Startle Stimuli Reduce the Internal Model

Control in Discrete Movements

BY

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THESIS

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LIST OF ABBREVIATIONS

CNS	Central Nervous System
SAS	Startle Acoustic Stimulus
EMG	Electromyography
SCM	Sternocleidomastoid
CCW	Counterclockwise
CW	Clockwise
IDE	Initial Direction Error
ANOVA	Analysis of Variance
MVC	Max Voluntary Contraction
CCI	Cocontraction Index
VD	Visual Distortion
ERM	Early Release of Movement

SUMMARY

A well-known and major component of movement control is the feedforward mode, which utilizes a learned internal model that predicts and compensates, based on recent experience, for expected perturbations seen during a movement, so that a well-learned task such as reaching to a target can be executed in a smooth, straight manner. When the perturbation is suddenly removed after training to execute the require movement within the perturbed environment, people tend to make errors, termed after-effects. In another line a research, recent work has shown that the state of preparation of planned movements can be tested using a startling acoustic stimulus (SAS). SAS presented before or coincident with an expected "go" cue (GO) can result in the early release of a preplanned feedforward motor program (i.e. internal model). In this thesis, we performed a series of four experiments that made use of a typical motor adaptation paradigm to test if SAS influences the size of after-effects that are typically seen after the unexpected removal of a perturbation.

In the first experiment, subjects trained making reaching movements within a dynamically perturbed environment using robotic forces. During catch trials, subjects suddenly experienced either the removal of the forces (i.e. No SAS) or the removal of forces accompanied with SAS at one of the three temporal settings (i.e. SAS @ -0ms, -250ms and -500ms) before expected movement initiation (i.e. GO), revealing the after-effects of adaptation. We found a reduction in the magnitude of after-effects when the movements were accompanied with SAS (SAS @ -0ms timing condition was significantly different than the No SAS condition). Furthermore, the magnitude of the reduced after-effects was not further modulated by the timing of SAS. However, the intensity of the startle stimulus was insufficient to elicit a typical startle response, thus movements were not released early by SAS as expected.

Thus, we performed a second experiment using the same adaptation paradigm and a more intense startle stimulus likely to have a higher probability of eliciting typical startle responses. Similar to experiment one, we observed a reduction in after-effects when SAS provoked a complete startle response (SAS @ -0ms and -250ms timing conditions were significantly different than No SAS condition). Also, the size of after-effects were not further modulated by the timing of SAS. These results provide evidence that startle may interfere with the release of a recently learned internal model. However, the possibility that startle causes subjects to cocontract may pose as a potential confound.

We alleviated this potential confound in a third experiment by changing the mode of adaptive training to a visual distortion instead of a force-field. Similar to the results of the previous experiments, we found that, in all subjects that exhibited a startle response or at least a partial startle response, startle significantly reduced after-effects in all three SAS timing conditions. The results further confirm that startle disrupts the recall of a recently learned internal model that cannot be confounded by cocontraction.

In experiment four, we further investigated the effects of startle on learned preparatory control by administering startle while subjects performed within the visually distorted field. We found that startle also reduces performance of the recently learned task in a similar fashion as reducing after-effects. Because startle reduced but did not eliminate the recall of learned control, we suggest that multiple neural centers (cortical and subcortical) are involved in such learning, and that startle may interfere more with the release of unconsolidated motor programs. These results may impact training areas such as piloting, teleoperation, sports, and rehabilitation.

I. INTRODUCTION

The human nervous system contains many layers of complex neural processes that allow us to control a range of movements that include drinking a cup of coffee to piloting a fighter jet. Learning to control movements in the face of differing environments and external disturbances relies on multiple modes of motor control. Researchers are constantly exploring for new tools for revealing the underlying mechanisms behind the human motor control system. One such tool that has been recently gaining the attention of researchers is an acoustic startle stimulus which may be capable of uncovering the important components related to the preparation and storage of recently learned movements [1-4].

Due to physiological delay of neural feedback mechanisms, fast and smoothly coordinated arm movements cannot be executed without specialized strategies that plan movements in advance. Researchers agree that the Central Nervous System (CNS) is able to achieve proficient movements by compiling a model of the action, which estimates the necessary motor commands [5]. This is referred to as the feedforward mode of motor control, whereby an internal model is acquired through motor learning. Many studies have revealed the existence of internal models by unexpectedly changing features within the environment people are interacting., which causes sporadic movements termed after-effects [6-10]. Many critical aspects of internal models have been revealed based on the work performed to understand the adaptation and learning processes in humans. Yet the underlying mechanisms behind the formation and retrieval of internal models are still unclear.

Researchers have recently discovered a novel form of an experimental probe that has offered new insights on the movement preparation responses in humans [1, 2, 4]. Issuing a loud acoustic noise, intense enough to elicit a startling response, has been shown to cause a premature release of an intended feedforward motor program [1, 2, 4, 11]. Startle has provided essential details on the storage and release of feedforward control, most notably, that movement preparation requires the build-up of a motor program [12, 13]. It is unclear, however, whether movement preparation of a recently learned task, such as adapting to an external perturbation, requires the same type of build-up.

This thesis introduces startle in a typical adaptation paradigm to investigate the storage and release of internal models learned through adaptive training. We describe the use of a pre-existing robotic system, where subjects learn how to operate the machine in the presence of challenging dynamic and visual perturbations, to test if startle influences the after-effects that are typically seen after adaptive training. This study is an important step in understanding the relationship between startle and motor learning which may impact training areas such as military, sports, teleoperation and piloting.

A. BACKGROUND

This thesis begins with a review of the literature on (1) motor learning and adaptation and (2) startle and movement preparation. We first focus on how the formation of neural models drives feedforward control and how such models are experimentally exploited when adapting to novel environments. We then discuss the relevant concepts that have been extracted from using

startle as a tool to probe movement preparation responses. We finally present some of the unanswered questions that motivate this study and present the corresponding hypotheses.

1) Motor Learning and Adaptation

The process of forming internal models is functionally relevant in that they help us learn new movements and allow us to execute them in an accurate and efficient way, but only in predictable and stable environments. Due to the vulnerability of internal models to unanticipated changes in the environment, the associated motor commands need to be constantly updated and modified so that movements can be smoothly and accurately carried out. Thus, these unexpected errors that occur during such events promote the remapping of the inverse dynamics of the new environment through learning. Many studies have provided an understanding of the learning and adaptation processes of movement control by challenging subjects to execute movements within unique environments. Examples include: artificial gravity environments where subjects undergo a period of weightlessness simulating orbital space flight [14, 15]; rotating rooms that produce Coriolis forces during reaching movements [16]; inertial outriggers attached to the forearm that complicate the dynamics of movements [17]; robot-applied force-fields [6, 7] and kinematic visual distortions [8, 9, 10 18]. Continued research on the properties of feedforward control, including internal model formation and adaptation, and corresponding neural substrates may enhance motor learning and recovery and lead to improved rehabilitation or neuroregeneration methods for people with neurologic injuries.

