along three response dimensions: Arm (Left or Right), Direction (Forward or Backward), and Extent (Near target or Distant target). The IS involved the presentation of a coloured dot corresponding to one of the associated colour-coded response buttons, and the task was to press the corresponding button as quickly as possible following the IS. On some trials, partial information regarding the

upcoming response was provided via a block letter code. This was referred to as a “precue,” that provided information that rendered one or more of the response dimensions (Arm, Direction, and/or Extent) certain. For example, the experimenter could have indicated that the upcoming movement would require the Left arm. In this case, it was assumed that the participant could prepare Arm in advance. Similarly, the experimenter could have indicated that the upcoming movement would be a Forward movement to one of the Near targets. In this case it was assumed that the participant may be able to prepare Direction and Extent in advance, and would simply have to specify the required Arm following the IS.

Rosenbaum (1980) found as more information was provided by the precue (more parameters cued), RT decreased. However, the RT benefit was not the same for each parameter. For example, when only one parameter was precued, precuing Arm resulted in faster RTs than precuing Direction or Extent alone. Based on these findings, Rosenbaum introduced a parameter specification model which suggested that the three parameters tended to be specified individually, that each one required a different amount of time to program, and that they could be specified in advance if known.

Evidence that Precues Affect Stimulus Identification and Response Selection (Non-Motoric Processes)

Rosenbaum’s assertion that the precues differentially affected the response programming, or *motoric*, processes was met with some skepticism. From an information processing perspective, the precue could have acted on either the traditionally “early” non-motoric (e.g. stimulus identification and response selection) processes or on the later motoric processes. It was suggested that Rosenbaum’s precuing method confounded the

motoric processes of response programming with the processes of response selection (Zelaznik and Hahn 1985). This was because as the number of precued parameters increased, there was a corresponding decrease in the remaining number of stimulus-response (S-R) alternatives, and it has long been known that RT decreases along with the number of S-R alternatives (Hick 1952). A revised precuing method held constant the number of S-R pairs at two, while manipulating the number of precued parameters (Zelaznik and Hahn 1985). For example, if the two precued response alternatives indicated the two short-extent targets in the forward direction, direction and extent (2 parameters) were precued. However, if the precues indicated the forward-left-near target and the backward-right-near target, only extent (1 parameter) was precued. This same method could be used to precue zero parameters while keeping the number of S-R alternatives constant. No significant RT differences were found between the precue conditions when using this method, indicating that once the effect of the number of S-R alternatives was removed, the differential effect of the precues on RT was eliminated (Zelaznik and Hahn 1985). However, several studies that have since employed this method have found a significant precuing effect (Dornier and Reeve 1990; Larish and Frekany 1985; Lepine et al. 1989; Vidal et al. Macar 1991), suggesting that the number of S-R alternatives may not have been the only contributing factor to the observed differential RTs.

The original precuing method (Rosenbaum 1980) was also criticized based on the complexity of the cognitive transformations involved in the S-R sets used. It was suggested that in Rosenbaum's method, extra non-motoric processing was required to translate stimuli from symbolic information (coloured dots) to spatial information (target

buttons), which could have led to the observed differential RT effects (Goodman and Kelso 1980). Thus, several studies that followed used direct spatial relationships between stimuli and responses to overcome this problem (e.g. Goodman and Kelso 1980; Lepine et al. 1989; Zelaznik and Hahn 1985). Using this method, differences in RT between the precuing conditions disappeared, indicating that any differential effect of the precues on RT arose from non-motoric stimulus translation processes (Goodman and Kelso 1980). In contrast, differential precuing effects have since been found even under highly spatially compatible conditions (Larish and Frekany 1985). Other non-motoric processes implicated in giving rise to the differential precuing effect include S-R translation (Dornier and Reeve 1990) and attentional processes (Bock and Eversheim 2000).

Evidence that Precues Affect Response Programming (Motoric Processes)

Several lines of research suggest that the differential precue effect may be due to motoric processes. One of these lines was based on the hypothesis that if precues could be used in advance to partially prepare an upcoming response, the time required for motor programming during the RT interval would be shorter. For example, more complex responses (e.g. longer movements) often lead to longer RTs in a CRT paradigm, but not always in a SRT paradigm (Klapp 1996, 2003; Vidal et al. 1991). Thus if duration is precued then RT should be no different between long and short duration movements. Experiments investigating the result of precuing duration found no difference in RT between conditions in which duration was cued, however, when the response hand was precued but duration was not, short duration responses resulted in shorter RTs than longer duration responses (Vidal et al. 1991; Vidal and Macar 1998). This finding indicated that

duration could be prepared in advance whether or not the response hand was known in advance.

An alternative line of research reasoned that measuring components of brain activity derived from the electroencephalogram (EEG) during a precuing task might provide additional evidence that precues affect late motoric processes, as well as support for the parameter specification model as proposed by Rosenbaum (1980). These components, the Contingent Negative Variation (CNV) and the Lateralized Readiness Potential (LRP) measure cortical activation associated with motor readiness. It has been shown that that CNV changes as a function of the amount of advance information provided regarding the upcoming response (Leuthold et al. 2004; MacKay and Bonnet 1990; Vidal et al. 1995). Similarly, because a foreperiod LRP can be elicited when one hand is precued, it was inferred that the information was used in advance of the stimulus to activate the corresponding motor cortex indicating advance preparation of hand (Osman et al. 1995, 2003). Additionally, it was suggested that the temporal locus of the dimensional precue effects could be determined using the LRP onset (Osman et al. 1995). Because the LRP-response interval was shorter when one-parameter was precued compared to zero-parameters precued, this indicated that the motoric processes occurring during this time were shortened (Jentzsch et al. 2004; Leuthold et al. 1996; Mueller-Gethmann et al. 2000; Osman et al. 1995; for a review see Leuthold et al. 2004). It was argued that since less motor programming time was required in the one-parameter precued conditions, that the precue enabled partial advance preparation of the response.

As a result of the finding that the programming of the different parameters took different amounts of time to specify, Rosenbaum (1980) argued that the precues must

have affected the response-programming portion of the RT interval. Rosenbaum concluded that the participants were able to utilize the precued movement dimension information to partially prepare the upcoming movement in advance, thereby reducing RT. However, similar results suggested that knowledge of movement direction was required in order to be able to use any other precues, since direction provided knowledge about the pattern of muscle innervation (Larish and Frekany 1985). Thus a hierarchical model was proposed in which decisions about the arm and extent could not be made until the agonist-antagonist muscle relationship was established (Larish and Frekany 1985).

In sum, several lines of evidence indicate that the precuing method affects mainly motoric processes even when the number of S-R alternatives was held constant (Larish and Frekany 1985; Lepine et al. 1989; Rosenbaum 1980). However, it appears that the programming that could be accomplished in advance was dependent on the task characteristics. For example, it was shown that response duration effects were eliminated in a precuing paradigm indicating that in this case the duration parameter could be pre-programmed (Vidal et al. 1991; Vidal and Macar 1998). However, when hand was precued it was shown that a foreperiod LRP was elicited (e.g. Leuthold et al. 1996), and a shorter LRP-response interval was observed, indicating that the hand may be specified in advance (Jentzsch et al. 2004;, 2004; Mueller-Gethmann et al. 2000; MacKay and Bonnet 1990; Osman et al. 1995, 2003). Finally, it was shown that in some cases, the agonist-antagonist pattern of muscle activation was required in order to prepare any part of the response in advance (Larish and Frekany 1985).

The Use of Startle to Probe Response Programming

It is evident that there exists controversy regarding the processes affected by precues. Some authors argue that precues act to shorten RT by affecting mostly early non-motoric (perceptual and decision making) processes (Bock and Eversheim 2000; Dornier and Reeve 1990; Goodman and Kelso 1980; Zelaznik and Hahn 1985), whereas others have implicated mostly late motoric (programming) processes (Jentzsch et al. 2004; Larish and Frekany 1985; Lepine et al. 1989; Leuthold et al. 1996, 2004; Mueller-Gethmann et al. 2000; Osman et al. 1995, 2003; Rosenbaum 1980; Vidal et al. 1991, 1995). In order to further distinguish which processes are more influenced by the precue, it may be possible a startling stimulus which has been shown to act as an early trigger for prepared actions.

Several recent studies have shown that motor commands can be triggered at short latencies by a loud acoustic stimulus (>124 dB) that is capable of eliciting a startle response (Carlsen et al. 2003a, b, 2004a, b; Seigmund et al. 2001; Valls-Solé et al. 1999). The observed effect was shown to be distinct from that of simple stimulus intensity facilitation (Woodworth 1938, p. 318; Kohfeld 1969). That is, irrespective of the intensity of the stimulus, when a startle reaction was detected, the RT facilitation was different and larger than that brought on by increases in stimulus intensity alone (Carlsen et al. 2007). Due to the extremely short RT latencies observed, it was suggested that the short-latency startle-elicited movements could not have involved conventional cortical processing pathways (Valls-Solé et al. 1999). It was therefore argued that details of the required movement were stored in subcortical structures common to the voluntary and startle response pathways (Carlsen et al. 2004b, 2007; Rothwell 2006; Rothwell et al. 2002;

Valls-Solé et al. 1999), and that a startle acted to trigger the response directly without the usual cortical trigger. Critically, however, when the response was not known beforehand (i.e. in a choice RT task) the startle had no effect. This indicated that the response must be pre-programmed in order for startle triggering to occur (Carlsen et al. 2004a).

For the current study, it is hypothesised that if precues do result in partial *advance* response programming then a partially prepared movement should also be accessible by the startle. As such, when the participant is startled, any movement elicited at short latencies should reflect the prepared motor dimensions. When no precue is given, presumably none of the response aspects are programmed in advance of the IS. In this case there should be no programmed movement aspects for a startling stimulus to trigger (see Carlsen et al. 2004a). Therefore, the purpose of the present investigation was to determine whether a response was partially or fully pre-programmed within the context of a precuing RT paradigm. This was accomplished by presenting a startling auditory stimulus in conjunction with the IS in a CRT paradigm in which the number of precued response parameters was systematically manipulated.

Method

Participants

Sixteen right-handed volunteers (9M, 7F; ages 26 +/- 3 years) with no obvious upper body abnormalities or sensory or motor dysfunctions participated in the study after giving informed consent. All participants were naïve to the hypothesis under investigation. This study was conducted in accordance with ethical guidelines established by the University of British Columbia (see Appendix A).

Positioning

Participants sat in a height-adjustable chair equipped with an automobile racing harness (Racer Components Inc.) in order to constrain movement to only the wrists. The participant's arms were secured in a semi-prone position with the palms facing inward, to two custom-made aluminum wrist manipulanda that moved in the transverse plane with an axis of rotation at the wrist joint. The arm portions of the manipulanda were oriented at an angle of 15 degrees outward from body midline, as this has been found to be a more comfortable position than an orientation parallel to the body midline. The wrist starting position was neutral (neither flexion nor extension) and was indicated by both online visual feedback and tactile feedback (using a magnet as a non-contact detent).

Recording Equipment

Surface EMG data were collected from the muscle bellies of the following superficial muscles: right and left flexor carpi radialis (FCR), right and left extensor carpi radialis longus (ECR), and left sternocleidomastoid (SCM) muscles using preamplified bipolar Ag/AgCl surface electrodes connected via shielded cabling to an external amplifier system (Therapeutics Unlimited Inc. Model 544). 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 malleolus. Wrist angular displacement data were collected using potentiometers attached to the central axes of the manipulanda. On each trial, data were digitally sampled at 1 kHz (National Instruments® PCI-6024E) for 3 sec using a customized program written with

LabVIEW® software (National Instruments Inc.). Data collection was initiated by the computer 500 ms prior to the imperative stimulus.

Task and Instructions

The experimental task was to perform an active wrist flexion or extension, using either the right or left hand, as fast as possible to a fixed target region located at +/- 20 degrees of angular displacement from the starting position. Real-time wrist position feedback was visible along with four horizontally aligned targets on a computer monitor located 1 m directly in front of the participant (see below for a description of stimuli, response targets, and feedback). The participants were informed that they would first hear a warning tone indicating the start of a trial. Following the warning tone, one or more of the targets would be specified by a blue box appearing around the target(s), and that this would inform them about the possible target(s) for the upcoming trial. Participants were instructed about the different possible combinations and what the combinations meant, and that they should prepare whatever part of the movement that they could. In other words, participants were encouraged to prepare the precued response dimension(s) if possible. The participants were told that once the box(s) disappeared there would be a short pause, and then a bright yellow box would appear around one of the previously indicated targets accompanied by an auditory tone of variable intensity. Instructions were to move “as fast and as accurately as possible” from the starting position and to stop on the target and emphasized fast RTs, quick movements, as well as the minimization of errors. Similar to previous experiments in our lab (e.g. Carlsen et al. 2004a) a monetary bonus was offered for fast RTs.

Response Targets and Feedback

Four response targets were used in this experiment; each consisting of a fixed point at 20 degrees of angular displacement into either flexion or extension with respect to wrist's starting position. Real time wrist position feedback was given by representing the position of each manipulandum with a 1 cm yellow vertical graphical line within each of two horizontal (1cm x 15cm) black rectangles located beside one another on the computer screen. The starting point of the position lines was the middle of the black rectangles. Two blue lines, 2 cm from the right and left edges of each of the rectangles represented the targets for flexion and extension. In this way, four vertical blue target lines were aligned horizontally across the screen. The movement of each position line within the black rectangles corresponded directly to movement of the respective manipulandum. For example, if the right wrist was flexing, the yellow line in the right rectangle moved to the left. After each trial, the computer monitor displayed feedback information about the trial just completed including target accuracy (degrees), and reaction time (in ms).

Stimuli

The warning tone consisted of three short beeps (100 ms, 1000 Hz, 82 dB each, separated by 500ms) generated by the computer using a 16 bit sound card (Creative SoundBlaster® 16) and standard computer speakers (Juster® sp-691n). Following the warning signal, a visual precue denoting the possible responses on the upcoming trial was presented to the participant. Visual stimuli consisted of 4 possible boxes (3 x 3 cm) that could appear around the targets aligned horizontally across the computer screen in front of the participant. Precues were shown for 3 seconds duration. There were five precue

conditions: In the full precue condition (1 S-R alternative), the exact target was indicated for the upcoming movement (i.e. precuing both hand and direction). Hand (2 S-R alternatives) was precued by displaying either both left boxes (precuing left hand), or both right boxes (precuing right hand). Direction (2 S-R alternatives) was precued by displaying either both inside boxes (precuing flexion), or both outside boxes (precuing extension). The Ambiguous (2 S-R alternatives) precue (left flexion + right extension, or left extension + right flexion) was precued by displaying either the left-inside and right-outside boxes (e.g. rightward movement) or the left-outside and right-inside boxes (leftward movement). Finally a no-precue condition (4 S-R alternatives) displayed all four boxes, thus no information was provided about the upcoming target (see Figure 5.1 for examples of visual stimuli and feedback).

A variable foreperiod of 1.5 to 2.5 sec. spanned the time between the offset of the precues and onset of the imperative stimulus (consisting of a yellow 3 x 3 cm box that appeared around the required target for that trial). Either the control auditory stimulus or the startle (ST) stimulus was presented in conjunction with the visual imperative stimulus on every trial. A computer program generated the trial auditory stimuli consisting of a narrow band noise pulse (1 kHz, 40ms duration). The signal was amplified and presented via a loudspeaker (<1 ms rise time) placed directly behind the head of the participant with an intensity of either 82 +/-2 dB (Control stimulus) or 124 +/-2 dB (Startle stimulus). The stimulus intensities were measured using a sound level meter (Cirrus Research model CR:252B) at a distance of 30 cm from the loudspeaker (approximately the distance to the ears of the participant).

Participants performed 4 movement trials to each target in each of the five precue conditions (total 80 movements) in randomized order. For the right hand extension movement only, 2 Startle trials replaced control trials in each of the 5 precue conditions (total of 10 startle trials per participant). The right hand extension movement was chosen to eliminate RT differences due to hand, and because extension is a movement opposite to the generalized flexion usually elicited by a startle response (see Davis 1982). Because startle response habituation leads to a decreased probability of eliciting a startle response (although this is mitigated by a concurrent RT task, see Carlsen et al. 2003b; Valls-Solé et al. 1997), few startle trials can be presented to each participant. In order to discourage false starts 4 catch trials in which there was no IS also occurred randomly. Erroneous trials, in which the participant initiated a response towards an incorrect target, or changed the response mid-trial were noted, but were nonetheless subject to analysis.

Data Reduction

Only data from trials in which the right hand extension movement was indicated were analyzed in any of the conditions in order to control for variables not attributable to the experimental manipulation. Thus five precue conditions (format: [number of S-R alternatives]-[precue type]) were analyzed (1-full, 2-hand, 2-direction, 2-ambiguous, 4-none). Startle trials in which no detectable startle response (SCM activity) was observed were discarded (see Carlsen et al. 2003a, 2007). These non-startles comprised 10% of all startle trials and no two trials were discarded from a single participant in any of the precue conditions.

Movement onset was defined as the first point of a change of more than 0.2 deg of angular displacement from the starting position following the stimulus. 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 activity increased to more than 2 standard deviations above baseline (mean of 100 ms of EMG activity preceding movement). Onset was then verified by visually locating and manually adjusting the onset mark to the point at which the activity first increased. This method allowed for correction of errors due to the strictness of the algorithm. Premotor RT (PMT) was defined as the time between stimulus onset and EMG onset in the ECR muscle. EMG offsets were marked in a similar fashion to onsets, with the activity between EMG onset and EMG offset being defined as a distinct burst.