Robot-applied force-fields are a common and reliable experimental tool for studying adaptation processes of internal models by introducing a dynamic change in the environment [6, 7]. When exposed to these forces, subjects tend to make errors in their movement. After a long training phase, the subjects eventually learn to move in the presence of these forces and begin to move in a straight line as they would if undisturbed [7]. When the forces are unexpectedly turned off on random intermittent trials, termed catch trials, they make errors in their movements. This unpredicted mistake, labeled an after-effect, takes on a shape that is nearly symmetrical to the initial errors that occur when the subjects are first exposed to the forces [7]. After-effects reveal the existence of the learned internal model that predicted the dynamics of the movement before it even began.

The recovery of the kinematic profile of the movement path through training is one piece of evidence supporting the idea that adaptation to a force-field is a result of the composition of an internal model. Planar reaching movements are characterized by a smooth translation of the hand along a straight line path [19] and hand velocity is bell-shaped in nature [20]. When subjected to a dynamical force-field, these characteristics are significantly distorted. However, through training, it has been shown that there is a convergence of hand trajectory kinematics similar to those observed in the null field [6]. One possible strategy to maintaining a movement about a desired path is by reducing speed, known as the speed accuracy trade-off [21].

From a dynamics point of view, another possible strategy to reduce error is by increasing the stiffness of the arm, accomplished by simultaneously cocontracting muscles. Cocontraction may initially exist to compensate for the unfamiliar perturbation, but has been shown to reduce

with learning [22, 23]. Furthermore, the presence of after-effects during catch trials suggests that improved performance during training is a result of a *learned* internal model, rather than cocontraction.

Visual perturbations are another helpful experimental tool in studying the learning processes in humans. A visuomotor distortion has been implemented through prisms [19], nonlinear mappings [10] and rotations or scaling [9, 18]. Similar to force-field adaptation studies, an unexpected rotation or translation of the visual field leads to movement errors. Subjects revert back to desired trajectories through training by creating a visuomotor map (i.e. internal model). After-effects are evident when returned to the "normal" world, marked by improper movements opposite of those when initially altered, revealing the internal model.

Similar to using dynamically changed environments as a mode of adaptation, overcoming kinematically altered environments elicits learning an internal model, but requires updating different input characteristics (i.e. states) of the inverse model. The inverse model is able to compensate for arm dynamics, but when an unexpected force is applied, the motor commands are insufficient. Thus, the added dynamics must be compensated for by modifying the amount of force input into the model. In contrast, a perceived change in the visual environment requires a change in direction [5].

Although it has not been directly studied, co-contracting, in an attempt to reduce error, can be considered unnecessary when adapting to a visually rotated environment. In this case, the act of co-contracting muscles alone actually takes place about an erroneous path. A change in

kinematics, specifically, the path of the arm, is required to move the visual feedback in a straight line fashion to the target. Thus, the option of exchanging speed for accuracy still exists as slowing down might improve performance. Similar to adapting to a force-field, movement speed and the time to complete the movement must be controlled for to avoid such techniques by subjects.

The feedforward mode of neural control is often confused with corrective feedback control mechanisms that commonly occur after a noticeable error in a movement is realized. In this case, an efference copy of the motor command that is controlling the arm position is sent to a forward model which predicts the position and dynamics of the arm. The differences between the actual position, perceived visually or through proprioception, and the predicted position is sent back to the controller, which then compensates for any error. In a discrete reaching movement where adaptive control is applied, feedback mechanisms can occur while executing the movement or in conjunction with the feedforward motor command. The time delay for when remedial feedback ensues is on the order of 150-250 ms for visual feedback [5]. For relatively fast movement durations (500ms) in many arm-length activities and short distances (15cm), this is about half-way along the movement path. Only the initial portion of the movement reflects the intent of the feedforward program, whereas any movement rectifications after this point are correlated with feedback.

2) Startle and Movement Preparation

The startle response (or startle reflex) was first scientifically examined by Carney Landis and William A. Hunt in 1939 using high speed photography. These pioneers described the startle response as a patterned response of several bilateral stereotyped muscle movements [24]. Since then, scientific investigators have further canvassed the physiological nature of the startle response in humans and animals, with results yielding a more thorough understanding of the specific neuronal pathways involved at several levels of the CNS. In brief, the startle circuit follows a subcortical reflex pathway where the sensory pathway activates the motor center of reticular formation and the descending reticulo-spinal tract to the spinal cord activating motor neurons of the limbs [25]. Often hypothesized as a primitive response, the startle response can be summarized as an immediate whole-body physiological reaction consisting of a pattern of muscle flexion (ocular, facial, limb etc.) and increased CNS and autonomic activity initiated by an unexpected intensified stimulus (i.e. acoustic, visual, mechanical or electric) [26, 27]. This involuntary response in humans that leads to abrupt physiological and neurological reactions is an example of how the brain has competing primitive, autonomic and cortical processing.

Prior to the initiation of a movement there is a progressive build-up of planned movement-related cortical activity associated with the neuronal preparation of a motor program [28, 29]. Researchers have discovered that presenting a startling acoustic stimulus (SAS) can cause the involuntary release of this motor program, but only if the program is prepared in advance [30, 31]. The release of movement is defined as the initiation of movement either voluntarily, or in the case of SAS, involuntarily. SAS not only has the effect of releasing a

prepared response, but movements are released earlier than voluntary responses (marked by shorter latencies in premotor reaction times) [1, 4].

Voluntary movements are triggered by the cerebral (motor) cortex after receiving a neural signal from the sensory pathway that detects the onset of a stimulus. Humans respond to visual stimuli on the order of 180ms, whereas, response to auditory stimuli is on the order of the 140ms [32]. The temporal differences in reaction times between these two sensory responses can be attributed to the difference in the amount of time for transduction of the stimulus into the appropriate neural signal. In contrast, movements released by startle have been shown to be released ~80ms earlier than voluntary responses [4]. Since there is a fixed time needed for the transduction of an auditory or visual stimulus and for neural transmission from the motor cortex to the motor output, the earlier reaction times seen in response to SAS suggest that prepared responses must be stored in a place other than the motor cortex. The short latency in movement onsets when startled provides a piece of evidence that allows researchers to suggest that the motor program must be stored and released from subcortical structures, thus bypassing the expected command from the motor cortex [4].