Statistical Analyses

Dependent measures were analyzed for differences using repeated measures analysis of variance (ANOVA) procedures described below. Greenhouse-Geisser corrected degrees of freedom were used to correct for any violations of the assumption of sphericity. Differences with a probability of less than .05 were considered to be significant. Tukey's Honestly Significant Difference (HSD) post-hoc tests were administered to determine the locus of the differences.

Results

Errors

In all analyzed trials, the imperative stimulus indicated the right hand extension target. Therefore, any other and / or extraneous movements recorded were considered as errors and classified according to the observed displacement. Specifically, if more than .2

deg of movement was initiated by either the left hand or with the right hand initially moving towards flexion, an error was recorded. Raw data is provided in Figure 5.1 showing examples of the most commonly observed errors in each of the startled 2-choice precue conditions. Examples are not provided for the full precue condition since comparatively few errors occurred, or for the no-precue condition, since the observed error types were much more variable. Error rates were analyzed between stimulus (startle vs. control trials) and precue condition. A main effect was found for stimulus, $F(1,15) = 82.803$, $p < .001$, $\eta_p^2 = .847$, indicating many more errors were made in the startle trials (46.3%) compared to the control trials (8.2%). A main effect was also found for precue condition, $F(4,60) = 11.422$, $p < .001$, $\eta_p^2 = .432$; however, it was the significant interaction between stimulus and precue, $F(4,60) = 5.984$, $p < .001$, $\eta_p^2 = .285$, that was more interesting. Post-hoc analysis indicated that for all precue conditions *except the full precue*, significantly more errors ($p < .05$) were made in startle trials (see Figure 5.2). Since the amount and types of errors observed in each condition was variable for each participant (e.g. some errors were not observed at all for some participants), repeated measures statistical analysis of error type was not possible. However, descriptive statistics regarding the quantity of various error types by precue are presented in Table 5.1. Note that in the startle trials, particularly in the 2-choice (hand, direction, and ambiguous precue) conditions, a very high proportion of the observed errors reflected multiple movements toward the precued targets (for example raw data see Figure 5.1).

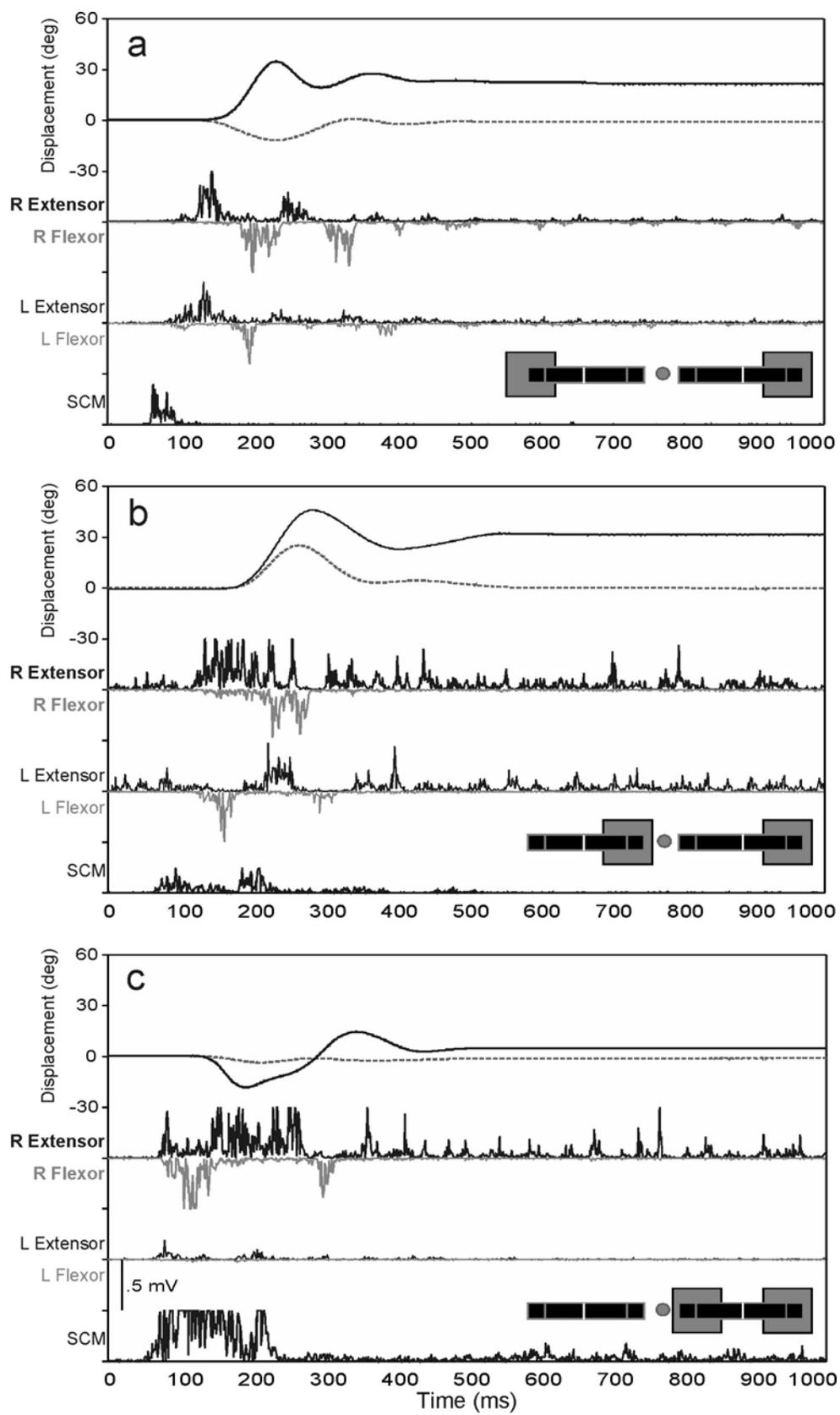


Figure 5.1 Error trial examples for the three startled 2-choice precue conditions. Each panel includes, from top, right hand displacement (bold line), left hand displacement (dashed line), EMG (labelled) from right extensor, right flexor, left extensor, left flexor, and sternocleidomastoid (SCM). Rightward displacement is positive, leftward negative. EMG traces are rectified raw data. Note short latency SCM activity indicating the participant was startled. Precued targets are displayed in bottom right of each panel. a: Direction precue, showing short latency onset of extension movements of both the left and right hands. b: Ambiguous precue, showing short latency dual rightward movements. c: Hand precue showing short latency onset of flexion with a subsequent correction into extension (however note that EMG onsets are well synchronized possibly indicating co-activation).

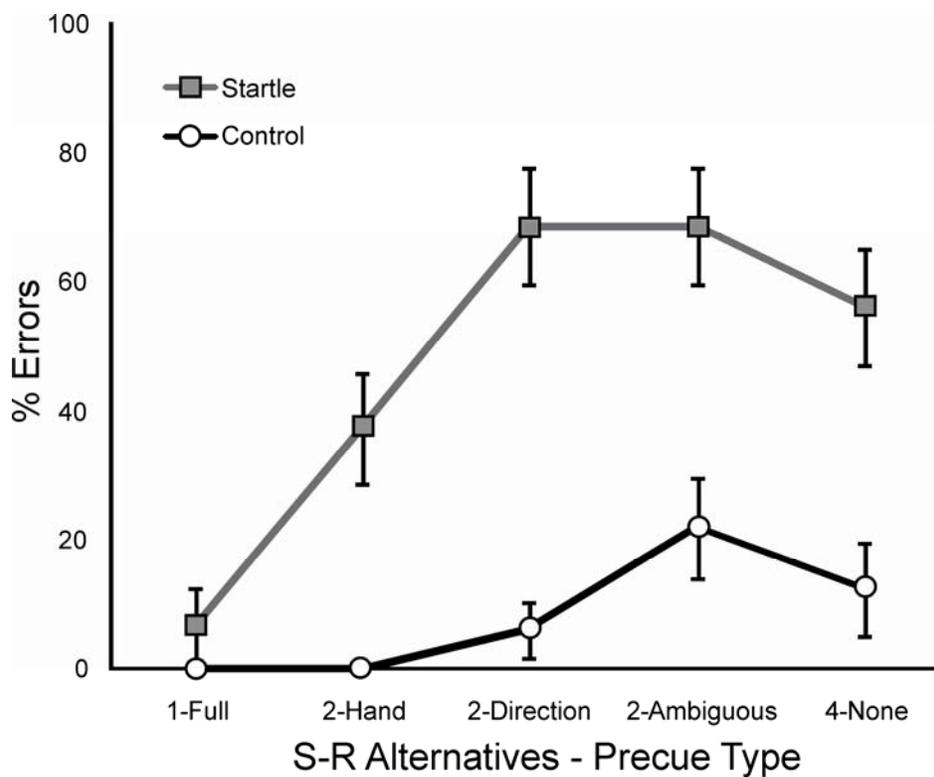


Figure 5.2 Mean (\pm SE) percentage of trials in which a movement error was observed between stimuli and for each precue condition. Open circles are control (82 dB stimulus) trials, whereas filled squares are startle (124 dB) trials.

Table 5.1 a. Error rates (in percent) by auditory tone condition (overall) and by precue type (startle condition only). b. Percentage of each type of error observed by precue when errors occurred in the startle condition. Note that a majority of movement errors (bold) reflected movements toward the precued targets.

a. Overall Error Rate		Startle-Only Error Rate				
Condition		S-R alternatives - precue				
Control	Startle	1-Full	2-Hand	2-Direction	Ambiguous	4-No-precue
8.2	46.3	6.3	37.5	68.75	68.75	56.3
b.		Movement observed				
	Bimanual flexion	0	0	0	0	22.2
	Bimanual extension	100	27.3	95.2	10.0	11.1
	Bimanual rightward	0	0	4.8	90.0	33.3
	Right flex-extend	0	72.7	0	0	16.7
	Other	0	0	0	0	16.7

Reaction Time

In order to determine if the precues had a differential effect on PMT, control trials were analyzed separately using a 5 factor (precue condition) repeated measures ANOVA. A significant main effect was found, $F(4,60) = 38.756$, $p < 0.001$, $\eta_p^2 = .721$, indicating a PMT difference between conditions (see Figure 5.3, control). Post-hoc analysis revealed that PMT was only significantly different based on the number of S-R alternatives ($p < .05$); that is, the full precue (simple RT) had the shortest PMT, the no-precue (4 S-R alternatives) had the longest PMT, however, in the three conditions in which the number of S-R alternatives was held constant (2), there was no effect of precue on PMT ($p > .05$).

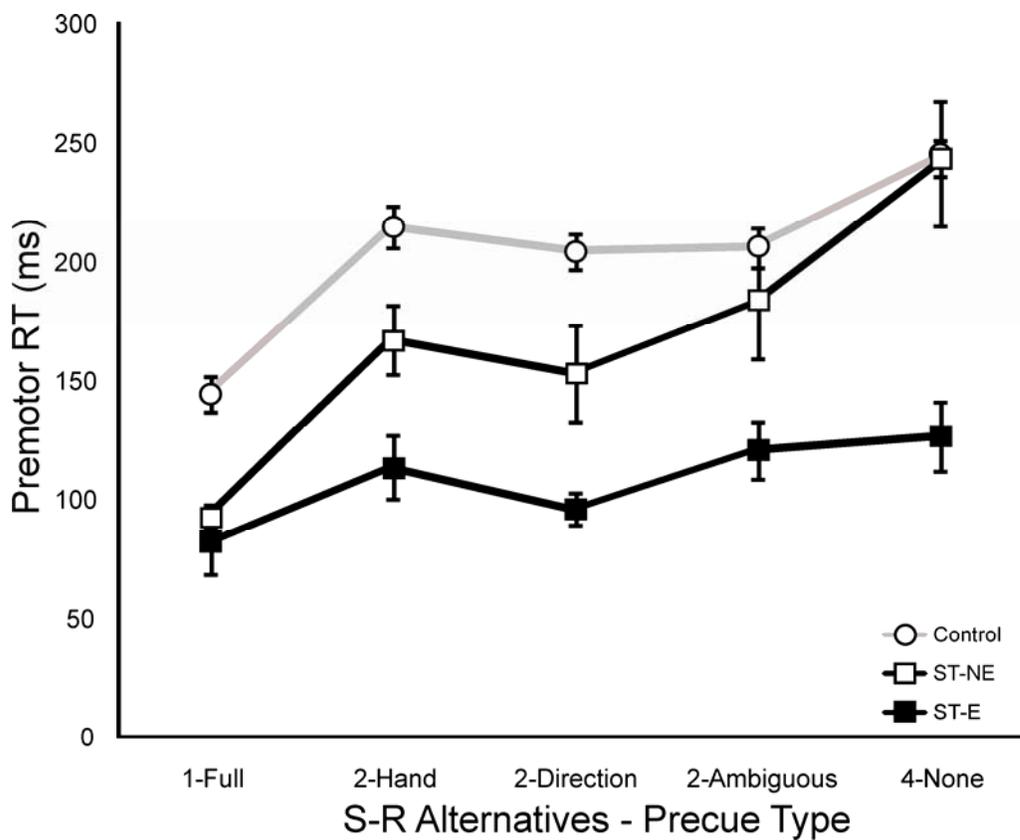


Figure 5.3 Mean (\pm SE) premotor reaction time (RT) by stimulus (separate lines) and for each precue condition. Open circles are control (82 dB stimulus) trials, open squares are non-errorful startle (124 dB) trials (ST-NE) whereas filled symbols are error startle (ST-E) trials.

As previously described, there were a large number of errors of differing type observed in the startle condition. In order to evaluate the effect of startle on PMT across the different precue conditions, errorful startle trials (ST-E) were separated from non-errorful startle trials (ST-NE) for the premotor RT analysis. Because of the large number and different types of errors observed due to startle, repeated measures statistical analysis was not possible. Thus, ANOVA was performed as a between-groups analysis with data for each condition assigned to separate groups. Thus 15 groups were assigned, 3 stimulus (control, ST-E, ST-NE) x 5 precue. Main effects were found for both stimulus, $F(2,269) = 57.802, p < .001, \eta_p^2 = .301$, and for precue, $F(4,269) = 15.763, p < .001, \eta_p^2 = .190$. Post-hoc analysis showed that PMT was significantly different between all the stimulus conditions with ST-E having shortest PMT followed by ST-NE and Control, $p < .05$ (Figure 5.3). Univariate ANOVAs were also performed as a between groups analysis for ST-E and ST-NE on their own, with data for each condition assigned to five separate precue condition groups. A main effect was found for precue, $F(4,66) = 17.652, p < .001$, in the ST-NE trials, mirroring the control trial results (Figure 5.3). However, no difference in PMT was found between the precue condition for the ST-E trials, $F(4,62) = 1.402, p = .244$ (Figure 5.3).

Discussion

Previous precuing RT studies that involved providing some advance information about the upcoming response have led to equivocal results. At issue is the information processing stages affected by the precue. While some evidence indicated that early non-motoric stages such as stimulus identification and response selection processes were shortened by the precue (Bock and Eversheim 2000; Dornier and Reeve 1990; Goodman

and Kelso 1980; Zelaznik and Hahn 1985), other evidence implicated late motoric stages, including response programming (Jentzsch et al. 2004; Larish and Frekany 1985; Lepine et al. 1989; Leuthold et al. 1996, 2004; Mueller-Gethmann et al. 2000; Osman et al. 1995, 2003; Rosenbaum 1980; Vidal et al. 1991, 1995). The purpose of the current study was to determine the amount and nature of response pre-programming occurring in a precued choice RT experiment by employing the triggering effect of a startling stimulus. The results agree well with some of the previously published precuing experiments and also with previously published startle data. Here we show that although the no differential precuing effect was observed when the number of S-R alternatives was held constant, the presence of a startling stimulus often resulted in the early triggering of the prepared response. Moreover, these fast responses reflected a preparation of multiple movements to the precued targets. Our results indicate that participants often used the information provided by the precue to pre-program multiple responses, particularly in conditions where the two targets were on separate hands.

Results from the current study showed no reliable differential RT effect of the precued dimension independent of the number of S-R alternatives. Thus, from an information processing perspective, it appears that the precues simply acted to decrease the number of response choices, leading to decreased PMTs. The effect of the number of S-R alternatives on RT (Hick's Law) is characterized by a relatively constant decrease in RT when the number of S-R alternatives is halved (Hick 1952). Specifically, in the present study, when the number of S-R alternatives was held constant at 2 (hand, direction, and ambiguous precues), there was no significant difference in PMT (Figure 5.3, control). This finding is similar to results reported by others (Goodman and Kelso

1980; Zelaznik and Hahn 1985) when a direct spatial S-R mapping was used, and at odds with the suggestion that precues affected the response-programming portion of the RT interval (Rosenbaum 1980). Based on these results it is tempting to conclude that in the current study, the precues affected mainly non-motoric processes. However, adding a startle condition revealed more about how the precues affected the motoric response programming processes, and about the amount of programming occurring in a precueing paradigm.

Effect of Startle

First and foremost, the presentation of a startling acoustic stimulus in conjunction with the IS led to a dramatic increase in the amount of “errorful” responses observed (Figure 5.1 & Figure 5.2, Table 5.1). Specifically, significantly more errors were committed by participants in the startle condition (46.3%) compared to control trials (8.2%). However, the bulk of the startle trial errors occurred when a choice had to be made, occurring in more than 50 % of trials. On the contrary, in the full precue, errors only occurred in 6.3 % of trials (Figure 5.1, Table 5.1). It is important to note that because in all analyzed trials the correct target was the right hand extension target, there were seven possible error types: Unimanual left flexion, unimanual left extension, unimanual right flexion, bimanual right flexion + left flexion, bimanual right flexion + left extension, bimanual right extension + left flexion, and bimanual right extension + left extension. However, in the 2-choice startle trials (direction and ambiguous precues, and to a lesser extent the hand precue), a very high proportion of the recorded errors reflected multiple movements toward the precued targets (Table 5.1b). If the errors were random, one would expect the precued targets to be reflected in only 1/7 (14.3%) of errors. However,

since many trials were classified as errorful due to concurrent movement with the left hand, many “errors” included the correct right hand extension movement. Importantly, *all* of the movement errors produced in the bimanual 2-choice precue conditions (direction & ambiguous precues) involved bimanual initiation of movements towards more than one target. Furthermore, these multiple movements nearly always reflected the precued response alternatives. That is, in the direction precue condition in which the precued targets indicated both the left and right hand extension targets, 95.2% of the errors were bimanual extension movements (Table 5.1b & Figure 5.1a). Similarly, bimanual rightward movements (left flexion and right extension) were the most commonly observed error (90% of errors) in the startled ambiguous precue condition (Table 5.1b & Figure 5.1b).

The question arises as to why a startle would result in such a large increase in the error rate, and why these errors would largely consist specifically of multiple movements to the precued targets. It has been previously shown that when a startling acoustic stimulus is paired with a simple RT task, the pre-programmed intended movement is elicited early by the startle without the usual voluntary response initiation (Carlsen et al. 2003, 2004b, 2007; Cressman et al. 2006; Seigmund et al. 2001; Valls-Solé et al. 1995, 1999). In the current experiment, for such response triggering to occur, movements must have been programmed in advance of the startling stimulus. Yet when the IS (control or startle) occurred in conditions aside from the full precue, there was still a choice to be made between the possible response alternatives. This leads to a paradox, since how could the response be prepared and triggered by the startle if the response was not known in advance? It was suggested from earlier precuing experiments (e.g. Rosenbaum 1980)

that the pre-programming of one or more of the response dimensions could occur in advance of the stimulus if they were known. In the current experiment, participants were encouraged to prepare whatever they could based on the identity of the precues. Thus, it is possible that participants were preparing *multiple full responses* and simply selecting and triggering the appropriate response following the IS. Although it was previously shown that participants are able to prepare multiple responses in advance if specifically instructed to do so (Rosenbaum, 1980), this was thought to be an inefficient method of response preparation, and could not work for high numbers of S-R alternatives. However, more recent evidence involving Evoked Response Potential (ERP) activity, derived from EEG, suggests that parallel response preparation may occur, when two hands are cued or when one foot and one hand are cued (Leuthold and Jentzsch 2001, 2002; Jentzsch et al. 2004). Because we instructed participants to prepare whatever they could, it is possible that in our experiment participants used a strategy of preparing multiple responses, particularly in the bimanual 2 S-R alternative precue conditions, and the startle simply elicited whatever was pre-programmed.

For the sake of comparison, in a previous experiment involving a startled choice RT task, errors were only recorded in 13.3 % of startle trials involving choice, and only 1/3 of these were movement production errors (Carlsen et al. 2004a). It seems apparent, therefore, that participants were preparing differently in these two studies. However, in the Carlsen et al. study (2004a), the 2 S-R alternative condition was limited to flexion or extension of the right wrist. This is the same situation as the hand precue in the current experiment. For the hand precue it intuitively seems difficult to prepare multiple movements to both flexion and extension targets. Also, the majority of errors observed

(72.7 %) involved movement initiation into flexion with a subsequent quick correction into extension with the right hand (Figure 5.1c). It is doubtful, however, that there is any other type of error that would be produced in this condition. For example, if there are only two targets, and both cannot be prepared concurrently, the only error that might be observed would be initiation towards the wrong target. Additionally, only 37.5% of all hand precue startle trials were errorful, which was much less than in the bimanual precues (68.8%). Thus only 27% of hand precue startle trials resulted in the most commonly observed error. In this case it is difficult to argue that both movements were being prepared, although it cannot be completely ruled out as some early co-activation was observed in the wrist muscles which might be indicative of the initiation or release of two movements (see Figure 5.1c).

A second piece of evidence that the precues led to the pre-programming of multiple responses is the early EMG onset latencies observed for the errorful movements. In the startled 2- and 4-choice precue conditions, errorful responses (ST-E) had EMG onsets that were shortened to latencies that were not significantly different to those observed in the startled full precue condition (Figure 5.2). That is, no PMT difference was observed between the precue conditions in the ST-E trials. This represents a RT decrease in ST-E trials of more than 50% compared to control in most cases. RT decreases due to startle have been previously observed in many movement effectors and movement types including wrist flexions / extensions (Carlsen et al. 2003a, 2004a, 2007; Cressman et al. 2006; Valls-Solé et al. 1995, 1999), arm extensions (Carlsen et al. 2004b), neck flexions (Seigmund et al. 2001), eye saccades (Castellote et al. 2007) and anticipatory postural adjustments (MacKinnon et al. 2007). Because of the dramatic

nature of the RT decreases that have been observed, and the fixed time required for transducing the stimulus and neural conduction, it was suggested that startle elicited RTs were too short to have involved cortical loops (Carlsen et al. 2004b, 2007; Valls-Solé et al. 1999). It has been hypothesised that sufficient details about the movement (e.g. the motor program, see Keele 1968) are stored subcortically, possibly in brainstem and spinal centres (e.g. the pontine reticular formation) that are common to both the voluntary activation and the startle response pathways (Carlsen et al. 2004b; Rothwell 2006; Rothwell et al. 2002), allowing the startle response neural activation to trigger the prepared action directly (Carlsen et al. 2003; Valls-Solé et al. 1999) instead of the usual cortical “go” signal (Keele 1968; Klapp 2003; Wickens et al. 1994). However, these tasks involved exclusively simple RT tasks (i.e. 1 S-R pair). When a choice RT task was studied, no RT shortening due to startle was observed (Carlsen et al. 2004a). Thus it has been argued that a startling stimulus can act as an early trigger for a movement but only if the upcoming response is certain and the response can be prepared in advance, or “pre-programmed” (Carlsen et al. 2004a). Thus, because the EMG onset latencies observed in trials in which an error was committed were so short, and because many of the errorful responses elicited reflected multiple movements to the precued response options, it appears that the participants often prepared multiple responses, and that these were elicited at short latencies by the startle. This was particularly evident when there were two precued alternatives involving separate hands.

The effect of a startle on PMT when no error was detected (ST-NE) is shown in Figure 5.3. When the required response was known (full precue), the startle led to a large decrease in mean PMT from 145.0 ms to 93.1 ms. This result was not surprising, since it

has been shown several times that in a simple RT task, presentation of a startling stimulus coincident with the IS results in a dramatic decrease in RT (Carlsen et al. 2004b, Valls-Solé et al. 1999). The pattern of RT decrease due to startle observed here when more than one response alternative was present, however, is somewhat different to that observed in a previous study looking at the effect of startle on a choice RT task (Carlsen et al. 2004a). Specifically, it was previously found that when erroneous trials were removed (only 13% of all trials), there was no difference in RT between control and startle trials if a movement choice had to be made based on the identity of the IS. This was the case irrespective of whether 2 or 4 choices were presented (Carlsen et al. 2004a). However, in the current experiment, mean PMT in the ST-NE trials was significantly shorter than in control trials, although the pattern of RTs was similar to control trials. That is, PMT in the full precue was shortest RT, whereas PMT in the 2 S-R alternative precues were longer, and PMT for the no-precue condition was longest (Figure 5.3). It appears that no PMT facilitation resulted due to startle in the uncued (4 S-R alternative) condition. However, there was a RT facilitation due to startle of up to 51 ms in the non-errorful 2 S-R alternative precue conditions (Figure 5.3). Thus the question arises regarding the reason for the differences in the effect of the startle between the choice RT (Carlsen et al. 2004a) and precuing paradigms. In the ST-NE trials involving 2 or 4 S-R alternatives, the startle did not decrease PMT to the point that cortical activity can be ruled out (see Carlsen et al. 2004b; Valls-Solé et al. 1999), thus it could be that the observed PMT decrease was simply due to stimulus intensity (Piéron 1919, cited in Woodworth 1938; see also Kohfeld 1969). Furthermore, recent evidence suggests that the effect of startle on RT is distinct from the effect of stimulus intensity (Carlsen et al.

2007). Alternatively, in some circumstances, participants may have employed a guessing strategy based on the identity of several previous trials. If this were the case, one might expect to see some trials in which the correct response was pre-programmed leading to a shorter mean PMT. However, if errors were removed, and a guessing strategy was not used consistently, this should result in more variable PMTs. Looking at the PMT data for the ST-NE condition (Figure 5.3), it appears that the startled bimanual 2 S-R alternative conditions are more variable, although this was not confirmed statistically.

Other Considerations

Two aspects of the data have not yet been discussed, pertaining to the corrections observed in erroneous trials, and pre-programming in the erroneous no-precue trials. It appears that both responses were not triggered in their entirety in erroneous trials, as can be seen in Figure 5.2. Specifically, the hand or direction error appears to have been corrected at short latencies to return to the home position (for the left hand in the extension and rightward precues) or to be reversed (for the right hand precue). One explanation for this behaviour involves the order of events; the auditory startle triggered the response(s), but simultaneously the correct target was presented visually. It has been recently shown that short latency corrections can be made in visuo-motor targeting tasks (Pisella et al. 2000). The dorsal stream, which has been described as “vision for action,” (Milner and Goodale 1995) acts with a very short latency to enable online corrections to ongoing movements, some with movement times of less than 200 ms (Desmurget et al. 1998). Thus it is possible that although the responses were triggered by the startle, a short latency dorsal-stream mediated correction mechanism allowed for the errors to be rapidly attenuated and the final position altered.

The number of programmable multiple responses may be limited to 2 because although numerous errors were observed in the no-precue (4-choice) condition, no single error type was observed a majority of the time (Table 5.1b). This conclusion is supported by earlier results (Rosenbaum 1980) that found a high number of errors when participants were told to attempt to prepare multiple responses. These findings showed that participants were unsuccessful at pre-programming for high numbers of S-R alternatives (Rosenbaum 1980).

Conclusion

In summary, it appears that when provided information regarding the possible upcoming response alternatives through response precuing, participants used several distinct strategies. First, it appears that the task was often performed as a choice RT task, where participants did not select and prepare a response until the IS provided the correct target. Second, sometimes participants may have used a guessing strategy, pre-programming one of the possible responses in advance, in which case sometimes the startle triggered the correct response and sometimes the incorrect response. Finally, it is evident that often participants chose to pre-program up to 2 of the possible response alternatives, thus affecting mainly the motoric response programming processes. This result is novel in that it provides behavioural evidence for the pre-programming of multiple responses. Previous results have suggested that precues only aid in decreasing the number of S-R alternatives, in effect simply aiding the decision making processes (e.g. Goodman and Kelso 1980), or that precues act to allow for *partial* response programming of the known response dimensions (e.g. Rosenbaum 1980). Because the addition of a startle led to the production of movements that reflected the precued

response alternatives at short latencies, it appears that when faced with a maximum of 2 choices, particularly when the movements can be made with opposite limbs, a strategy that is employed is to prepare for *all* response alternatives.

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6. Experiment 5

When is an Action Prepared in an Anticipation Timing Task?

A version of this chapter will be submitted for publication:

Carlsen AN, Chua R, Inglis JT, Sanderson DJ, Franks IM (in preparation) When is an action prepared in an anticipation timing task?

Introduction

Many everyday tasks require people to respond to environmental stimuli by producing a movement coincident with some external event. For example, a batter in baseball or cricket needs to time their swing to coincide with the arrival of the ball. In certain circumstances, however, the movement must be halted prior to its execution (e.g. a “checked swing” in baseball) in order to achieve maximal success. If the decision to stop the action is made too long after the decision to execute the movement, it cannot be prevented. Using a stop signal or countermanding paradigm, Henry and Harrison (1961) found that participants were able to begin to stop their movement only when a stop signal was given shortly following a go signal (110 ms). If the stop signal was given 190 ms following the go signal, but still preceding any overt movement, participants were not able to even begin to slow the movement before it was completed. It was suggested that in these tasks, the motor program must have been prepared in advance and irreversibly triggered to run off in its entirety (see Keele, 1968). This implies that there was a “point of no return” after which it was not possible to prevent the execution of a prepared response.

Slater-Hammel (1960) concluded that a similar point of no return existed for anticipatory movements in which participants were required to lift their finger off of a button coincident with a clock hand, which moved around the clock face in 1 sec, reaching the 10 o’clock position. On some trials, the clock hand stopped prior to reaching the target. In these cases the participant was instructed to refrain from lifting off the button. When the clock sweep stopped 200 ms prior to reaching the target, participants were almost always able to prevent movement production (probability of moving = ~0).

Conversely, when the clock sweep stopped 80 ms prior to target, participants almost invariably carried out the button release (probability of moving = ~ 1). The point at which participants were only able to inhibit the movement 50% of the time was deemed to be the point of no return. In the case of Slater-Hammel (1960) this was found to occur at 168 ms before the anticipated time of movement.

An anticipation timing task is different from a reaction time (RT) task or a stop signal task, because in the timing task there is no temporal uncertainty regarding the action. In a RT task (and also a stop signal task), the time at which the required action must be executed is not known until a “go” signal is given. To achieve the fastest RTs in these tasks, it may be beneficial to prepare the response in advance and simply trigger the response following the imperative stimulus (e.g. Keele 1968; Klapp 2003). While it has been suggested that a prepared response is irreversibly triggered at some point in an anticipation timing task (Slater-Hammel 1960), it is unclear when the response is programmed with respect to the target. It is possible that the motor program is prepared when the warning signal is given (e.g. when the clock hand starts moving, Slater-Hammel, 1960), or any time up until response execution.

Through the use of a startling stimulus in an anticipation timing task, it may be possible to determine the time at which the response is pre-programmed. The presentation of a startling acoustic stimulus (124 dB) during RT tasks has resulted in significantly shortened RTs (Carlsen et al. 2004b; Siegmund et al. 2001; Valls-Solé et al. 1999). Due to the dramatic nature of the decrease in RT without any modification to the kinematics or neurophysiological characteristics (Carlsen et al. 2004b) of the movement, it was argued that the startle acts as an early “trigger” for a pre-programmed response.

Additionally, because some of the RTs observed when a startle was presented were so short (e.g. <70 ms) it was suggested that the motor program was somehow released via subcortical structures, bypassing the normal cortical execution pathways (Carlsen et al. 2004b; Valls-Solé et al. 1999). This was exemplified in an experiment by Carlsen et al. (2003b) in which participants extended the elbow and opened their hand at a prescribed target elbow angle without visual feedback. A startling stimulus was presented at various elbow angles prior to the target angle. When the participants were startled early in the extension (primary) movement, hand opening (secondary movement) was unaffected; however, when startled late in the primary movement, the secondary movement was elicited early. The authors suggested that this pattern of results indicated that the secondary movement was only prepared and “loaded” into a storage buffer late in the course of the primary movement (Carlsen et al 2003b).

Thus the purpose of the present experiment was to investigate the nature of the motor preparatory processes that occur during an anticipation timing task by introducing a startling stimulus into the paradigm. It was hypothesized that the startle would act to trigger the prepared response once it was programmed. In this way, the time at which the response was able to be triggered by the startle would reflect the time at which the response was programmed and ready for voluntary execution.

Method

Participants

Eighteen right-handed volunteers (11M, 7F; ages 26 +/- 4 years) participated in the study after giving informed consent. Testing of each participant took place in one afternoon session. All participants gave written informed consent, and the study was

conducted in accordance with the ethical guidelines set by the University of British Columbia (see Appendix A). A large proportion of participants were excluded from analysis due to the absence of a reliable startle response (see Results section). Thus the final analysis included data from 11 participants (7M, 4F; ages 26 +/- 4 years).

Participant Position

The participants sat in a height-adjustable chair facing a table, with their right arm resting on the table in a pronated position and oriented at an angle of 15 degrees to the right of the body midline, with the shoulder flexed and abducted approximately 30 deg. The right arm was secured to the table using a Velcro strap placed ~5 cm proximal to the wrist joint. The hand was resting in a neutral position with the middle and ring fingers (digits 3 & 4) in contact with a telegraph key. The starting position for the movement was to have the key depressed.

Task and Feedback

On a computer monitor, placed 1 m in front of the participant, a representation of an analog clock face (10 cm diameter) was provided except that only 10 digits were evenly spaced around the circumference, with "10" being in the topmost position. The clock hand was consistently timed so that it made one revolution in 1 sec. At the start of a trial, a warning tone indicated trial commencement. One second later, the previously stationary clock hand then moved from the topmost position (10) in a clockwise direction, stopping on the "8". The experimental task was for the participant to lift the hand off of the telegraph key coincidentally with clock hand reaching the 8 (800 ms) position on the clock face by using a quick wrist extension movement. On certain trials

(see below) the clock hand stopped prior to reaching the 8 which was accompanied by a concurrent acoustic stimulus, and on these trials participants were instructed to attempt to not produce the movement. Participants were instructed that the acoustic stimulus would be variable in loudness, but that it was irrelevant to the task, and they should simply ignore it. Timing error (ms) feedback was provided by a pop up display and the clock hand also indicated the time of button lift relative to the target on the same computer monitor display. Participants were encouraged (via monetary bonus) to time their movement as accurately as possible to minimize error. Trial initiation, as well as feedback presentation was controlled via custom software written with LabView® Software (National Instruments Inc.).