Furthermore, the spatial and temporal characteristics of the pre-planned movement sequence remain intact when involuntarily initiated by startle, indicating that the "intended" motor program is being released from subcortical structures [4, 11]. This result was revealed in a number of experiments involving relatively non-complex one degree of freedom movements about the wrist joint or elbow joint. For example, when subjects were asked to make arm extension movements as fast and accurate as possible to varying degrees, the Electromyography

(EMG) profiles and kinematic measurements of the movement, including accuracy, were unmodified when startled [4, 11]. This signifies that the unaltered, yet early responses are not due to a superposition of a natural startle reflex on top of a voluntary response, but rather due to the intended prepared motor program being released from subcortical structures [4, 11].

Evidence has shown that SAS will facilitate a prepared response if the motor task is pre-programmable [11]. For instance, when only a single motor program is mandated in response to a sensory stimulus prompting when to initiate movement, as in a simple reaction time task (i.e. wrist or elbow flexion/extension or reaching) where the task is known prior to GO, the required motor program can be programmed in advance. Knowing the required task does not guarantee advance preparation, as in the case of a "go/no go" task where subjects were cued by the response stimulus whether or not to initiate movement [33, 34]. Similarly, a task that requires a decision between two motor programs during the reaction time interval (i.e. choice reaction time task), movements are not prepared in advance and consequently not triggered early by startle [11]. During motor tasks of these types, the uncertainty between the response alternatives necessitates higher cortical processing that cannot be prepared prior to the stimulus, leading to longer reaction times [35]. Conversely, the motor programs associated with tasks that do require more complex neural processing, such as sequenced bimanual movements (i.e. movement of two arms separated by 100ms) or precued response alternatives (i.e. subset of possible lateralized responses precued prior to GO) have been shown to be prepared in advance [36, 37]. Furthermore, SAS, administered during post-stimulus planning does not release movement early, as evidence of pre-motor reaction times. The fact that only preprogrammable movements (even of more complex movements) can be released early by SAS contradicts the hypothesis that early

response times when startled are a consequence of increased activation levels of the sensorimotor system, but favors that startle triggers only prepared responses [11].

Furthermore, evidence has suggested that movement preparation involves the progressive buildup of feedforward motor program overtime. This result is quite dramatic in programmed stepping response actions, where the SAS triggers not only early reaction times, but a more and more complete feedforward control program (involving appropriate preparatory weight shifting) as the SAS stimulus timing approached the GO cue [12]. These findings are consistent with a feedforward mode of neural control whereby the motor sequence, including the associated postural adjustments, is prepared before voluntary movement. Precedent imaging studies also show that cortical activity starts to enhance a significant amount of time prior to GO or SAS [38]. These results suggest that the current state of a prepared motor program can be prompted by using various SAS timing conditions.

The time course for which the feedforward motor program begins to build depends on the temporal uncertainty of GO. Movement preparation occurs closer to the GO signal as the timing of the cue becomes more predictable or resolute, such as in an anticipation- timing task in which continuous temporal information is provided. In fact, movement preparation can be delayed until upwards to 150ms prior to GO. Whereas, when the response time is less predictable, such as in a variable foreperiod RT task, SAS presented up to 1500 ms prior to the cue can initiate the release of the planned movement [13].

It is necessary to briefly discuss some of the chief considerations for properly exercising a startling acoustic stimulus as an investigative technique to probe motor preparation. This includes optimal stimulus parameters, such as timing and intensity level, and methods for detecting a startle response. Key stimulus timing factors that should be followed include a rise time (the time for stimulus amplitude to reach a maximum) of less than 12ms, a frequency of SAS presentation less than 1 every 5 trials, and a duration between 40 and 50ms [3]. Also, a wide range of amplitude levels has proven to produce a startling effect, including short response latencies, but it has been shown that the probability of observing this response increases with increasing intensity, with 120+dB being optimal [39]. Furthermore, it was determined that neck muscle activity, particularly from the sternocleistomastoid (SCM), is the most reliable indicator of a startle response rather than the Orbicularis Oculi muscle that aides in eyeblinking. SCM activity seen within 30 to 120ms after the stimulus is a robust sign that there will be a short latency response [3].

One of the confounding factors in startle studies is the possible occurrence of response habituation to the acoustic stimulus. Habituation is marked by a decline in the behavioral response to repeated stimulus perturbations where SCM activity and subsequently short response latencies are absent. The startle response can vanish within a few presentations of the startle stimulus, but methods can be put in place, such as subtle changes to experimental parameters, in order to avoid habituation. Ultimately, the probability of eliciting a startle response depends on the subject's readiness to execute the movement [30].

In summary, this section has presented a background on two areas of research that have both contributed to our understanding of fundamental aspects of the feedforward mode of neural control. (1) Unique environments with dynamic or visual perturbations that require the formation of internal models have provided details about the adaptation and learning processes of humans. (2) A startling acoustic stimulus has proven to be a reliable tool for probing the movement preparation responses of humans by evoking an early, sometimes premature release of a pre-planned feedforward motor program. It is known that movement preparation involves the progressive buildup of a feedforward program over time, but what is not clear is whether adaptations to new environments involves the same type of progressive buildup. Therefore, this thesis has combined startle with a typical adaptation paradigm to investigate the storage and release of the internal model formed during adaptive training. We hypothesize that startle disrupts the release of movement trajectory consistent with the after-effects seen in force-field and visuomotor training. Such disruption might reduce or eradicate the size of after-effects. It is further hypothesized that the magnitude of the released internal model would progressively increase as the timing of SAS approached the onset of an imperative GO cue, related to the buildup and readiness of a possible feedforward motor program.

This thesis involved a series of four experiments that aim at providing an understanding of the preparation responses associated with a recently learned task. In the sections that follow, we will lay out the corresponding methods and procedures for each experiment. We will then discuss the key results and describe how potential confounds are further investigated in subsequent experiments. We will end with a general discussion of key results.

II. EXPERIMENT ONE

A. INTRODUCTION (EXPERIMENT ONE)

In this pilot study, we incorporated startle into a typical adaptation paradigm in an attempt to gain insight on its effect on the storage and release of a recently learned internal model. Subjects were required to make reaching movements to targets using a robotic apparatus and to build a new internal model of a dynamically changed environment that included a novel force-field. After learning to move within the presence of this disturbance, a startle-like stimulus was presented in catch trials (i.e. removal of the force-field) prior to or coincident with an imperative visual GO. The results reveal that the loud noise disturbs the internal model's intended trajectory, as evidence of reduced after-effects. Furthermore, the magnitude of reduced after-effects were unaffected by the timing of the startle stimulus. However, the startling acoustic stimulus did not lead to an early response in movement as expected. Although startle was naively practiced in this experiment, the fact that there was at least partial degradation in the after-effects of adaptation, provided evidence that the startle stimulus may interfere with the release of a recently learned internal model. The results of this experiment were presented at EMBC 2009 [40].