Stimuli

The warning tone (200 Hz, 80 dB, 100 ms) was generated by the computer using a 16 bit sound card (Creative SoundBlaster 16®) and standard computer speakers (Juster® sp-691n). The computer program generated the acoustic stimuli consisting of a narrow band noise pulse (1000 Hz, 40ms duration) which was amplified and presented via a loudspeaker (<1 ms rise time) placed directly behind the head of the participant with an intensity of either 82 dB (control stop tone) or 124 dB (startle stop tone). The stimulus intensities were measured using a sound level meter (Cirrus Research model CR:252B) at a distance of 30 cm from the loudspeaker (approximately the distance to the ears of the participant).

Experimental Trial Types

Control trials (C) were trials in which the clock hand continued to the target without stopping and no auditory stimulus occurred during the trial. Stop trials were trials in which the clock hand stopped moving at 80, 110, 140, 170, 200, 230, or 260 ms prior to the clock hand reaching the target. Control stop (CS) trials were trials in which the 82 dB stimulus was presented when the clock hand stopped, while Startle stop (SS) trials were stop trials in which the 124 dB startle stimulus was presented when the clock hand stopped.

Participants performed 2 blocks of 112 trials in which 21 CS (3 at each stop latency) and 7 SS trials (1 at each stop latency) were randomly dispersed for a total of 56 stop trials per participant out of 224 total trials. Thus stop trials (CS and SS) occurred with a frequency of .25, and no more than 2 consecutive trials were stop trials. SS trials did not occur within the first three trials of any block and there were never two consecutive SS trials. Participants were allowed to practice the coincident timing task prior to testing to familiarize themselves with the task and equipment. Task practice consisted of 2 blocks of 10 practice trials, the first block containing no stop trials, and the second block containing 3 control stop stimuli.

Recording Equipment

Surface Electromyographic (EMG) data were collected from the muscle belly of the right extensor carpi radialis longus (ECR), and the left sternocleidomastoid (SCM) muscles using bipolar preamplified Ag/AgCl surface electrodes (Therapeutics Unlimited). 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 radial styloid process. The EMG electrodes were connected via shielded cabling to an external amplifier system (Therapeutics Unlimited Inc. Model 544). The telegraph key provided a 5 V signal when the switch was depressed and 0 V when lifted. All data were digitally sampled at 1 kHz (National Instruments® PCI-6023E) using a customized program written with LabVIEW® software.

Data Reduction

Movement onset (i.e. key release) was determined by evaluating the telegraph key data for the first point at which the voltage abruptly changed from 5 V to 0 V. Target error was defined as the amount of time between the clock hand arriving at the target and key release. Negative error was when the key was released prior to the clock hand reaching the target, while positive error was when the key was released after the clock hand reached the target.

EMG burst onsets were defined as the point at which the EMG first began 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 preceding onset). 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. EMG offsets were marked in a similar fashion, with the activity between EMG onset and EMG offset being defined as a distinct burst. Peak EMG amplitudes were defined as the largest EMG amplitude,

rectified and filtered with a 25 Hz lowpass elliptic filter, recorded within an interval of 100 ms following EMG burst onset.

Statistical Analyses

Dependent variables were analyzed using repeated measures ANOVAs (described in Results section). Proportion variables were subjected to an arcsine square root transform prior to analysis. Greenhouse-Geisser corrected degrees of freedom were used to correct for violations of the assumption of sphericity. Differences with a probability of less than .05 were considered to be significant. Tukey's Honestly Significant Differences (HSD) post-hoc tests were administered to determine the locus of any differences.

Results

Startle Response

EMG activity in the sternocleidomastiod (SCM) muscle occurring within 120 ms of stimulus onset was used as an indicator of whether a startle response was elicited by the 124 dB stimulus (see Carlsen et al. 2003a, 2007). Startle trials in which no SCM activity was present were discarded from analysis, as it was the effect of a startle on the performance of the task that was of interest. For seven of the participants this procedure led to the elimination of a substantial number of startle trials, resulting in limited startle trial data that precluded appropriate analysis, thus data from these participants were excluded from analysis. For the remaining 11 participants no more than 1 startle trial was discarded from analysis.

SCM onset latency in the SS trials was analyzed for differences between the stop times (80 – 260 ms) using repeated measures ANOVA. No difference was observed in

latency between any of the stop times, $F(6,60) = 1.371$, $p = .241$, $\eta_p^2 = .121$ (collapsed mean SCM onset following the 124 dB stimulus was 53.8 ± 9.7 ms).

SCM peak amplitudes were normalized by expressing them as a percentage of the mean peak amplitude observed in the SS-170 ms condition (the midpoint of the possible stop times) for each participant. These were analyzed for differences between the stop latencies. Results are presented in Figure 6.1. A main effect was found for stop latency, $F(6,60) = 3.036$, $p = .012$, $\eta_p^2 = .233$; however, post-hoc analysis indicated that SCM amplitude was only larger in the SS-140 condition compared to the SS-260 condition. A significant linear trend was also present ($p = .011$), indicating that the SCM amplitude tended to increase as the time to target decreased.

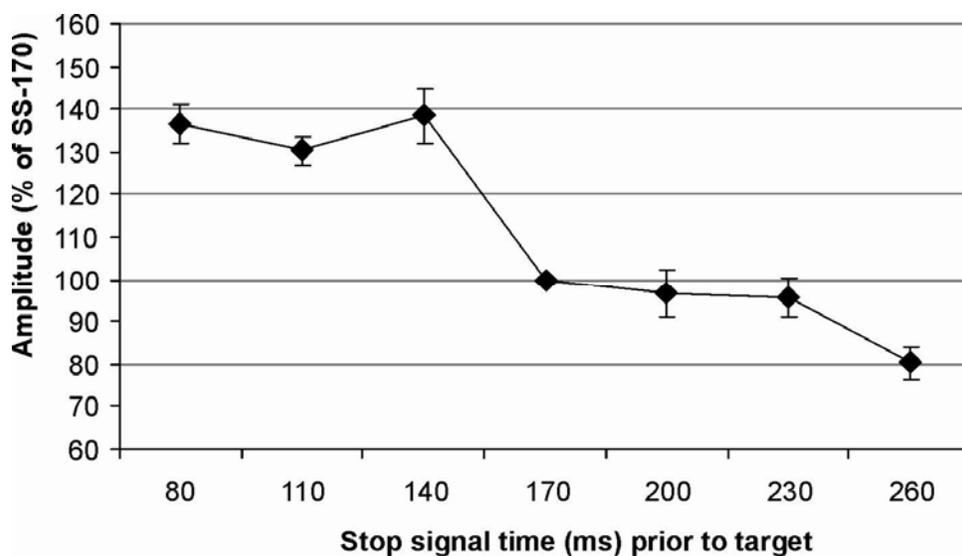


Figure 6.1 Mean amplitude (+/- SE) of sternocleidomastiod (SCM) EMG activity as a function of stop signal time prior to target in the startle stop (SS) condition. Values are grand means of EMG amplitudes as a percentage of each participant's SCM amplitude in the SS-170 condition (i.e. startle stop signal occurring at 170 ms prior to target).

Target Accuracy

Mean time of button lift was recorded for each participant. Mean constant error (CE), mean variable error (VE), and mean absolute error (AE) were then calculated in the control condition. CE was determined for each participant simply by calculating the mean of the raw difference between key liftoff and the target. VE was determined for each individual by calculating the standard deviation of the mean performance. AE was determined individually by taking the mean of the absolute values of the differences between the times of key lift and the target in control trials. Mean CE across participants was +0.98 ms, Mean VE was 30.0 ms, and Mean AE was 24.9 +/- 4.9 ms.

Probability of Responding

For each participant, the mean proportion of observed button lifts (overt responses) at each stop latency and for each stimulus was calculated. Results are presented in Figure 6.2. These were analyzed for differences using a 2 (stimulus) x 7 (latency) repeated measures ANOVA. A main effect was found for stop latency, $F(6,60) = 57.224$, $p < .001$, with shorter stop latencies prior to the target being associated with a higher proportion of observed button lifts. Importantly, no main effect was found for stimulus $F(1,10) = 2.223$, $p = .167$, $\eta_p^2 = .182$, and no significant interaction existed between the factors.

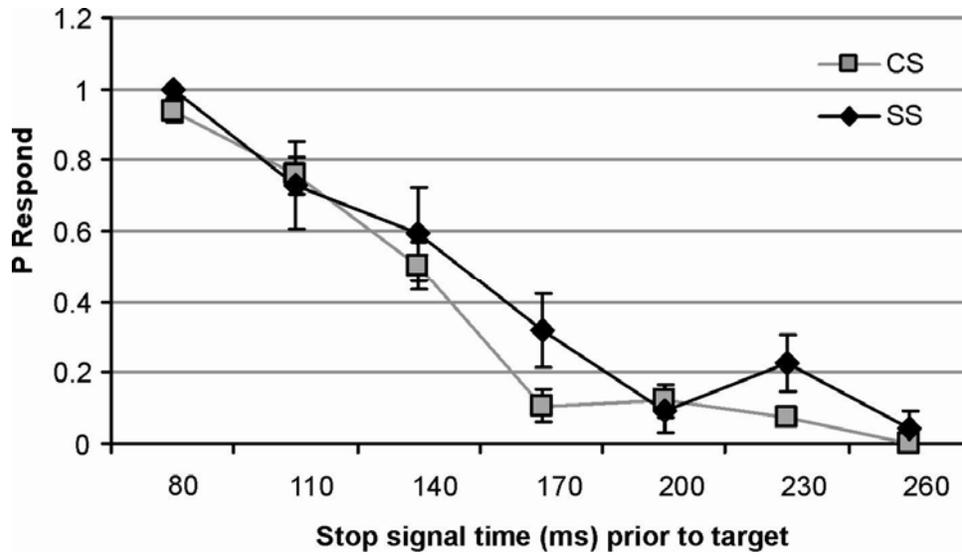


Figure 6.2 Mean (+/- SE) probability of observing an overt response (key lift) as a function of stop signal time prior to target in the startle stop (SS) and control stop (CS) conditions.

Partial Responses

Data regarding partial responses was drawn from a limited data set, since only 2 startle stimuli were presented at each stop latency. Thus, although these data are informative, caution should be exercised in their interpretation.

Partial responses were defined as stop trials in which no overt response was observed (i.e. no key lift was recorded), but EMG activity was nonetheless apparent in ECR (see Analysis section above). The probability of observing a partial response was analyzed for stop latencies of >170 ms (i.e. those stop latencies with a probability of responding of $<.5$, see Figure 6.2), in order that a sufficient number of trials was used to calculate this value. Thus the proportion of partial responses observed was analyzed using a 2 (stimulus) \times 4 (stop time: 170 – 260) repeated measures ANOVA. Data are presented in Figure 6.3A. A main effect was found for stimulus, $F(1,10) = 13.691$, $p = .004$, $\eta_p^2 = .578$, indicating that a larger proportion of partial responses was observed when a 124 dB startle stimulus was presented compared to 82 dB control. A main effect was also found for stop time, $F(3,30) = 3.104$, $p = .041$, $\eta_p^2 = .237$. Post-hoc analysis indicated that the only significant difference between the stop times existed between 200 ms and 260 ms ($p < .05$), however, a significant linear trend was found for stop time ($p = .024$), indicating that the proportion of partial responses tended to increase as the time at which the clock hand stopped prior to the target decreased. No significant interaction was found between the factors.

Partial response peak amplitudes were normalized by expressing ECR EMG as a percentage of the mean peak amplitude observed in the control (go) condition for each participant. Partial response peak amplitude is shown in Figure 6.3B. Because partial

responses were not observed in all conditions for all participants, it was not possible to analyze this variable using ANOVA, however, there appears to be a small trend toward larger amplitude partial responses as the time to target decreases. Although not statistically reliable here, this result agrees well with a previous study investigating response inhibition in a similar task (Coxon et al. 2006).

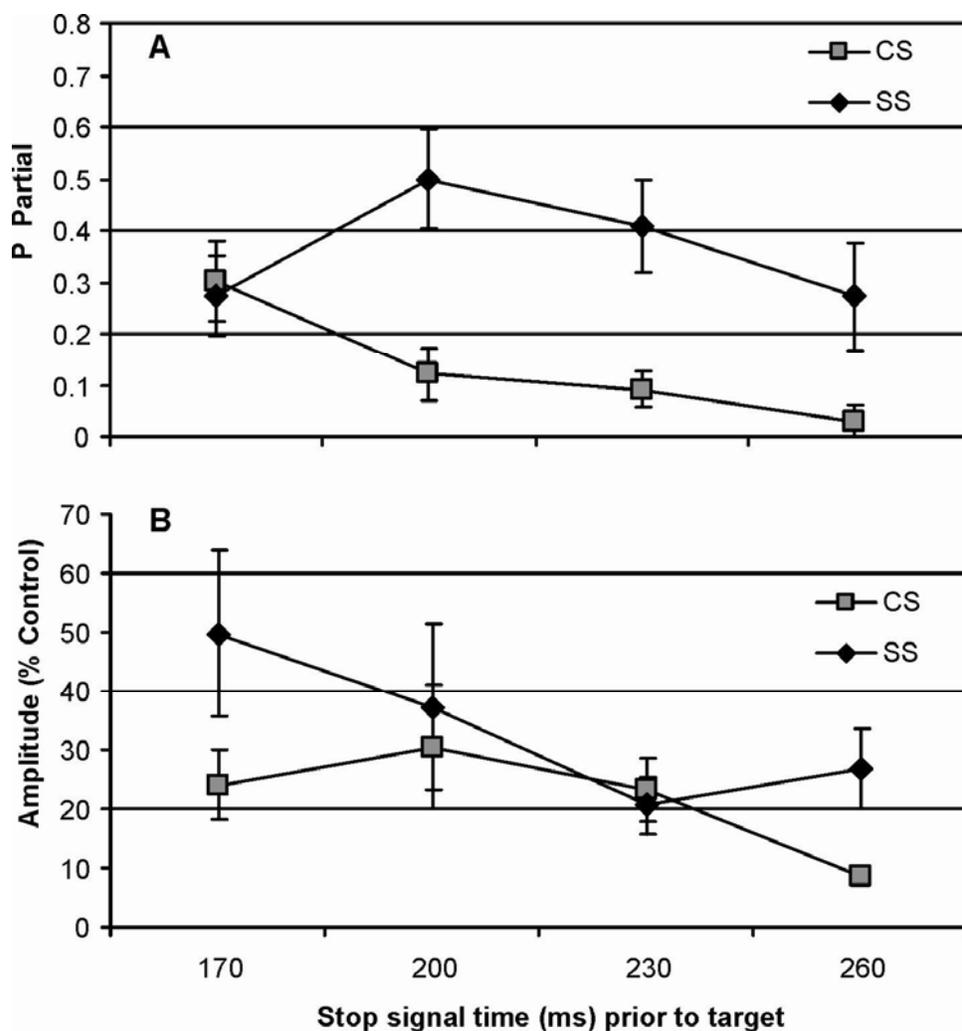


Figure 6.3 Data from observed partial responses. A) Mean (+/- SE) probability of observing a partial response (EMG activity with no key lift) as a function of stop signal time prior to target in the startle stop (SS) and control stop (CS) conditions (only for conditions in which probability of responding <.5). B) Mean (+/- SE) amplitude of ECR EMG observed in partial responses as a percentage of mean ECR EMG activity observed in each participant's control "go" trials.

Discussion

The purpose of the present experiment was to investigate when motor preparatory processes (e.g. motor programming) occur during an anticipation timing task by using a startling acoustic stimulus. Either a 124 dB (startle) or 82 dB (control) stimulus was presented in a coincident timing task that involved the possibility of not producing the movement if the clock hand stopped prior to reaching the target. Here we provide data that indicate that although some preparation of motor circuits is evident prior to response onset, the final motor program is not prepared until immediately prior to responding. This conclusion is based on three pieces of data: First, the presence of a startle did not result in the triggering of a prepared response, which would have been evidenced by a higher proportion of observed button lifts in startled stop trials compared to control. Second, activity in SCM increased linearly as the time to target decreased. Finally, the proportion and amplitude of partial responses increased as time to target decreased. These data suggest that motor preparatory activity begins to increase at least 260 ms prior to the target, but is not sufficiently developed to result in motor program release when a startling stimulus is presented.

Target Accuracy

Overall, participants were very accurate in the ability to time key liftoff with the clock hand reaching the target in “go” trials. Mean AE, which provides a gross measure of overall accuracy, across all participants was 24.9 ms, slightly smaller than that reported by Slater-Hammel (28 ms), indicating that participants were accurate in timing the lift off the telegraph key with target arrival. Similarly, mean VE was 30.0 ms, indicating that variability around the target was of a similar magnitude to that observed in

AE. Mean CE, on the other hand, provides a measure of response bias, which in the present study was +0.98 ms. This value was much smaller than that reported previously (+26 ms) by Slater-Hammel (1960), who suggested that if the possibility of a “stop” trials was present, participants waited a little longer before initiating movement in case a stop signal occurred, resulting in a consistently late movement onset bias. In the present study, participants were offered a monetary reward for target accuracy, and had an informal competition for who was most accurate, which likely counteracted the late bias strategy observed by Slater-Hammel, and led to the small observed response bias.

Probability of Responding

The probability of responding when the clock hand stopped prior to reaching the target was calculated for each of the stop times (Figure 6.2). From these results, it is apparent that the overall pattern observed by Slater-Hammel (1960) was approximated in both the control stop (CS) and startle stop (SS) conditions. In both cases, there was a high probability that the participants would produce the movement (key release) if the clock hand stopped with a short latency (80 ms) prior to the target, and a low probability of response production if the clock hand stopped sufficiently early with respect to the target (260 ms). Slater-Hammel (1960) suggested that the point in time prior to the target at which the probability of responding increased above .5 (i.e. a response was produced in >50% of trials) was the point of no return, where the motor program was triggered and a “stimulus presented after this point cannot be acted upon” (p.225). Slater-Hammel located this point at 140 ms prior to target (166 ms after correction due to +26 ms constant error). Similarly in the current experiment, the point at which the probability of responding increased above .5 was approximately 140-150 ms (see Figure 6.2). Thus it

appears that after this point, the programmed response was likely to be irreversibly triggered. More recent research employing psychophysiological measures (e.g. EMG), however, reveals that the point of no return may not be as clear as this. Specifically, evidence for partial and interrupted responses has been previously reported by McGarry and Franks (1997) indicating that an independent inhibitory process may be able to act upon the previously triggered “go” response. Irrespective of any inhibitory processes, however, the volitional response must be pre-programmed at some point prior to initiation in order to be triggered.

Importantly in the current experiment, there was no difference in the proportion of key releases at any of the stop times between the two acoustic stimulus conditions. This result indicates that the response was probably not “programmed” in its entirety until just prior to response production. The reason for this conclusion is twofold: First, the presence of a startle did not result in early triggering of a response as would be evidenced by an increased proportion of produced responses at all stop latencies. A startling stimulus, when presented coincident with the imperative stimulus (IS) in a RT task has been shown to act as an early response trigger for a pre-programmed action. This was first demonstrated by Valls-Solé et al. (1995) in a wrist extension task, and has since been replicated using various other tasks such as foot dorsiflexion (Valls-Solé et al. 1999), arm extensions (Carlsen et al. 2004b), neck flexions (Seigmund et al. 2001), eye saccades (Castellote et al. 2007), stepping (Reynolds and Day 2007), interceptive actions (Tresilian 2006), and postural adjustments (MacKinnon et al. 2007). It has been argued that the effect of startle is not simply a “stimulus intensity effect” (e.g. Woodworth 1938; Luce 1986), since RT was shortened significantly more when a startle response was observed

than when it was not observed for the same intensity stimuli (Carlsen et al. 2007). Critically, it appears that an action must have been prepared in advance (i.e. pre-programmed) in order for the startle to elicit the movement. For example, when participants were startled in a choice RT task where the required movement was provided by the identity of the IS, no shortening of RT was observed due to startle (Carlsen et al. 2004a). This was presumably because no pre-programming could occur when the required response was not certain. Thus it has been hypothesized that a prepared motor program can be triggered early by the startle, likely involving subcortical structures common to both the voluntary response pathway and the startle response pathway, such as the reticular formation (Carlsen et al. 2004b; Rothwell 2006; Rothwell et al. 2002).

In the present experiment, the presence of a startle response did not elicit the key lift any more often than a control acoustic stimulus (Figure 6.2), suggesting that the response was not pre-programmed and stored in motor circuits accessible to the startle volley. This is not particularly surprising considering the nature of the task. In an anticipation-timing task there is no temporal uncertainty, so there may be no benefit to pre-programming and storing the action. In comparison, during a simple RT task, where there is temporal uncertainty, pre-programming would provide a considerable speed advantage since only response execution or triggering would be necessary following the IS. Thus in a timing task it may not be of critical importance to program the movement in advance of execution.

In a previous experiment performed in our lab, a startle also did not elicit a motor program until shortly before execution. In a compound movement task requiring opening the hand when the arm reached a target elbow angle, the presence of a startling stimulus

only led to early release of the secondary movement (hand opening) when the arm neared the target (Carlsen et al. 2003b). Similar to the present experiment, when a startle was presented earlier in the movement, the secondary movement was not elicited, likely because it was not beneficial to pre-program until later. However, since kinesthetic information was used as a trigger for the secondary movement (Cordo et al. 1994), pre-programming was nevertheless necessary prior to execution and this program was able to be elicited by startle once programmed (Carlsen et al. 2003b).

A second piece of evidence suggests that limited response preparation occurred prior to response production: An unusually large proportion of participants did not exhibit a consistent startle reaction when exposed to the 124 dB stimulus. Under normal circumstances, the proportion of “low responders” who exhibit a limited startle response is approximately 20% (Abel et al. 1998; Geyer and Braff 1982). Here, data from 7 of 18 participants (38.9%) had to be excluded due to lack of startle related SCM EMG activity. It has been reported that participants will normally habituate to a startling stimulus within 2 - 6 random presentations (Brown et al. 1991), but habituation was reduced when participants were engaged in a RT task (Carlsen et al. 2003a; Valls-Solé et al. 1997). A reduction in habituation, or more precisely, dishabituation, was suggested to occur due to increased motor preparation. Specifically, it was argued that the increased excitability of the startle response pathway due to motor readiness was sufficient to allow the startle response to continue to be elicited after many more presentations than would normally result in habituation (Carlsen et al. 2004b). Therefore, in the present study, since a high proportion of participants did not exhibit a consistent startle response, it appears that there was insufficient motor preparation to counter the startle habituation.

Preparation of Motor Circuits

Although there appeared to be insufficient motor programming to either result in early response triggering by startle or to counter startle response habituation, there was some evidence of increased excitability in subcortical motor circuits. As the time prior to target decreased, SCM EMG activity became significantly larger, and the proportion and amplitudes of partial responses also increased.

EMG activity in the SCM muscle has been used previously employed as an indicator of both the presence and magnitude of a startle response (Brown et al. 1991; Carlsen et al. 2003a, 2007; Valls-Solé et al. 1997). Indeed, even in the present experiment data were excluded based on an absence of measurable SCM EMG activity. More recently, however, it was suggested that the excitability of subcortical motor pathways could be examined by using a startling stimulus in both simple and choice RT tasks (Kumru et al. 2006a, 2006b). These pathways include both startle reflex (Yeomans and Frankland 1996) and voluntary movement-related (Buford and Davidson. 2004; Schepens and Drew. 2004) circuits between the pontine reticular formation and limb motoneurons. Specifically, it was shown that SCM amplitude was consistently increased when participants were engaged in a simple RT task (Kumru et al. 2006b), while SCM amplitude was modulated based on whether participants were required to perform a choice RT task or Go/noGo RT task (Kumru et al. 2006a). It was argued that the amplitude of the SCM EMG activity reflected the underlying excitability of the subcortical motor pathways during these tasks. Similarly, in the present experiment, SCM amplitude was found to increase as the time to target decreased (Figure 6.1). Most

interestingly, the largest increase appears to coincide with the point (~140 ms prior to target) at which probability of responding increased above 50% (Figure 6.2).

A similar finding was reported by Coxon et al. (2006) who used transcranial magnetic stimulation (TMS) to investigate the corticomotor excitability. Using an anticipation timing task similar to the one used in the present experiment, it was found that as the time to target decreased, motor evoked potentials (MEPs) increased, particularly in the final 170 ms prior to target (Coxon et al. 2006). This result indicates that the excitability of the corticomotoneuronal pathway increased as the time to initiate the action approached. The results of the current experiment suggest that not only corticomotoneuronal pathways are enhanced as the time to target decreases, but that subcortical, reticulospinal pathways are similarly enhanced.

Partial Responses

On some stop trials, although the movement was not produced, there was nevertheless some EMG activity observed in the wrist extensor (ECR). These responses were classified as “partial” responses. Although a distinction has been made previously between partial and “interrupted” responses (see McGarry and Franks 1997), insufficient trials were available in the current study to make an appropriate analysis between the two classifications. As such, any conclusions based on these data should be weighted appropriately. As the time to target neared, there was a corresponding increase in the proportion of partial responses observed (Figure 6.3A), as well as an apparent increase in the amplitude of the observed partial responses (Figure 6.3B). This result has been shown previously (Coxon et al. 2006), with both the proportion and the size of partial responses increasing as the stop latency decreased (i.e. as time to target decreased). It has been

suggested that partial responses are the result of an independent inhibitory process acting upon the “go” response after it has been initiated either at the level of the motor neuron pool (McGarry and Franks, 1997) or at a cortical level (Coxon et al. 2006). Thus it is not surprising that more partial responses would be observed as the time to target decreased, as more time would have passed since the go response was initiated, leading to a lower probability of a later inhibitory process stopping the action. Interestingly, in the current experiment more partial responses were observed in the SS conditions compared to CS, suggesting that more “go” responses were initiated in the SS trials. This may be evidence that the startle sometimes acted to initiate the response early, but that inhibitory mechanisms were nonetheless able to successfully stop the production of the overt movement in time. Alternatively, the increased proportion of “partial responses” in the startle conditions may simply be startle response related EMG activity detected in the ECR muscle. Although the current data preclude a detailed analysis of these partial responses, further investigation is warranted due to the suggestive nature of the observed responses.

Conclusion

In summary, the present experiment investigated motor preparation occurring in an anticipation timing task by combining a stop signal and a startling stimulus at various latencies prior to a voluntary movement target. Although some evidence of preparatory activity was observed in subcortical motor pathways (Figure 6.1 & Figure 6.3), the startle did not act to trigger the response directly as no increase in proportion of overt responses was observed compared to control (Figure 6.2). These data indicate that when there is no

temporal uncertainty such as in an anticipation timing task, final motor programming occurs only immediately prior to response initiation.

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7. Experiment 6

Effects of Startle and Increased Response Complexity on Motor Preparation and Reaction Time

A version of this chapter will be submitted for publication.

Carlsen AN, Chua R, Inglis JT, Sanderson DJ, Franks IM (in preparation) Effects of startle and increased response complexity on motor preparation and reaction time.

Introduction

Early motor control theories attempted to explain the covert information processing stages that occur during a reaction time (RT) task in terms of the novel (at the time) computer. One theory envisioned that programming a movement was similar to retrieving information from a computer storage device called a memory drum (e.g. Henry and Rogers 1960). This analogy was used to explain the observation that RT increased as a function of response complexity. It was thought that more complex movements comprised more information and thus took longer to program. Henry and Rogers (1960) had participants perform several movement tasks of differing complexity (i.e. different number of movement components) within a simple RT paradigm. In each case the required response was known beforehand to the participant. The first task was a simple finger lift off of a button. The second task involved lifting the hand off the button and grasping a tennis ball that was hung from a string. The third task involved lifting the hand, striking the ball, pushing a second button and then striking a second ball. Their results showed that the RT increased with increasing movement parts, or complexity (for examples of other studies producing similar findings see Anson 1982; Christina and Rose 1985; Fischman 1984; Kasai and Seki 1992; Ketelaars et al. 1997; Van Donkelaar and Franks 1991).

Within a traditional information processing framework, the independent stages of processing (e.g. stimulus identification, response selection, and response programming) are thought to occur serially (Donders 1868/1969; Schmidt and Lee 2005). Henry and Rogers (1960) suggested that this response programming stage was lengthened for more complex movements resulting in longer RTs. However, in most simple RT situations

there is a single stimulus requiring a single known response, and as such, not all of these processes *must* occur between the onset of the imperative stimulus (IS) and the production of the response (i.e. during the RT interval). In particular, some evidence of pre-programming (completing the response programming stage in advance of the imperative stimulus) has been shown to occur in more recent studies in which the complexity of the response was manipulated (Klapp 1973, 1995, 2003). However, the ability to pre-program a response depends on how “complexity” was manipulated. Specifically, the manipulation of interest was between responses involving one movement component vs. multiple components. For example, Klapp et al. (1973) demonstrated that in a simple RT task involving pronouncing a word, increasing the word’s complexity by increasing the number of syllables to be pronounced in a word did not affect RT. Similarly, simple RT was not affected by the duration of a single button press. That is, RT was not different for a short duration (less complex) compared to a long duration (more complex) button press (Morse code elements dit-dah, Klapp 1995). It was suggested that when the required movement was known in advance, programming of the response could occur before stimulus onset so that only the response triggering was necessary following the IS (Klapp 1996, 2003). However, when complexity was manipulated by increasing the number of movement components Klapp (2003) reported a result in a simple RT task that was comparable to that of Henry and Rogers (1960). In particular, when the task involved a single button press vs. multiple button presses (more complex), RT was found to increase with complexity in a simple RT framework.

In order to reconcile the differences in the RT results between the two types of complexity (duration vs. multiple parts), Klapp (1995) proposed a dual process model of

response programming. One process involved programming the *internal* features of a movement element, or “chunk” (e.g. response duration), which he called process INT. The other process involved the *sequencing* of response elements (process SEQ)¹. The model proposed that process INT could be completed in advance of the IS if it was known, whereas process SEQ had to occur during the RT interval, that is, following the IS. Thus, it was suggested that that responses comprised of a single element or “chunk” may be fully pre-programmed, and because they only required an execution command (or “trigger”) following the IS, RT was unaffected by the complexity of the single response element. In contrast, for a movement comprised of multiple elements, one part of response programming (process SEQ) was completed following the IS and thus simple RT increased along with the number of response elements (Klapp 1996, 2003).

The aim of the current study was to further investigate this notion of differential response preparation depending on how response complexity is manipulated. Under certain circumstances, Klapp (2003) argued that a pre-programmed response only required triggering following the IS. Several recent studies have used a startle acoustic stimulus to trigger prepared responses (Carlsen et al. 2004b; Valls-Solé et al. 1999). In this way, response pre-programming can be probed through the use of this startling acoustic stimulus during a simple RT paradigm. In particular, it appears that in a simple

1. More recently, Klapp (2003) modified his account of process SEQ. The revised model suggests that SEQ does not involve the sequencing of movement elements per se, but involves the scanning of an abstract time frame in order to locate the starting element. Nevertheless, the distinction of interest for the current experiment involves whether response programming can be completed prior to the IS.

RT task, a loud (>124 dB) startling stimulus can elicit the required action directly without the usual voluntary command (Carlsen et al. 2003, 2004a, b, 2007; Cressman et al. 2006; MacKinnon et al. 2007; Seigmund et al. 2001; Valls-Solé et al. 1995, 1999). Because premotor RTs were so dramatically shortened due to the presence of a startle response, without the kinematics or EMG configuration of the response being affected, it was concluded that the startle acted as an early trigger for a pre-programmed response (Carlsen et al. 2004b; Valls-Solé et al. 1999). Moreover, it was shown that the startle effect was distinct from and larger than any effect due solely to the intensity of the stimulus (Carlsen et al. 2007). Importantly, however, for triggering to occur the response must be pre-programmed and presumably stored subcortically awaiting the usual cortical signal (Carlsen et al. 2004a; Rothwell 2006; Valls-Solé et al. 1999). When a startle was presented in both a simple and a choice RT task, premotor RT (PMT) was only dramatically shortened when the response was certain and could be pre-programmed (i.e. simple RT task), whereas when the correct response had to be selected during the RT interval (choice RT), a startle did not advance RT (Carlsen et al. 2004a).

This differential effect of startle depending on the ability to pre-program the response was used to investigate the preparation of complex responses. Response programming was investigated using a startled RT task that involved manipulating the complexity of the movement by either increasing the duration of the movement or by increasing the number of movement components. Klapp's dual process model of response programming suggests that a response cannot be fully pre-programmed when the movement contains multiple parts (or "chunks"), because those chunks must be sequenced whereas full response pre-programming may occur when the response

involves only a single chunk (Klapp 1996, 2003). It was therefore hypothesized that the presence of a startling stimulus would speed response execution when the response duration was increased but not when the number of movement elements was increased.

Method

Participants

Ten right-handed volunteers (5M, 5F; ages 22 +/- 2 years) with no obvious upper body abnormalities or sensory or motor dysfunctions participated in the study after giving informed consent. All participants were naïve to the hypothesis under investigation. This study was conducted in accordance with ethical guidelines established by the University of British Columbia (see Appendix A).

Positioning

Participants sat in a height-adjustable chair equipped with an automobile racing harness (Racer Components Inc.) in order to constrain movement to the wrists. The participant's right arm was secured in a semi-prone position with the palm facing inward, to a custom-made aluminum wrist manipulum that moved in the transverse plane with an axis of rotation at the wrist joint. The arm portion of the manipulum was oriented at an angle of 15 degrees outward from body midline, as this has been found to be a more comfortable position than an orientation parallel to the body midline. The wrist starting position was neutral (neither flexion nor extension) and was indicated by both online visual feedback and magnetic detent.

Recording Equipment

Surface EMG data were collected from the muscle bellies of the following superficial muscles: right flexor carpi radialis (FCR), right extensor carpi radialis longus (ECR), and left sternocleidomastoid (SCM) muscles using preamplified bipolar Ag/AgCl surface electrodes connected via shielded cabling to an external amplifier system (Therapeutics Unlimited Inc. Model 544). 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 ulnar styloid process. Wrist angular displacement data were collected using a potentiometer attached to the central axis of the manipulandum.