B. METHODS (EXPERIMENT ONE)

1) Apparatus

a) Manipulandum

All experiments proposed in this research use a planar haptics/graphics system called the manipulandum (Fig. 1), presented previously [41, 42]. Subjects interact with the robot by grasping a handle that allows two planar movements. The robotic arm is connected to two low-torque motors able to produce desired forces that could either assist or perturb the motion in two degrees of freedom. The robot records limb position and handle force at 200 Hz. An overlaying projector displays the current position of the hand on a screen located in front of the subject in the coronal plane.

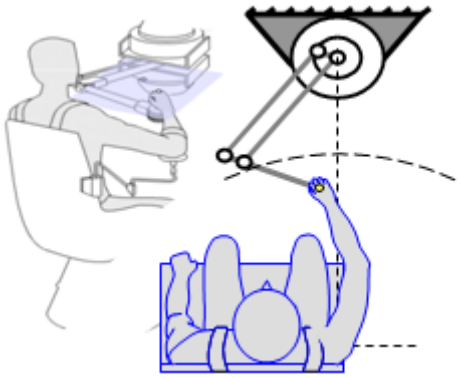

Figure 1: Manipulandum apparatus.

b) Startle Acoustic Stimulus

An analog tone (1 kHz, 40 ms pulse) produced by a function generator was used to create an auditory startle stimulus. The tone was amplified to produce a stimulus with an intensity of 104dB (measured with a Brüel & Kjaer Precision Level Sound Meter Type 732A) which was presented to the subject via headphones.

2) Protocol

Five healthy adult subjects (Mean ± SD of age in years = 22 ± 2 years), free from neurological or musculoskeletal disorders and naïve to the learning paradigms participated in this study after signing a consent form approved through Northwestern University IRB. Subjects grasped the handle of the robot and performed a series of reaching movements in two directions to a visual target located 15cm away from a start position (i.e. inward and outward movement). Each trial consisted of the appearance of a blue target followed by a change in its color to yellow after 2.5 seconds to indicate the imperative GO. Subjects were instructed to initiate a movement towards the target in a straight line manner in response to GO. Chair height was adjusted so that movements departed from a center point located in the horizontal plane, 30 cm below the chin (approximately standard table height) and 20 cm anterior to the chin.

The paradigm followed those of typical force-field adaptation experiments in which each of the subjects that participated in the experiment performed the following phases:

Familiarization: To become familiar with the experimental conditions, subjects made 60 movements between targets. The GO cue specified when to perform the movement. Based on our experience, 60 movements are more than enough for subjects to arrive at a full understanding of the task, to become comfortable and well seated at the apparatus and could perform movements correctly.

Baseline: Subjects attempted to perform five movements in both directions. Again, the GO cue specified when to perform the movement. This phase was used to establish a baseline pattern before prolonged training began. Based on our experience, five movements are enough statistically.

Initial Exposure: In a subset of 320 movements in all, on intermittent, randomly selected trials, (one in every 8 movements) subjects were exposed to either SAS or exposed to the well-known "curl" force-field [6, 7]:

$$F = \begin{bmatrix} 0 & -15 \\ 15 & 0 \end{bmatrix} \dot{x} \qquad (1)$$

where F is the force vector applied to the limb and $\dot{x}$ is the 2-dimensional velocity vector of the hand. This field provided a smooth disturbing force that is perpendicular to the current direction

of movement and proportional to the velocity of the hand that does not exist in any natural activity. The matrix is skew-symmetric and hence leads to no added or removed energy by the robot.

Training: A total of 200 movements were performed in all, where subjects consistently trained in the presence of the "curl" field with the goal to revert back to straight line movements.

Evaluation: 320 movements were performed with forces, but now several randomly selected intermittent trials (one in every 8 movements) evaluated the effects of learning and how it is modulated by SAS stimuli. In these trials, subjects experienced either the unexpected removal of forces (i.e. No SAS catch trials) or the unexpected removal of forces with SAS occurring at -500, -250 and 0ms prior to the GO (i.e. SAS catch trials). Fives trials per task condition per direction were evaluated. Since the force-field is dependent on the velocity of the handle, subjects were unaware that there was a removal of the force-field until movement was initiated.

3) Analysis

Angular deviation from a straight line is the primary measure of movement error, since initial exposure to the "curl" force-field results in a counter-clockwise (CCW) bend of the movement path and the after-effects of adaptation, seen when the force-field is unexpectedly removed, are clockwise (CW). Initial Direction Error (IDE) measures the degree at which after-

effects initially deviate from an ideal straight line capturing the intended feedforward motor program. IDE is defined as the angle between the vector that lies along an ideal straight line movement directed towards the target and the vector formed from the point when the handle reaches a threshold velocity (.1 m/s) to the point 150ms into the movement.

For both SAS and voluntary movements (i.e. No SAS), velocity-based movement onset is defined as the time when the robot handle reaches a speed of .1 m/s relative to the onset of GO (i.e. 0ms). We expect that movement onsets for the cases of startle to be significantly earlier than voluntary movements, indicating that startle released movements.

One-Way Repeated Measures Analysis of Variance (ANOVA) with a Tukey's post hoc test (modified) was used to determine if the movement errors of the three startle conditions were statistically different than the No SAS condition and to each other. Differences with a p-value less than .05 are considered to be significant. The Tukey's post hoc test used in the analysis of all pairwise comparisons in each experiment is a modified version of the more recognized Tukey's Honestly Significant Difference post hoc test and will be referred to as the Tukey post hoc test (modified). The basic principle of this version is that the Studentized Range Statistic (q) has the following relationship to the t-statistic:

$$q_{critical,\ \alpha}(k, df_{error}) = \frac{t_{\alpha}(df)}{\sqrt{2}} \quad (2)$$

where $q_{critical}$ is the critical q-value determined in a Studentized Range Statistic table, k is the number of means being compared, df_{error} is the degrees of freedom of the error term in a

Repeated Measure ANOVA, t is the t-statistic determined through a pairwise t-test, df is the degrees of freedom of the pairwise t-test, and α is the level of confidence (i.e. α = .05). This method is more liberal than Tukey's Honesty Significance Difference post hoc test, but more conservative to Fisher's Least Significant Difference test [43].

C. Results (Experiment One)

As expected, the trajectories for all subjects during four phases of experiment one followed those discovered in typical adaptation to force-field experiments of this type (Fig. 2). Baseline trajectories approximated straight lines in both the outward direction (Fig. 2A left) and the inward direction (Fig. 2A right). Initial exposure to forces perturbed motions in the CCW direction, whereas initial exposure to SAS did not inhibit the subjects' ability to make straight line movements (Fig. 2B). Motions again approximated straight lines by the end of training, disclosing the subjects' ability to move in the presence of forces and the learned internal model (Fig. 2C). Trajectories were distorted in a CW direction in catch trials when the forces were unexpectedly removed (Fig. 2D). These after-effect trajectories are nearly mirror images to those seen when initially exposed to the force-field and reveal the after-effects of adaptation. Similar patterns in the after-effects were also visible when the SAS was presented (Fig. 2D).

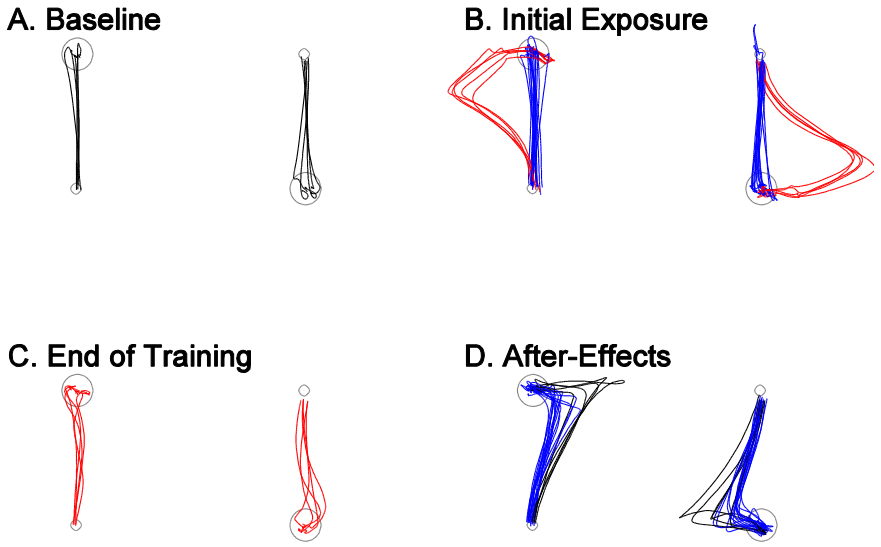

Figure 2: One subject's movement trajectories during the different phases of experiment one for one subject. Outward directed and inward directional movements are separated to the left and right, respectively, under each phase. (Black – Null Field, Blue – Null Field with SAS presented at either -0ms, -250ms or -500ms, Red – Force-Field Present)

Although the patterns of trajectories for after-effects were similar for when the acoustic stimulus was present or absent, the magnitude of the after-effects for both cases were compared. Group trends reveal that the initial direction angles between the ideal straight line trajectory and the after-effect trajectories were smaller for the cases of SAS. Differences across conditions are shown in Fig. 3 using a wings plot that shows the means and 95% confidence interval of movement errors in each subject for each condition and the group means and 95% confidence interval for each condition. One-Way Repeated Measures ANOVA revealed a main effect of task condition $F(3,12) = 6.26$, $p = .0084$. The group mean and standard error of movement errors for the No SAS catch trials was calculated to be 14.97° (± 1.48°). The group means and standard

errors of movement errors for when SAS was administered at -500ms, -250ms and -0ms was calculated to be 11.84° (± 1.23°), 11.72° (± 0.85°) 11.01° (± 0.69°), respectively. Tukey post hoc test (modified) showed that movement errors for when SAS was administered at -0ms was significantly different than the No SAS condition ($p<.05$).

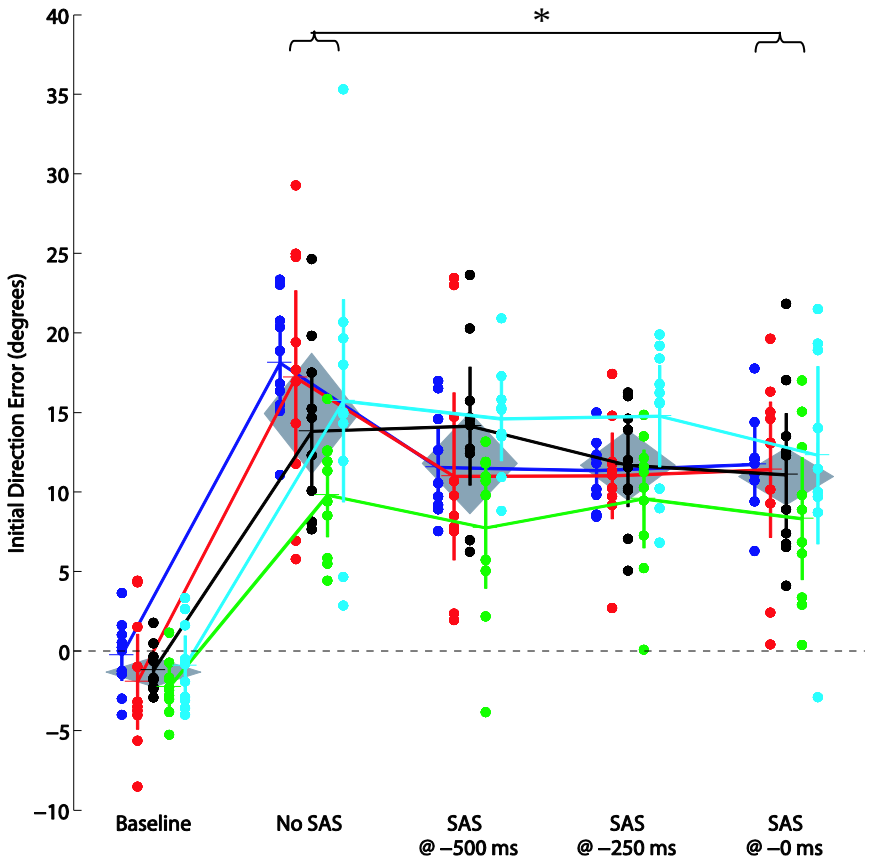

Figure 3: Movement errors in after-effect catch trials for the case of No SAS and the three cases of startle compared to baseline error (horizontal axis). Each subject is a color, each trial's data is a dot, each subject's mean is indicated by a colored horizontal bar, each subject's 95% confidence interval for that condition is indicated by a colored vertical bar, and each group mean and 95% confidence interval of the means is indicated by a diamond shaped shaded area. Statistical comparison of group means revealed a significant difference between the No SAS condition and the SAS @ -0 ms timing condition (shown by black lines connecting brackets and an asterisk at the top).

Group velocity-based movement onset times relative to GO showed that subjects did not initiate movement early as a consequence of the startle stimulus (Fig. 4). One-Way Repeated Measures ANOVA revealed a main effect of task condition $F(3,12) = 6.11$, $p = .0091$. Tukey post hoc test (modified) did not show a significant difference between the SAS conditions and the No SAS condition. Only a small number of recorded movement onsets among the SAS trials were indicative of a startle response.