Task and Instructions

The experimental task on any trial involved performing one of three different active wrist extension movements of the right hand to fixed target regions in a simple RT framework. The first movement task was a 15 deg. wrist extension from a neutral starting position to a target. The second movement was a 30 deg. extension from a neutral position to a target. The third movement (15+15) was a 15 deg. + 15 deg. extension movement to a target located at 30 deg. Real-time wrist position feedback was visible along with two horizontally aligned targets on a computer monitor located 1 m directly in front of the participant (see below for a description of stimuli, response targets, and feedback). The participants were informed that they would first hear a warning tone followed by a pause, and then a target box (visual imperative stimulus) would appear accompanied by an auditory tone. Participants were instructed to respond by making a

movement “as fast and as accurately as possible” from the starting position and to stop on the final target. For the 15+15 deg. movement, participants were instructed to try to stop “very briefly” on the 15 deg target, and to continue to the 30 deg (second) target as quickly and accurately as possible. Instructions emphasized fast RTs and quick movements. A monetary bonus was offered for fast RTs.

Response Targets and Feedback

Real time wrist position feedback was given by representing the position of the manipulandum with a yellow vertical graphical line within a horizontal (1cm x 15cm) black rectangle located on the computer screen. The starting position of the position was indicated by a green marker on the left side of the black rectangle. The movement of the position line within the black rectangle corresponded directly to movement of the manipulandum. For example if the wrist was extending, both the right hand and the yellow line moved to the right. After each trial, the computer monitor displayed feedback information about the trial just completed including target accuracy (degrees), and reaction time (in ms). Two target lines were placed 5 and 10 cm to the right of the starting position (to represent the 15 deg and 30 deg targets respectively). Prior to each trial the target(s) for the upcoming trial were presented for 3 sec. while a visual warning signal appeared instructing the participant to “get ready for the upcoming target(s).” Thus the required task was known prior to each trial. For the 15 deg. and 30 deg. tasks, only the correct target appeared (single blue line). For the 15+15 deg. task, both targets appeared, but the first 15 deg target was grey, while the 30 deg target was blue.

Stimuli

A warning tone consisting of a short beep (200 ms, 2000 Hz, 80 dB) was generated by the computer using a 16 bit sound card (Creative SoundBlaster® 16) and standard computer speakers (Juster® sp-691n). A variable foreperiod of 2 - 3 sec. spanned the time between the end of the warning tone and the imperative stimulus. A computer program generated the trial auditory stimuli consisting of a narrow band noise pulse (1 kHz, 40ms duration). The signal was amplified and presented via a loudspeaker (<1 ms rise time) placed directly behind the head of the participant with an intensity of either 82 +/-2 dB (control stimulus) or 124 +/-2 dB (startle stimulus). The acoustic stimulus intensities were measured using a sound level meter (Cirrus Research model CR:252B) at a distance of 30 cm from the loudspeaker (approximately the distance to the ears of the participant). Visual imperative stimuli consisted of 2 possible boxes (3 x 3 cm) that could appear around the 15 and 30 deg. targets aligned horizontally across the computer screen in front of the participant. One of these boxes would appear (yellow) following the foreperiod depending on the identity of the trial. Either the control auditory stimulus or the startle stimulus was presented in conjunction with the visual imperative stimulus on every trial.

Trial Types

The three movements were all completed in randomized order. Participants performed 10 to 20 practice trials involving all three tasks with online feedback in order to become familiar with the tasks and equipment. Control trials were trials in which the control auditory tone (82 dB) accompanied the visual imperative stimulus, and the participant carried out the normal protocol of the experiment. Startle trials were trials in

which the startle stimulus (124 dB) was given in conjunction with the visual imperative stimulus. Participants performed 25 movement trials to each target where five control trials were replaced by startle trials for each movement for a total of 15 startle presentations per participant.

Data Reduction

On each trial, data were digitally sampled at 1 kHz (National Instruments® PCI-6024E) for 3 sec using a customized program written with LabVIEW® software (National Instruments Inc.). Data collection was initiated by the computer 500 ms prior to the imperative stimulus. Movement onset was defined as the first point of a change of more than 0.2 deg of angular displacement from the starting position following the stimulus. 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 activity increased to more than 2 standard deviations above baseline (mean of 100 ms of EMG activity preceding movement). Onset was then verified by visually locating and manually adjusting the onset mark to the point at which the activity first increased. This method allowed for correction of errors due to the strictness of the algorithm. Premotor RT was defined as EMG onset in the ECR muscle. EMG offsets were marked in a similar fashion, with the activity between EMG onset and EMG offset being defined as a distinct burst.

Statistical Analyses

Startle trials in which no detectable startle response (SCM activity) was observed were discarded (see Carlsen et al. 2003a, 2007). Dependent measures were analyzed for differences between complexity condition (15, 30, 15+15) and stimulus condition (Control vs. Startle) using a 3 x 2 repeated measures analysis of variance (ANOVA). Greenhouse-Geisser corrected degrees of freedom were used to correct for any violations of the assumption of sphericity. Differences with a probability of less than .05 were considered to be significant. Tukey's Honestly Significant Difference (HSD) post-hoc tests were administered to determine the locus of the differences.

Results

Electromyographic (EMG) activity was measured in SCM in order to determine whether or not a startle reaction was present following the 124 dB acoustic stimulus. Only trials in which SCM activity was observed were analyzed; 124 dB trials with no observed SCM activity were discarded. No more than two trials in any condition were discarded from any single participant suggesting the loud sound did indeed startle the participants. SCM onset latency was not statistically different between any of the tasks in the startle condition, $F(2,18) = 1.41$, $p = .270$, (mean SCM onset for 15, 30, and 15+15 tasks was 73.7 +/- 19.0 ms, 77.8 +/- 18.4 ms, and 83.6 +/- 20.2 ms respectively), indicating the 124 dB stimulus resulted in a similar startle response across tasks. As there was a non-significant trend towards increased SCM onset latency with increased complexity, the effect size was examined. However, only a small amount of the observed variance was attributable to this factor, $\eta_p^2 = .135$.

Premotor RT (PMT), the time from stimulus onset to EMG onset in the ECR muscle (prime mover) was analyzed between stimulus condition and task. Data are presented in Figure 7.1. Main effects were found for both stimulus, $F(1,9) = 109.39$, $p < .001$, $\eta_p^2 = .924$, and for task, $F(2,18) = 21.09$, $p < .001$, $\eta_p^2 = .701$, however, there was no significant interaction between the factors, $F(2,18) = .47$, $p = .634$, $\eta_p^2 = .049$. The main effect for stimulus indicated that the startle stimulus led to significantly shorter PMT for all tasks. Post-hoc analysis of task revealed that PMT for the 15 deg. and 30 deg. tasks was significantly shorter than for the 15+15 task ($p < .05$), irrespective of the stimulus, while no PMT difference was evident between the 15 deg. and 30 deg. tasks (Figure 7.1).

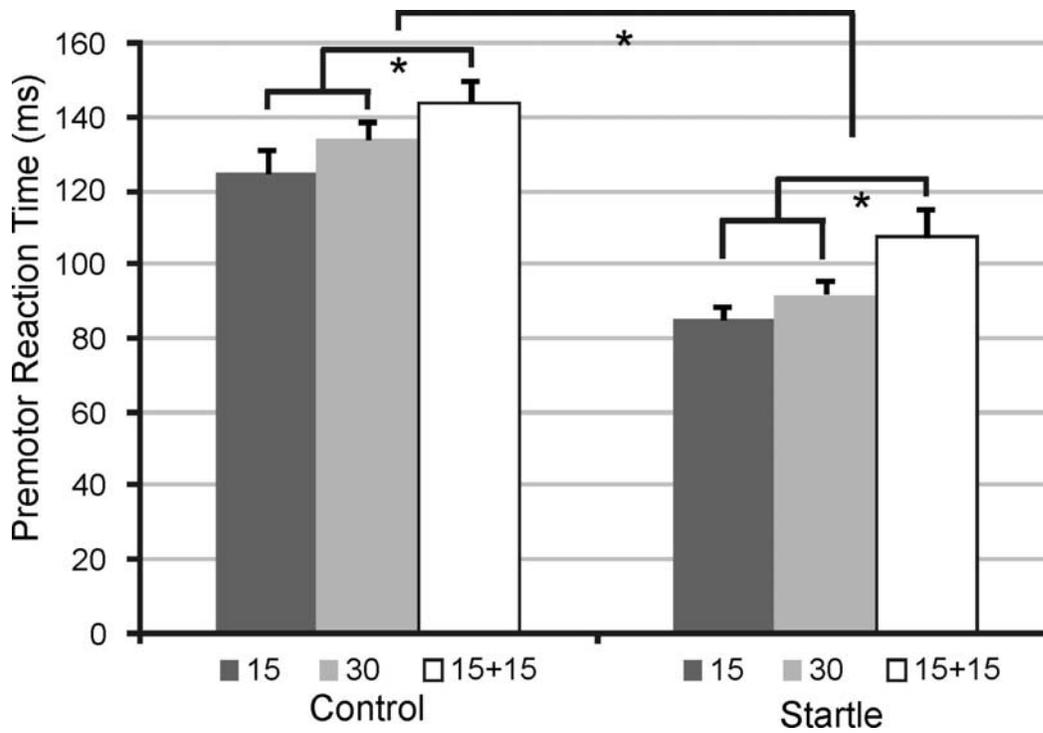


Figure 7.1 Mean (+/- SE) premotor reaction time (ms) for the 15 deg, 30 deg, and 15 + 15 deg (15+15) movements for control (82 dB) and startle (124 dB) conditions. * denotes a significant difference between conditions ($p < .05$).

In order to determine if the addition of a startling stimulus had an effect on the production of the movement, various kinematic and EMG dependent measures were analyzed for differences between stimulus and task. Because of the kinematic and EMG differences required for successful movement production between tasks, it is not useful to report any statistical effects for *task* that were present in these kinematic and / or EMG variables, except that each task was performed accurately. These data are presented in Table 7.1. More relevant to the current investigation, no main effects were observed between the control and startle trials in any of the kinematic or EMG measures (except premotor RT, see above), and no interactions were observed between task and stimulus. These results indicate that a similar movement with similar EMG pattern was produced between the stimulus conditions for each movement task. Examples of the movements and associated EMG patterns are presented in Figure 7.2.

Table 7.1 Mean (+/- 1 SD) EMG and kinematic data values for each task and stimulus type.

Stimulus		Control			Startle		
		15	30	15+15	15	30	15+15
Task							
EMG Measures (ms)							
†*	Premotor RT	125.2 (19.5)	134.2 (15.8)	144.3 (17.9)	85.7 (10.7)	92.1 (11.3)	107.9 (23.9)
*	ECR1 burst duration	74.0 (12.9)	90.0 (16.0)	75.8 (15.8)	86.1 (22.0)	94.2 (15.7)	74.7 (18.6)
	ECR1 to FCR inter-onset time	49.1 (17.4)	48.0 (20.1)	61.1 (13.4)	47.0 (27.9)	58.6 (23.2)	41.8 (22.9)
*	ECR1 to ECR2 inter-onset time	115.1 (15.2)	124.1 (17.1)	226.4 (43.8)	128.4 (25.6)	126.6 (22.5)	199.4 (32.3)
Kinematic Measures							
*	Final position 1 (deg)	17.1 (2.1)	26.2 (2.4)	16.4 (2.9)	18.9 (3.3)	28.6 (4.6)	17.8 (3.9)
	Final position 2 (deg)	-	-	30.8 (3.2)	-	-	31.7 (5.8)
*	Movement time 1 (ms)	231.1 (37.0)	233.2 (31.9)	199.6 (10.5)	237.0 (38.0)	244.6 (37.4)	186.7 (4.9)
	Movement time 2 (ms)	-	-	419.5 (43.8)	-	-	379.9 (37.1)

Note. Standard deviations in parentheses, † signifies a significant main effect for stimulus condition, * signifies a significant main effect for task. No significant interactions were observed. ECR1 is initial (accelerating) EMG burst from the extensor carpi radialis muscle. FCR is first (braking) EMG burst from the flexor carpi radialis muscle. ECR2 is second EMG burst from the extensor carpi radialis muscle: dampening burst for single component (15, 30 deg) movement s, second accelerating burst for two component (15+15) movement. Final position 1 and movement time 1 values are for component 1 of all tasks. Final position 2 and movement time 2 values are for component 2 of the 15+15 task.

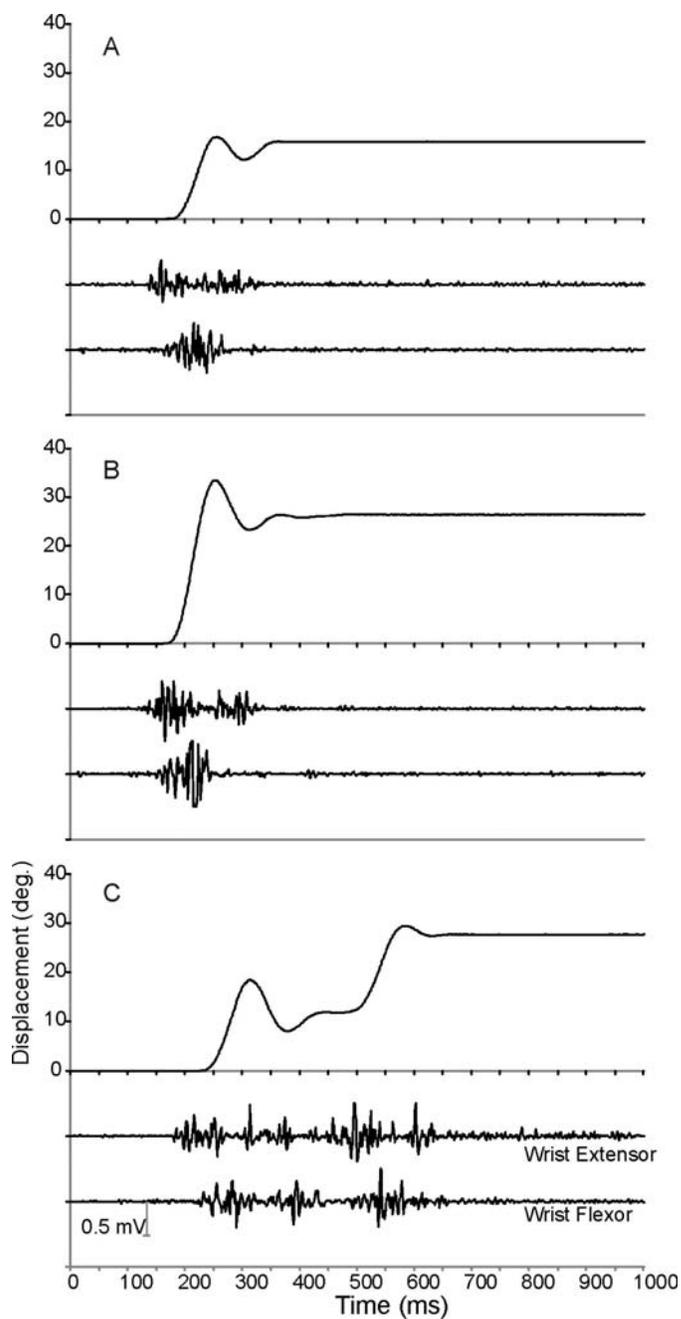


Figure 7.2 Example raw data from control trials (82 dB) for the three movement tasks from a single participant. Each panel includes displacement data (top trace), and EMG data from the wrist extensor (ECR, see text) and wrist flexor (FCR). A) 15 deg movement task. B) 30 deg. movement task. C) 15+15 deg movement task. Time zero is IS onset.

Discussion

Increases in movement complexity have been shown to result in increases in RT even when the required movement is known beforehand (Henry and Rogers 1960). However, in a simple RT task, these RT differences tend to disappear when complexity is manipulated by increasing the duration of the movement. It was suggested that when duration was increased, it remained possible to pre-program the movement (Klapp 2003). However, RT differences are preserved when manipulating the number of movement components, presumably, because some of the programming of multi-component movements must occur *following* the IS, even in a simple RT task (Klapp 1996, 2003; Khan et al. 2007). Since a pre-programmed movement can be elicited without voluntary initiation when participants are startled by a loud (e.g. 124 dB) acoustic stimulus (Carlsen et al. 2004a, Valls-Solé et al. 1999), this provides a window into the normally covert process of response programming. Here we show that when participants were startled, a 30 deg movement was elicited at similarly short latency to a startled 15 deg response. In contrast, a startling stimulus did not shorten RT to the same extent when a multi-component (15+15 deg) response was required. These data are consistent with a model in which multiple component responses cannot be fully pre-programmed (e.g. Klapp 2003; Khan et al. 2007).

Recent studies have employed a loud acoustic stimulus that is capable of eliciting a startle reaction to investigate response pre-programming. It was shown that premotor RT (PMT) was considerably shortened when the usual “go” signal was replaced by a startling sound (Carlsen et al. 2004a, b, 2007; Valls-Solé et al. 1995, 1999). Similarly, in the present experiment, when the normal 82 dB IS in a 15 deg wrist extension movement

was replaced with a 124 dB stimulus that elicited a startle response, mean PMT was shortened from 125 ms to 86 ms (Figure 7.1). Furthermore, the kinematics of the response and the EMG pattern configuration were unchanged between control and startle trials (Table 7.1). This result replicates previous experiments (Carlsen et al. 2004b; Valls-Solé et al. 1999) involving the use of a startling stimulus in which it was argued that because the observed response was unchanged, and several of the resulting PMTs were so short (< 70 ms), it was unlikely that normal cortical triggering processes were responsible for response initiation during startle trials. Thus it was suggested that the startle must have acted to trigger a pre-programmed response that was stored in subcortical areas (Carlsen et al. 2004b; Valls-Solé et al. 1999). The midbrain reticular formation, specifically the nucleus reticularis pontis caudalis (NRPc), plays an important role in mediating the startle response (Yeomans and Frankland 1996; Koch 1999). Furthermore, the NRPc has been implicated in voluntary movement preparatory-related activity (Buford and Davidson. 2004; Schepens and Drew). Therefore it has been proposed that the startle response may interact with the prepared voluntary movement at the level of reticular formation leading to early response initiation (Carlsen et al. 2004b; Rothwell 2006; Rothwell et al. 2002).

The more interesting results of the current study involve the more complex 30 deg and 15+15 deg movements. Previous studies utilizing a startle protocol have mainly involved simple movements such as wrist flexion or extension (Carlsen et al. 2004a, b, 2007; Cressman et al. 2006; Valls-Solé et al. 1999, 2005), arm extension (Carlsen et al. 2004b), foot plantar flexion (Valls-Solé et al. 1999), neck flexion (Seigmund et al. 2001), and eye saccades (Castellote et al. 2007). Although some more “complex” patterns of

EMG activity have been observed in response to a startle (e.g. anticipatory postural responses, MacKinnon et al. 2007; stepping modification, Reynolds and Day 2007; interceptive actions, Tresilian 2006), no systematic manipulation of response complexity has been attempted.

In the present experiment, complexity was varied in two distinct ways. First the amplitude (extent) of the movement was varied in a single component movement: that is, in addition to the 15 deg movement, a 30 deg movement was completed by participants. In previous experiments when complexity was manipulated in terms of response duration (e.g. long vs. short button press, or pronouncing multiple syllable vs. single syllable words), there was no RT effect in a simple RT task. This indicated that these responses could be pre-programmed in their entirety (Klapp 1996, 2003). In the current study, the final position for the 30 deg movement and the associated EMG pattern were significantly different compared to the 15 deg movement, however, the movement time (MT) and PMT were similar between the movements (Table 7.1). This indicated that for the 15 and 30 deg targets different movements were performed, but in the same amount of time, and with a similar RT.

PMT for the 30 deg movement was significantly shorter in the startle condition compared to control (Figure 7.1). Additionally, for the 30 deg movement there were no differences in any of the kinematic or EMG configuration measures between the control and startle conditions (Table 7.1). Notably, for startle trials there was also no significant difference in PMT between the 15 deg and 30 deg movements (Figure 7.1). These data taken together indicate that the startle had a similar response triggering effect on the 30 deg movement as it did on the 15 deg movement, resulting in the early release of the

correct response at significantly shortened latencies. This result is similar to a previous report, where startle led to similar PMT reductions for 20, 40 and 60 deg arm extensions (Carlsen et al. 2004b). In this earlier study it was suggested that the startle triggered the appropriate movement irrespective of the required extent. It should be noted that in the current experiment the 30 deg movement was completed in a similar amount of time to the 15 deg movement, thus the “duration” was not manipulated, only movement amplitude. Although it has been previously shown that longer amplitude movements can lead to increases in RT (Lajoie and Franks 1996; Khan et al. 2007), these studies have generally attributed RT increases to an increase in the index of difficulty of the movement (i.e. an increase in the ratio of movement amplitude to target size, Fitts 1954). Regardless of whether movement amplitude led to an increase in “complexity,” it appears that when a movement is adjusted in terms of increasing movement extent, pre-programming is nonetheless possible, and a startle can act to trigger these pre-programmed responses.

The second way in which complexity was manipulated here was by increasing the number of movement components. Thus in addition to the 15 deg movement, participants performed a 2-component (15+15) movement consisting of an initial wrist extension to a 15 deg target, with a very brief pause followed by another 15 deg extension to a target located at 30 deg. In comparison to the 15 deg movement, PMT for the 15+15 deg movement was significantly increased from 125 ms to 144 ms. An increase in RT has been reported in several studies that have manipulated complexity by increasing the number of movement components (Henry and Rogers 1960; Kahn et al. 2006, 2007; Klapp 1995, 2003; Lajoie and Franks 1996). These results have been interpreted as

evidence that *full* response pre-programming cannot occur for multiple-component movements even when the response is known beforehand (i.e. simple RT task).

Specifically, Klapp (2003) suggested that the sequencing (SEQ process, see also Klapp 1996) of response elements must be performed following the IS, during the RT interval, leading to longer RTs for movements including more response components.

In the present experiment, when a 124 dB startling stimulus replaced the usual 82 dB IS in the 15+15 movement, PMT was significantly shortened compared to control (Figure 7.1), while no differences in EMG configuration or response kinematics were evident indicating that a similar response was produced between the two stimulus conditions (Table 7.1). Because there was no interaction between stimulus and task, it appears that PMT in the 15+15 task was facilitated to a similar extent as both the 15 and 30 deg movements. However, this result means that even in the startle condition, the 15+15 movement had a significantly longer PMT than both the 15 and 30 deg tasks. Thus the question arises regarding whether the RT facilitation in the multi-component response occurred through the same mechanism as in the single component responses. Mean PMT in the startle condition for the 15+15 movement was 108 ms, significantly longer than PMT for either the 15 deg or 30 deg movements (Figure 7.1), and arguably long enough to have involved cortical response pathways. Although it is possible that the startle acted to facilitate the 15+15 deg multi-component movement in the same way as the single component 15 and 30 deg movements, the significantly longer PMT latency compared to the 15 and 30 deg movements suggests that the startle simply acted to speed the response through more traditional stimulus intensity facilitation (see Kohfeld 1969; Luce 1986; Woodworth 1938, p.318). It is believed that stimulus intensity facilitation has a

perceptual basis, and is the result of faster cortical perceptual processing (Levick 1973). In contrast, the facilitatory effect of startle is thought to have a subcortical origin. The PMT for the 15+15 movement startle trials (108 ms) is also similar to that observed when no startle response was detected (104 ms) in a previous experiment involving a loud 124 dB stimulus (Carlsen et al. 2007). In this experiment, it was observed that the stimulus intensity facilitatory effect did not shorten the RT to the same extent as startle triggering (Carlsen et al. 2007). Thus, the results of the present experiment indicate that the 15+15 task was not directly triggered by startle in a similar fashion to the 15 and 30 deg movements. These results suggest that for a multi-component response, sufficient pre-programming does not occur prior to the IS to enable response triggering by startle. This conclusion is also congruent with a dual process model of response preparation for complex movements described earlier (Klapp 2003).

No evidence for pre-programming of the first component of the 15+15 movement, followed by online control was observed. First, PMT was longer for the 15+15 movement, indicating that the extra response programming required for the multiple components took longer (e.g. Henry and Rogers 1960). Secondly, if the first component was programmed, and the second component was performed online, one would expect different results due to startle than those observed in the current experiment. For example, the expectation would be for the startle to elicit the initial pre-programmed movement at a similar latency to the 15 and 30 deg movements (which was not the case, Figure 7.1), followed by a lengthened interval between the first and second components. A longer pause time would be expected because it has been previously shown that a startle can interfere with ongoing cortical processing (Woodhead 1959) including

processing ongoing movements (Vlasak 1969). No differences in EMG configuration or response kinematics were observed (including time from the end of movement component 1 to the end of movement component 2, see Table 7.1) indicating that the 15+15 response was likely programmed in its entirety prior to initiation.

In conclusion it appears that a single component movement such as a 15 deg wrist extension can be pre-programmed in its entirety and is susceptible to early response triggering by startle. Furthermore, increasing the amplitude of the movement (30 deg) has no effect on the ability to preprogram the movement. However, it remains to be seen whether the ability to preprogram for a longer duration movement (i.e. longer MT) is similarly unaffected. Finally, when the upcoming movement involves several serial movement components, it appears that some critical element of pre-programming (likely the sequencing of movement components, Klapp 2003) cannot occur in advance of the IS and the response is therefore not susceptible to startle facilitation.

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8. General Discussion

The goal of this dissertation was to elaborate on neuromotor preparation and response programming processes in various motor tasks to gain a better understanding of how humans prepare the motor system for upcoming actions. In order to investigate these processes, a novel paradigm was employed involving the presentation of a startling acoustic stimulus primarily during reaction time (RT) tasks. This startle paradigm has been shown previously (e.g. Carlsen et al. 2004b; Valls-Solé et al. 1999) to result in dramatic decreases in RT, thought to be caused by the early release of a prepared response, and thus can be used to probe motor preparation. However, since the startle paradigm is still a novel method and has not been fully described, there remained several other plausible explanations for the RT speeding observed in startle trials. Thus it was an important first step to determine whether presenting a startling stimulus in a RT task indeed resulted in the early release of a prepared response. The first two experiments in this dissertation, along with results from previous experiments (Carlsen et al. 2004a, b) investigated several theories of why RT might be decreased when a startle was presented in a RT task. These experiments supported the notion that startle could trigger a pre-programmed action, indicating that it is possible to use startle to investigate motor programming processes in humans. To this end, four additional experiments utilized a startle method paired with traditional motor control experimental protocols. Results from these four experiments showed that motor programming processes can be very different depending on the goals of the task, yet indicate that humans adopt the most strategically beneficial preparation to accommodate task demands, respond most quickly with the least amount of errors, and decrease energy demands.

On the Origin of the Response Speeding Effect of Startle

The addition of a startling acoustic stimulus, coincident with the “go” signal, or imperative stimulus (IS), has been shown to result in dramatically reduced RT during a simple RT task (Carlsen et al. 2004b; Valls-Solé et al. 1999). Due to the fixed amounts of time required for neural transmission, it was argued that when premotor RTs (time from stimulus to EMG onset, hereafter referred to as simply RT) of less than 65 ms were observed, the responses likely did not involve normal cortical processing for response initiation (Valls-Solé et al. 1999). This value was calculated by summing the time between an acoustic stimulus and the first volley of activity arriving at the auditory cortex (35 ms, Erwin and Buchwald 1986), with the time required for neural conduction between the primary motor cortex and the muscles (20-30ms, Jones et al. 1996; Rothwell 1997). It was argued that for RTs of 65-70 ms, there was almost no time for cortico-cortical transmission, let alone any cortical processing for the shortest RTs observed. Thus it was suggested that adequate details of the prepared action were pre-programmed and somehow stored in subcortical (i.e. brainstem and spinal) structures, and that the prepared response was triggered automatically by the startle (Carlsen et al. 2004b; Valls-Solé et al. 1999).

This “subcortical triggering hypothesis” was appealing as it presented a behavioural means of investigating motor preparation occurring at a subcortical brainstem level, without the need for more invasive techniques. However, because few studies had utilized a startle paradigm the source of the RT speeding remained somewhat uncertain. In particular, there remained several other alternative explanations that may have accounted for the RT speeding effect of startle equally well. Thus in order to be able

to use a startle to investigate motor preparation it first had to be established more firmly that the root of the effect was indeed the early triggering of a subcortically stored program.

Startle has previously been used to show that an action is pre-planned during various simple RT tasks involving different effectors, including wrist flexion / extension (Carlsen et al. 2004a; Valls-Solé et al. 1999), arm extension (Carlsen et al. 2004b), foot dorsiflexion (Valls-Solé et al. 1999), neck flexion (Seigmund et al. 2001), and eye saccades (Castellote et al. 2006). However, in these experiments it was possible that the RT speeding was not due to the triggering of a stored motor program, but that startle may have simply resulted in increased neural activation and thus decreased neural thresholds throughout the central nervous system. In this way, the presence of a startle may result in a decreased amount of time required for nervous transmission (e.g. Day et al. 1989), manifesting as decreased premotor RTs. Whereas the subcortical triggering hypothesis requires that a response is pre-programmed awaiting the “go” signal, it was reasoned that if decreased neural propagation time was responsible for RT advancement, having a response pre-programmed would not be a requirement, and response speeding would be seen even when a response was not programmed in advance of the IS. This possibility was tested in an experiment previous to this dissertation (Carlsen et al. 2004a) in which a startle was presented during a choice RT task, where the response presumably had to be programmed *after* the IS. In this experiment it was found that when a choice was required, there was no speeding effect of startle (Carlsen et al. 2004a). Therefore it was suggested that the action was probably not pre-programmed when a choice had to be made between various possible responses. Based on these results it was argued that

neural excitability was likely not the mechanism by which the startle effect acted and that only actions that were pre-programmed were subject to startle RT facilitation.

More recently, however, some RT speeding *has* been observed in some choice RT tasks where a startling acoustic stimulus was presented. For example, it was observed that in a choice RT task involving wrist flexion with either the left or right hand in response to left or right stimuli, RT was shortened from a mean of 324 ms to 257 ms when a startle was presented (Kumru et al. 2006). Similarly, in a task involving stepping towards a target that could possibly change mid-step, the presence of a loud stimulus resulted in a decrease of 20 ms in target switch response time from 134 to 114 ms (Reynolds and Day 2007). In addition, some evidence of RT shortening was observed in the current dissertation when a choice between two precued response alternatives was required and no errors were made (see Experiment 4, Figure 5.3). In this experiment, in the 2-choice conditions mean RTs were decreased from 208 ms to 168 ms. Thus it remains somewhat unclear why a startle led to some RT speeding in these choice tasks whereas none was observed previously (Carlsen et al. 2004a). One possibility is that for tasks involving a choice between multiple effectors (e.g. responses involving separate hands, Kumru et al 2006; Experiment 4), some partial pre-programming, or even programming of multiple responses was nevertheless possible (see Experiment 4). This is in contrast to when the choice between responses involves opposite direction movements with a single limb (Carlsen et al. 2004a), where it may be much more difficult or may not be possible to program multiple opposing responses.

A second possibility is that the RT shortening effect observed due to startle was simply due to an increase in the intensity of the acoustic IS in *both* the simple RT and

choice RT tasks. Stimulus intensity facilitation, first identified by Piéron (1919, cited in Woodworth 1938 p. 318), is concerned with the observed decrease in RT as stimulus intensity increases. As such it was possible that all of the RT facilitation previously observed due to startle was simply a result of the stimulus intensity effect, thought to be caused by a decrease in cortical *perceptual* processing time (Levick 1973). In Experiment 1 of the present dissertation it was shown that, consistent with the stimulus intensity effect, RT decreased with increasing dB level. However, the critical difference was that, irrespective of dB level, when a startle response was observed (defined as observed EMG activity in the sternocleidomastoid, SCM muscle), RT was significantly shortened to approximately 80 ms (Experiment 1, Figure 2.1). This result indicated that the startle facilitated responses were different than stimulus intensity facilitated responses, in particular for simple RT tasks. During choice RT tasks, however, although the percentage of RT shortening was similar and in some cases greater than that observed in simple RT tasks, the startle trial RTs reported (e.g. 114 – 257 ms, Reynolds and Day 2007; Kumru et al. 2006; Experiment 4), were not sufficiently short to rule out cortical involvement as per the subcortical storage and triggering hypothesis, and were much longer than RTs reported for startle triggered responses in simple RT tasks (e.g. 70 – 77 ms, Carlsen et al. 2004b; Valls-Solé et al. 1999). Thus, it is suggested here that the bulk of the observed startle related RT speeding observed during choice RT tasks (Kumru et al. 2006; Reynolds and Day 2007) was attributable to stimulus intensity. However, since the startle-related RTs observed in simple RT tasks (i.e. when a response can be pre-programmed) are often sufficiently short to preclude cortical involvement (Carlsen et al.

2004a, b; Valls-Solé et al. 1999; Experiment 1), startle-related RT speeding likely involves a different subcortical mechanism as first suggested by Valls-Solé et al. (1999).

As previously suggested, in order to be able to understand subcortical motor preparation it was important to more firmly establish the mechanism by which startle RT facilitation occurs. An alternative to the subcortical triggering hypothesis was the possibility that the startle acted to speed the RT by acting through an unconventional (as yet undefined) fast transcortical route. It was feasible to investigate this possibility by designing an experiment done within a simple RT framework that necessitated the use of a cortical route for response initiation for one movement, and allowed subcortical initiation for another. For this dissertation (Experiment 2) the movement tasks chosen were an arm extension task, which has been shown to have extensive subcortical (reticulospinal) connections (Davidson and Buford 2006), and an index finger abduction, thought to be strongly mediated by corticospinal pathways (Lawrence and Kuypers 1968). The primary muscle responsible for the finger abduction movement, first dorsal interosseus (FDI), has been traditionally understood to receive little control influence from reticulospinal pathways as stimulation of reticulospinal tracts does not appear to have much influence on intrinsic hand muscles (Davidson and Buford 2006). However, recent studies indicate that some reticulospinal connections with distal finger muscles exist, and modulate their activity with movements of the finger (Baker and Riddle 2007; Soteropoulos et al. 2007). Yet, since these reticulospinal connections are seen less frequently than corticospinal connections (Baker and Riddle 2007) they may be less functionally effective. This is further evidenced by earlier studies showing that following permanent lesions of the corticospinal tract, monkeys were unable to produce individual

finger movements for tasks such as eating and grooming, although they recovered the ability to use more proximal muscles for climbing and walking (Lawrence and Kuypers 1968). In Experiment 2 of the current dissertation, when a startle response was observed, RT was significantly shortened for the arm extension task as has been observed previously (Carlsen et al. 2004b). However, no such RT shortening was seen for the finger abduction task (Experiment 2, Figure 2.1). Because the finger abduction movement likely involves stronger cortical connections for response initiation, it appears that only movements that involve strong reticulospinal connections for response initiation are susceptible to startle facilitation, and support the hypothesis that the RT shortening observed due to startle is a subcortical effect.