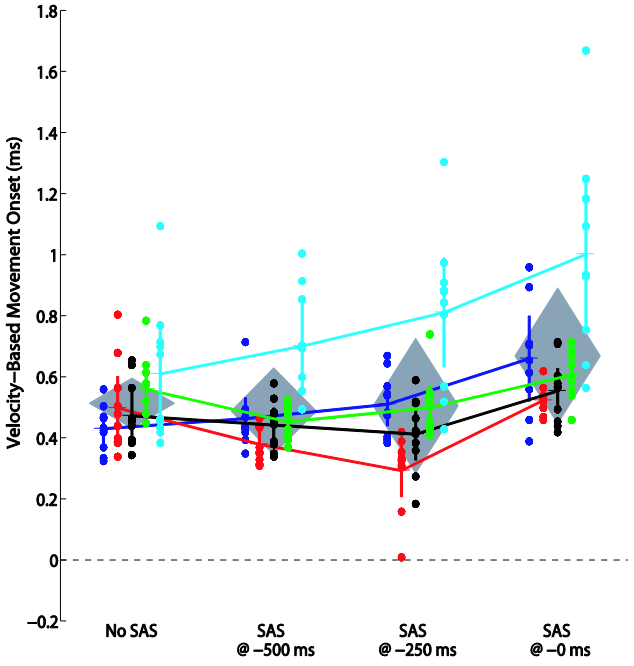

Figure 4: Velocity-based movement onset times relative to GO for No SAS catch trials (i.e. voluntary movements) and SAS catch trials. Line types and conventions are same as previous figure. Startle did not cause the early release of movement and some response times were delayed.

D. DISCUSSION (EXPERIMENT ONE)

We found that, for all subjects, the after-effect magnitudes were reduced, but not entirely eliminated when movements were accompanied with a startle stimulus. Only the movement errors for the SAS @ -0ms timing condition were significantly different than No SAS condition. However, the time at which subjects initiated the movements appeared unaffected by SAS, indicating that SAS did not release their movements in accordance with a characteristic build-up of a motor program. The differences may be explained by a number of different experimental factors, including, stimulus intensity, frequency of administering the startle stimuli and task instruction [3].

The intensity of the stimulus was lower in this study compared to most startle studies (104 dB vs. 118+) and although it has been shown that this intensity can elicit a startle response and consequently an early release of movement, the probability mitigates at lower levels [39]. It is likely that this intensity was insufficient to produce a startle response or that subjects habituated to the stimulus due to the number of times exposed to the stimulus. The slower movement onsets calculated, even for voluntary responses, can be attributed to the lack of readiness of subjects to perform the task and the differences in movement onset measurement techniques (velocity onset vs. EMG onset). Subjects were not instructed to move as fast as possible in response to the GO, which may have inhibited their response to startle.

It is evident that startle responses were absent in this experiment, requiring us to redefine the acoustic stimulus as merely a loud noise or startle-like stimulus that possibly posed as a

distraction, but did not release movement early. The fact that movement onsets SAS @ -0ms timing condition were comparatively slower than voluntary movements supports this idea. It is evident that the size of after-effects were reduced when accompanied with this startle-like stimulus, but it is unclear whether startle-like stimulus was the cause of such disruption in the internal model that was learned through adaptive training. Because the movement responses to the startle-like stimulus were unchanged and because the stimulus was only administered during catch trials, it is possible that subjects changed their motor program after the stimulus that allowed them to compensate for the removal of the forces. The way startle manifested itself was not consistent, however, this initial study provided preliminary encouraging evidence, and thus the startle methods were revised in a subsequent study.

III. EXPERIMENT TWO

A. INTRODUCTION (EXPERIMENT TWO)

Since the intensity of the startle stimulus used in experiment one was deemed insufficient to elicit a startle response consistent with other studies, experiment two attempted to examine the consequences of startle on a recently learned internal model with a more intense stimulus. The 120+ dB acoustic startle stimulus, compared to the 104 dB stimulus used in the previous experiment, theoretically has a higher probability of eliciting typical startle responses. In addition, EMG recordings were implemented to detect a startle response based on the presence of neck muscle activity and to measure movement onset, which is also more consistent with the methods used in startle studies of this type.

Subjects were again required to train making reaching movements to targets within a dynamically changed environment (i.e. "curl" force-field). After learning to move within the presence of this disturbance, the more intense startle stimulus was presented during catch trials (i.e. removal of forces) prior to or coincident with an imperative GO. We compared after-effect magnitudes of movements released by SAS, which produced typical startle responses, to those release voluntarily.

Results show that the increased stimulus intensity led to short latency movement response times compared to voluntary response times and were marked by the presence of neck muscle activity, indicating that subjects were startled. Similar to experiment one, the after-effects of

adaptation associated with SAS reduced (SAS @ -0ms and -250ms timing conditions were significantly different than No SAS condition) and the magnitude of reduced after-effects did not demonstrate any further modulation by the timing of SAS. However, it was evident that some subjects increased cocontraction in response to the startle stimulus, which may pose as a confounding factor in a force-field adaptation experiment as stiffening the arm may be the cause of reduced movement error, rather than startle.

B. METHODS (EXPERIMENT TWO)

1) Apparatus

a) Startle Acoustic Stimulus

The acoustic startle stimulus was revised in an attempt to increase the yield of the number of startle responses elicited during the course of the experiment. Instead of headphones, the generated tone (1400 Hz, 40ms) was amplified and presented via a marine horn (MG M-58H Horn Speaker) at a distance of 30 cm posterior the head of the subject. The intensity of the sound was measured at 124dB closely resembling the level used in most startle experiments [3].

b) EMG Recordings

To further follow startle experimental protocol, surface EMG recordings were implemented to gain a more realistic measurement of movement onset time and to assess startle responses based on the presence of neck muscle activity. Surface EMG recordings were collected

from the following superficial muscles: anterior deltoid, posterior deltoid, long head triceps brachii, long head biceps brachii, and sternocleistomastoid (SCM) using a Bagnoli EMG System. Data was digitally sampled at 1 kHz (National Instruments USP-6229) and continuously collected using a customized program in Labview. Post-processing of raw EMG data included removal of bias, full-wave rectification and low-pass filtering (cutoff 25 Hz) using a 5^{th} order two-way Butterworth filter [32]. Data for the triceps and biceps was further normalized for cocontraction measurements using calculated max voluntary contraction (MVC) values. Prior to performing the task, subjects were asked to hold isometric maximum voluntary contractions of the biceps and triceps (three times for each muscle) for 2-3 seconds. The average EMG amplitude within a 250ms time window were averaged across the three tries to determine the MVC values. For some trials, particularly those involving SAS, greater muscle activation than calculated MVC values were observed. The maximum amplitude was then substituted as the normalization factor.