Thus far the current dissertation has provided evidence that the startle effect is a subcortical phenomenon (Experiment 2) acting on a pre-programmed response (Carlsen et al. 2004a). Furthermore, the RT speeding effect is associated with an overt startle reaction and is not simply due to either increased stimulus intensity (Experiment 1) or increased neural activation (Carlsen et al. 2004a). Therefore it appears more likely that the startle acts to shorten RT via the mechanism first proposed by Valls-Solé et al (1999), and less likely that it acts via an alternative mechanism. The subcortical storage and triggering hypothesis (Valls-Solé et al. 1999) is based on interconnections between the neural pathways involved in both voluntary reactions and startle. The startle reflex pathway involves connections between the cochlear nucleus and the caudal reticular formation, with the giant neurons of the nucleus reticularis pontis caudalis (NRPc) acting as control neurons for the startle reflex (Yeomans and Frankland 1996; Koch 1999). In addition, voluntary movement preparation-related activity has also been recorded from

the NRPC in animal models (Buford and Davidson 2004; Schepens and Drew 2004). Thus it was suggested that the startle reflex may interact with the voluntary response at the level of the reticular formation (Carlsen et al. 2004b; Rothwell 2006; Rothwell et al. 2002) leading to early direct triggering and thus release of the pre-programmed and stored movement without the normal cortical trigger signal. This was suggested because of the drastic nature of the RT decrease observed, and because estimates of stimulus transduction and nerve conduction delays precluded a transcortical pathway for responses with PMTs of less than 65 ms (Valls-Solé et al. 1999).

On Motor Preparation and Pre-programming

The notion that a response may be pre-programmed prior to the IS in a RT task is not entirely novel and has formed the basis of RT experiments for many years (e.g. Wadman et al. 1979). However, what is novel is the suggestion that a fully formed motor program may be prepared in advance and offloaded to a temporary subcortical “buffer” or “storage area” in readiness for responding. This is in no way intended to diminish the role of cortex in preparing the response in the first place (see Valls-Solé et al. 1999), simply to suggest that once pre-programmed, the response may be offloaded and stored to free up the cortex to perform more pressing functions. In retrospect, this idea appears to not only fit well with previous data, but it makes sense from a strategic perspective. For example, when a response is certain, but the time of the required response is not known (e.g. a simple RT task) it seems plausible that in order to respond as quickly as possible, a good strategy is to prepare the response in advance. Furthermore it would also seem be beneficial, both for fast responses as well as the ability to carry out ongoing functions, to simply require “go” or trigger signal from the cortex in order to initiate the action. Thus

subcortical storage of a prepared motor program would appear to be a beneficial strategy to employ when possible. Previous evidence from startle experiments supports the notion that when a known response is required quickly, it is prepared in advance of the IS and stored subcortically ready to be triggered by cortex. A startle can then act to directly (and possibly inadvertently) trigger that prepared response (Carlsen et al. 2004a, b; Valls-Solé et al. 1999). This has been shown using a startle stimulus paired with various simple RT tasks as outlined above. Furthermore, it has been shown that the response can be held “in readiness” for at least 5.5 sec, since the length of time between the warning signal and the IS did not appear to change the ability of a startle to directly trigger the response (Cressman et al. 2006).

In most choice RT situations it is not possible to prepare the response in advance of the IS since it is the IS that informs of which response must be made. Indeed, it was observed that a response was not triggered early by startle when the stimulus informed whether a flexion or extension of the right hand was required (Carlsen et al. 2004a). In another type of RT task, the identity of the IS indicates whether a response is to be made or withheld. This task, generally referred to as a “Go / No-go” task, usually involves two stimuli, one of which is the go stimulus (e.g. green light), and one which in the no-go stimulus (e.g. red light), whereas the required response is always certain. Donders (1868/1969) proposed that a Go / No-go task required only stimulus discrimination and response execution following the IS. That is, since the response was known in advance, it did not have to be selected and programmed during the RT interval. If a beneficial strategy to enable fast responses is to pre-program and store a known response subcortically, it was thought that the single known response would always be pre-

programmed in a Go / No-go RT task. However, presenting a startling acoustic stimulus in addition to both the “Go” and “No-go” stimuli in the current dissertation did not lead to early response initiation (Experiment 3, Figure 4.1), and led to increased error rates (Figure 4.2). This result is similar to that obtained when a startle was presented in a choice RT task (Carlsen et al. 2004a), indicating that a Go / No-go task may be treated similarly to a choice RT task in terms of response programming. That is, participants may wait until after the IS to prepare the response, even if the probability of having to respond is high (e.g. 80% Go). This suggests that when participants are presented with the mere possibility of not having to respond, they use a strategy of balancing speed with correctness in responding (c.f. Ramautar et al. 2004). This strategy is in contrast to one used by participants in a simple RT task in which maximal advance preparation would be most advantageous to optimal performance of the task. It may be that when confronted with a choice between some mutually exclusive actions, humans are biased toward accuracy (i.e. correctness) of responding, over a small decrease in speed of responding. Future experiments using startle may be used to investigate the effect of manipulating this bias on response pre-programming.

The requirement of having to make a choice, however, does not imply that motor preparation can never occur prior to the IS in a RT task where a decision must be made regarding which response to make or whether a response should be made at all. For example, using the lateralized readiness potential, a measure of lateralized differences in cortical activation derived from EEG, it was seen that there was some evidence of increased activation (i.e. preparation) of cortical motor structures during a Go / No-go RT task, particularly when Go probability was high (Low and Miller 1999). Increased

activation of subcortical motor circuits, evidenced by the amplitude of the SCM response in startle trials, was also reported for a choice RT task as well as a Go / No-go task (Kumru et al. 2006), although a response was not triggered by the startle. Indeed, an increase in SCM amplitude in startle trials was also observed in the current dissertation as time of responding neared in a timing task (Experiment 5, Figure 6.1). Thus although in many cases a response is not pre-programmed in its entirety and stored subcortically for later triggering, there is evidence that some preparation of the motor system is undertaken, evidenced by observed increased activation of related motor circuits.

Whereas it has been shown that some increased activation of the motor system can result when a choice must be made, it has also been suggested that perhaps partial motor pre-programming can occur if some part of a response is known in advance of the IS (e.g. which limb will be used to respond). This would make sense if in order to be able to respond most quickly, it is advantageous to pre-program a response when it is known in advance. It was suggested that using a precuing paradigm, in which the arm to be used to respond, the direction of response, or the amplitude (extent) of the response was provided in advance, might allow for advance motor programming to be at least partially completed based on the known response parameter (Rosenbaum 1980). However, in the current dissertation (Experiment 4), when a startle was presented along with the visual IS in the two-choice precue conditions, *multiple responses* were often elicited at short latencies towards the two possible (i.e. precued) targets. For example, if the precues provided information that an extension movement was required but did not provide information regarding which hand would be used to respond, the presentation of a startle often led to the triggering of simultaneous left and right hand extension responses.

Similar results were observed for the precue condition that indicated either a flexion movement with the left hand or extension with the right. That is, it appears that when the precue indicated dichotomous bilateral targets, multiple responses were elicited at short latency by startle (Experiment 4, Figure 5.1 & Figure 5.3). Thus it appears that under certain circumstances participants chose to pre-program multiple responses in parallel, particularly when the response possibilities involved one distinct movement for each hand (i.e. direction / ambiguous precues, see Experiment 4). This would appear to contradict the results of some of the previous experiments that showed that no response was pre-programmed when a choice had to be made between several targets. It may be that in cases where programming of one response interferes with another, such as opposing movements for a single hand, no pre-programming takes place. However, the difference in Experiment 4 was that most often when multiple responses were elicited, one of the responses was the correct response. Perhaps when there is little danger of having to reverse a movement and possibly re-program it, such as independent movements for each hand, multiple responses are prepared in advance. In this case, under normal circumstances the correct response is simply initiated or triggered by cortex once known. If, for some reason the wrong response was initiated, the correct response would still be prepared and ready to be initiated.

Thus far, the discussion surrounding when humans choose to pre-program a response has been centered within the framework of RT tasks. In many cases, the responses were made some time following a temporally uncertain “go” stimulus. Although a constant foreperiod has been employed in some startle experiments (e.g. Carlsen et al. 2003a), this was unknown to participants, and catch trials in which no IS

occurred were used to discourage false starts. These startle experiments indicated that when speed of responding is necessary and the required response is known, pre-programming a response is a beneficial strategy if it is uncertain *when* the response is to be made. Of interest, however, was whether participants would pre-program a known response when there was no temporal uncertainty. A stop-signal paradigm has been used previously to infer when a ballistic response was initiated with respect to a consistently timed event (point of no return, Slater-Hammel 1960). Participants were asked to release a response key coincident when a consistently timed clock hand reached a target. However, if the clock hand stopped prior to reaching the target, participants were instructed to refrain from lifting off the response key. Previously, it was shown that if the clock hand stopped close to the target, participants were unable to stop their movement, indicating the ballistic response had already been initiated by that point (Slater-Hammel 1960). However, it was uncertain when the response was programmed prior to this “point of no return.” If the response was programmed and stored at some time prior to initiation it was thought that it may be elicited at short latency following a startle.

In Experiment 5 of the current dissertation participants showed no increased probability of responding when a startle was presented in conjunction with the clock hand stopping, irrespective of how close to the target the clock hand was when it stopped (Experiment 5, Figure 6.2). It appears that the strategy adopted by participants was not to pre-program the response well in advance as seen in a simple RT task. Rather, participants chose to wait until the response was required and then programmed and initiated the action together. This does not appear to be entirely surprising once the differences between RT and anticipation timing tasks are considered. While preparing in

advance may greatly benefit RT when there is temporal uncertainty, there would not be a similar benefit to responding when temporal uncertainty is removed. It may be that if the time of responding is known, preparing a response in advance is an inefficient use of CNS resources. Previously however, in a somewhat similar task, it was shown that a secondary movement whose initiation was based on the position of the limb *was* elicited once the limb was <400 ms from reaching the target, indicating that the secondary movement was programmed and stored subcortically at some point prior to this (Carlsen et al. 2003b). It was suggested that the normal trigger for the initiation of the secondary movement was based on proprioceptive information from the arm in this situation (Cordo et al. 1994). Therefore in cases where the executive (i.e. cortex) does not have exclusive control over the timing initiation of a response, pre-programming of the secondary response may be required. While it may be suggested that the possibility of having to stop influenced the strategy chosen by participants in Experiment 5 (c.f. Kumru et al. 2006; see also Experiment 3), pilot data (currently being analyzed) using a similar startled timing task but omitting the possibility of having to stop, similarly indicates that participants did not program the response well in advance of the target. These data suggest that it is more likely that participants do not pre-program the action due to the influence of the temporal certainty in the task. Interestingly, as previously noted, analysis of SCM EMG showed that amplitude increased as the response target neared, indicating that some preparation of subcortical and spinal motor circuits did occur in advance of the target (Experiment 5, Figure 6.1), and increased as time to the required response neared. This is similar to results reported by Coxon et al. (2006) who showed increases in motor

evoked potentials elicited by transcranial magnetic stimulation during a similar timing task.

If one accepts the notion that it is beneficial to pre-program a response in a RT task if it is known in advance, it becomes necessary to ask, what are the limits of pre-programming? Most of the previous tasks involving a startling stimulus described in this dissertation (including Experiments 1 - 5) involved simple actions mainly involving one degree of freedom and performed as quickly as possible (e.g. wrist extension, Carlsen et al. 2004a). It has been suggested, however, that a more complex task involving a sequence of sub-movements cannot be programmed in advance. It was suggested that this was because a final “assembly” of the parts of the movement sequence had to occur following the IS (Klapp 1996, 2003). In Experiment 6 we found, as in previous experiments, that single component movements (15 deg, 30 deg wrist extensions) were triggered by the startle (Experiment 6, Figure 7.1). It has been suggested that longer duration (Klapp 1996) and larger amplitude (Lajoie and Franks 1996) movements are more “complex,” yet since a 30 deg wrist movement was nevertheless elicited early by startle it appears that it was not too complex to be pre-programmed. Similar results have been observed between 20 deg and 60 deg arm extension movements (Carlsen et al. 2004b). In contrast, it appears that a two-component (15 + 15 deg) wrist extension movement was not susceptible to the same startle related RT facilitation (Experiment 6, Figure 7.1). These results support previous findings (Klapp 1996, 2003) suggesting that some critical component of movement programming (likely sequencing of movement components) cannot be completed until *after* the IS when the movement involves multiple sub-components. Although it was shown that a larger amplitude movement (30

deg wrist extension) could be pre-programmed, this was still within the context of responding as fast as possible. It remains unclear at what point a similar response is no longer pre-programmed when the *duration* (i.e. movement time) of the response is manipulated. At some point it would seem that pre-programming the response would no longer be beneficial or even possible. For example, suppose the same 30 deg movement was made with a movement time goal of 200 ms, 500 ms, 1 sec, or 2 sec. At what point would the response no longer be pre-programmed? Thus even for the same movement the requirements of the task may at some point limit the benefit of pre-programming.

Although humans may adopt different pre-programming strategies depending on the task, sometimes the nature of the task itself may inherently limit the ability of the performer to program a response in advance.

Concluding Remarks

In conclusion this dissertation reached two important main findings. First presenting a startling acoustic stimulus during a simple RT task appears to lead to dramatically reduced RTs via the mechanism first proposed by Valls-Solé et al (1999). That is, the evidence suggests that when a motor action can be prepared in advance, it is pre-programmed and stored subcortically awaiting the normal cortical “go” signal. A startle appears to directly activate structures that are involved with the voluntary response channel leading to early triggering of the prepared response, and dramatically reduced RT. Alternative hypotheses regarding the mechanism of startle RT facilitation, including increased neural activation, stimulus intensity effect, and a fast transcortical route were rejected based on results from Experiments 1, 2, and previous experiments (Carlsen et al. 2004a).

Second, this dissertation presented data which together provide insight into motor programming processes, and the circumstances under which humans either choose to, or are able to pre-program a response. These circumstances appear in some cases to be different to those previously thought to govern the tasks investigated here. It was suggested that in many cases, whether or not a response was pre-programmed was dependent on a balance between the benefits of quick responses versus the costs of errorful responding, or the energetic costs of preparing the system. The results showed a known response was not pre-programmed when the possibility of not having to make the response (Go / No-go, Experiment 3) existed. Similarly, the response was not programmed well in advance when there existed temporal certainty regarding responding (Experiment 5). However, while it was thought that having to make a choice between several response alternatives precluded pre-programming (e.g. Carlsen et al. 2004a), it appears that sometimes it may be more beneficial to prepare for all response alternatives in advance and initiate only the correct response once known (Experiment 4). Finally, the ability to pre-program a response may not be possible in some cases, such as when a response involves multiple sequenced sub components, (Experiment 6).

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9. Appendix A

UBC Behavioural Research Ethics Board Certificate of Approval



The University of British Columbia
Office of Research Services
Behavioural Research Ethics Board
Suite 102, 6190 Agronomy Road, Vancouver, B.C. V6T 1Z3

CERTIFICATE OF APPROVAL- MINIMAL RISK RENEWAL

PRINCIPAL INVESTIGATOR: Ian M. Franks	DEPARTMENT: UBC/Education/Human Kinetics	UBC BREB NUMBER: H98-80046
INSTITUTION(S) WHERE RESEARCH WILL BE CARRIED OUT:		
Institution	Site	
UBC Other locations where the research will be conducted: N/A	Point Grey Site	
CO-INVESTIGATOR(S): Paul Nagelkerke Romeo Chua Anthony N. Carlsen		
SPONSORING AGENCIES: Natural Sciences and Engineering Research Council of Canada (NSERC) - "Electromyographic Patterns of Fast Goal-Directed Arm Movements: Comparison of Perturbed and Unperturbed Movements" - "Influence of Contralateral Arm Movement on Latency, Kinematic and Electromyographic (EMG) Measures of the Ipsilateral Arm During a Discrete Aiming Movement" - "Preparation and Control of Rapid Voluntary Movement"		
PROJECT TITLE: Electromyographic Patterns of Fast Goal-Directed Arm Movements: Comparison of Perturbed and Unperturbed Movements		

EXPIRY DATE OF THIS APPROVAL: April 27, 2008

APPROVAL DATE: April 27, 2007

The Annual Renewal for Study have been reviewed and the procedures were found to be acceptable on ethical grounds for research involving human subjects.

Approval is issued on behalf of the Behavioural Research Ethics Board
and signed electronically by one of the following:

Dr. Peter Suedfeld, Chair
Dr. Jim Rupert, Associate Chair
Dr. Arminee Kazanjian, Associate Chair
Dr. M. Judith Lynam, Associate Chair
Dr. Laurie Ford, Associate Chair