2) Protocol

Five new healthy adult subjects, naïve to the paradigm, participated in this experiment that used a similar test protocol. SAS was administered at the same time points relative to GO (i.e. -500ms, -250ms and -0ms) in catch trials which appeared randomly (i.e. one in every 8 trials) during the evaluation phase. In the initial exposure phase, subjects were only exposed to the force-field (one in every 8 trials) with no intermittent SAS trials in an attempt to avoid habitation to the startle stimulus. An auditory GO was presented via a piezoelectric buzzer (83dB). Feedback on the peak speed during each movement allowed control of movement speed.

Color coded text (i.e. “Good Speed” in green and “Too Fast” or “Too Slow” in red) was displayed on the screen at the end of each trial. Movement speed within a predetermined range of .7m/s to 1.1 m/s was considered a “Good Speed”. The numerical value of the velocity based movement onset time was also displayed on the screen after each trial. Subjects were encouraged to decrease onsets in a goal directed manner. The time the handle velocity reached a threshold of .1m/s relative to the time of GO determined movement onset.

3) Analysis

a) Movement Error Measurement

The primary measure of movement error was angular deviation from a straight line during the initial portion of the movement. IDE is defined as the angle between the vector that lies along an ideal straight line movement directed towards the target and the vector formed from the point when the handle reaches a threshold velocity (.1 m/s) to the point 150ms into the movement.

b) EMG Movement Onset Measurement

Surface EMG recordings were used to assess the movement onset based on initial agonist muscle activation. The point at which muscle activity started a sustained rise above baseline levels (two standard deviations above the average resting activity) for 25ms defined EMG onset. EMG onsets were measured relative to stimulus onset (i.e. startle stimulus for SAS trials and GO

for No SAS trials). The muscles used for marking movement onset were determined in accordance to the direction of movement and the initial muscle activity. The anterior deltoid and posterior deltoid posed as initial agonist muscles for outward and inward movements, respectively. Due to the strictness of this algorithm, it was sometimes necessary to manually adjust the position of this marker.

d) Startle Response Measurements

A startle response is marked by a short latency in the onset of movement and the onset of SCM [32]. Inherently, during reaching movements, neck muscle activity sometimes acts to stabilize the head in order to counteract the interaction torques transferred from distal joints. Thus, it is sometimes difficult to distinguish startle related SCM activity from other SCM activity. SCM onset and amplitude for startle trials was individually examined and compared to respective control trials. In general, a response in a given SAS trial was considered to be related to startle if SCM onset was within the time window of 30-120ms [3].

c) Cocontraction Measurement

EMG profiles in this experiment exhibited noticeable differences in amplitude, agonist-antagonist inter-onset time, and agonist duration when startled. A measure of cocontraction between two muscles (i.e. biceps and triceps) was used in an effort to encompass all of these EMG characteristics. There are no generally accepted measures of cocontraction, but the main feature that such measure should hold for the purpose of this study, is one that temporally links

to the chosen error measurement. This ensures association with the initial part of movement, rather than with any co-activation that might occur during the error correction phase of the movement. Overlap Cocontraction Index (CCI) is defined as the overlapping area between two overlaying EMG envelopes divided by the period of interest.

$$\frac{1}{T}\int_{0}^{T} A_{ij}(t)dt \qquad (3)$$

where T is the period between agonist onset to 200ms after, encompassing any electromechanical delay between muscle activation to force output (~30-70ms) and a portion of the actual movement [44].

e) Statistics

One-Way Repeated Measures ANOVA with Tukey post hoc test (modified) was used to determine statistical differences in after-effects between the three SAS conditions and the No SAS condition [43]. For the CCI measurement and movement onset measurement, the data was separated by movement direction and all SAS timing conditions were combined since these measurements are not expected to reflect any significant differences between the three SAS timing conditions. A pairwise t-test was used for both measurements to compare combined SAS catch trials to No SAS catch trials. Only SAS trials in which a startle response was detected were included in the analysis. Differences with a p-value less than .05 are considered to be significant.

C. RESULTS (EXPERIMENT TWO)

Increasing the startle stimulus intensity led to a higher yield in the number of startle responses elicited. Based on the presence of neck muscle activity, a startle response was observed in 115 of the 150 trials (77%) in which SAS was administered. Fig. 5 shows subject data indicating the SAS trials during the evaluation phase in which a startle response was detected. A high incidence (>90%) of startle responses was seen in 3 subjects, whereas 2 subjects seemed to be less affected by SAS (<55%). These subjects appeared to habituate to the startle stimulus [32].

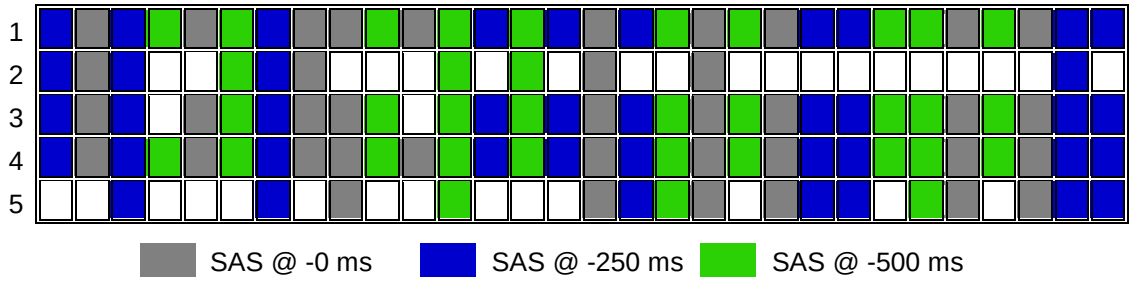

Figure 5: Individual participant data indicating SAS trials in which a startle response was detected based on presence of SCM. Each box represents a SAS trial (color indicates SAS timing condition). Shaded box indicates startle response. Blank box indicates no startle response.

Group means in EMG movement onset times revealed that startle lead to an early release of movement (Fig. 6). For outward movements, a paired t-test showed that the mean movement onsets for combined SAS catch trials (i.e. all three timing conditions combined) were released significantly earlier than No SAS voluntary movements (i.e. catch trials); $t_{.05}(4) = 3.12$, $p = 0.035$. For inward movements, the mean movement onsets for the combined SAS catch trials were not significantly different than those of the No SAS catch trial condition; $t_{.05} = 1.25$, $p = 0.28$. There is a visible learning curve associated with EMG onsets as the number of experimental trials increased indicating that subjects became very skilled at quickly initiating movement relative to GO. For movements in both directions, EMG onsets noticeably decreased from the baseline phase to No SAS catch trials. This learning may have attributed to the lack of noticeable influence of startle on movement onset.

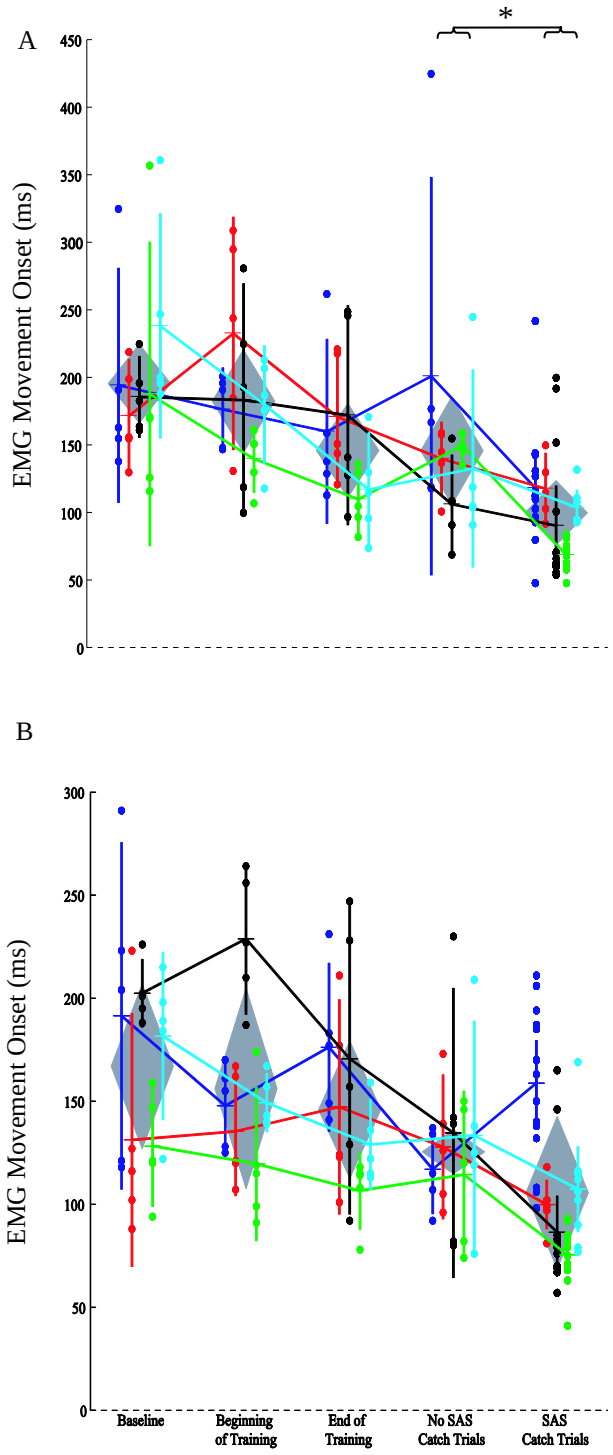

Figure 6: Group means of EMG movement onset times during different phases of the experiment. Only SAS trials that exhibited a startle response are shown. (A) Onsets for outward directed movements measured from anterior deltoid. SAS catch trials were significantly different than No SAS catch trials (indicated brackets with connecting lines and an asterisk) (B) Onsets for inward directed movements measured from posterior deltoid. Despite learning to move relative to GO, startle led to an early release of movement.

After-effects for No SAS catch trials were compared to those of each of the three SAS timing conditions (Fig. 7). The mean of movement errors for the No SAS condition was calculated to be 8.65° (± 0.46°). The means of movement errors for when SAS was administered at -500ms, -250ms and -0ms were calculated to be 5.41° (± 0.89°), 4.81° (±1.36°), 5.69° (± 0.73°), respectively. One-way RMANOVA showed a main effect of task condition $F(3,12) = 4.28$, $p = 0.029$. Tukey post-hoc test (modified) showed that the means of movement error when SAS was administered at -0ms and -250ms was significantly different than the No SAS condition ($p<.05$).

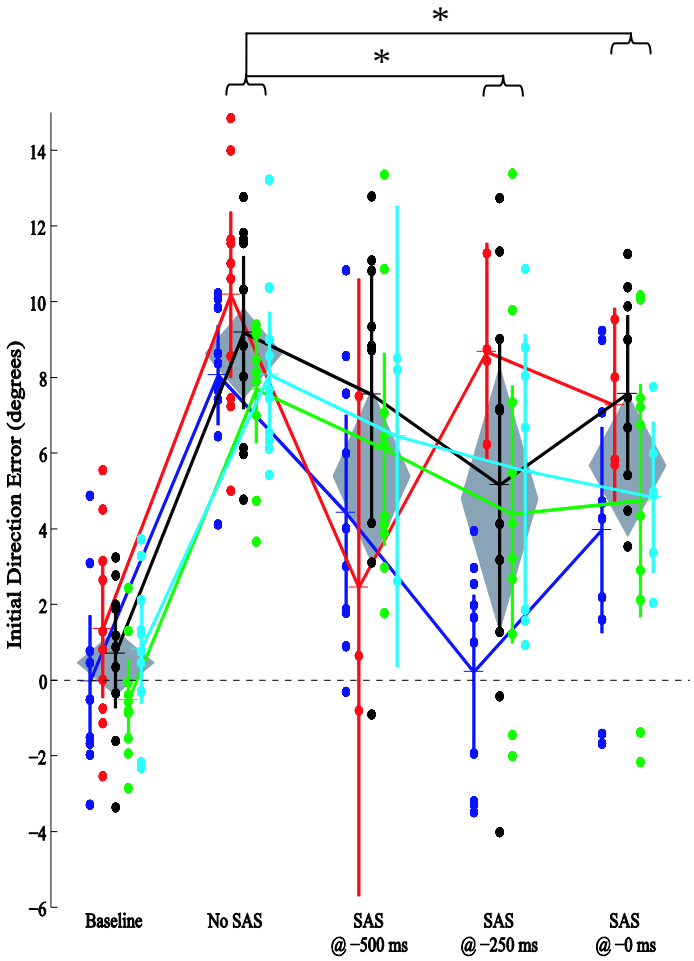

Figure 7: Movement errors for No SAS condition compared to three SAS timing conditions. Only SAS trials in which a startle response was detected are shown. After-effects were reduced when startled. SAS @ -0ms and -250ms timing conditions were found to be significantly different than the No SAS condition (shown by black lines connecting brackets and an asterisk at the top).

We compared the level of cocontraction, using a CCI that measures the overlapping area of two EMG profiles (biceps and triceps), between SAS catch trials and No SAS catch trials to determine if startle induced changes in the dynamics of the arm (Fig. 8). Although a few subjects showed an increase in cocontraction when startled, a paired t-test did not reveal a significant difference in either direction of movement; Outward direction $t(4) = 2.18$, $p = 0.094$; Inward Direction $t(4) = 2.12$, $p = 0.10$.

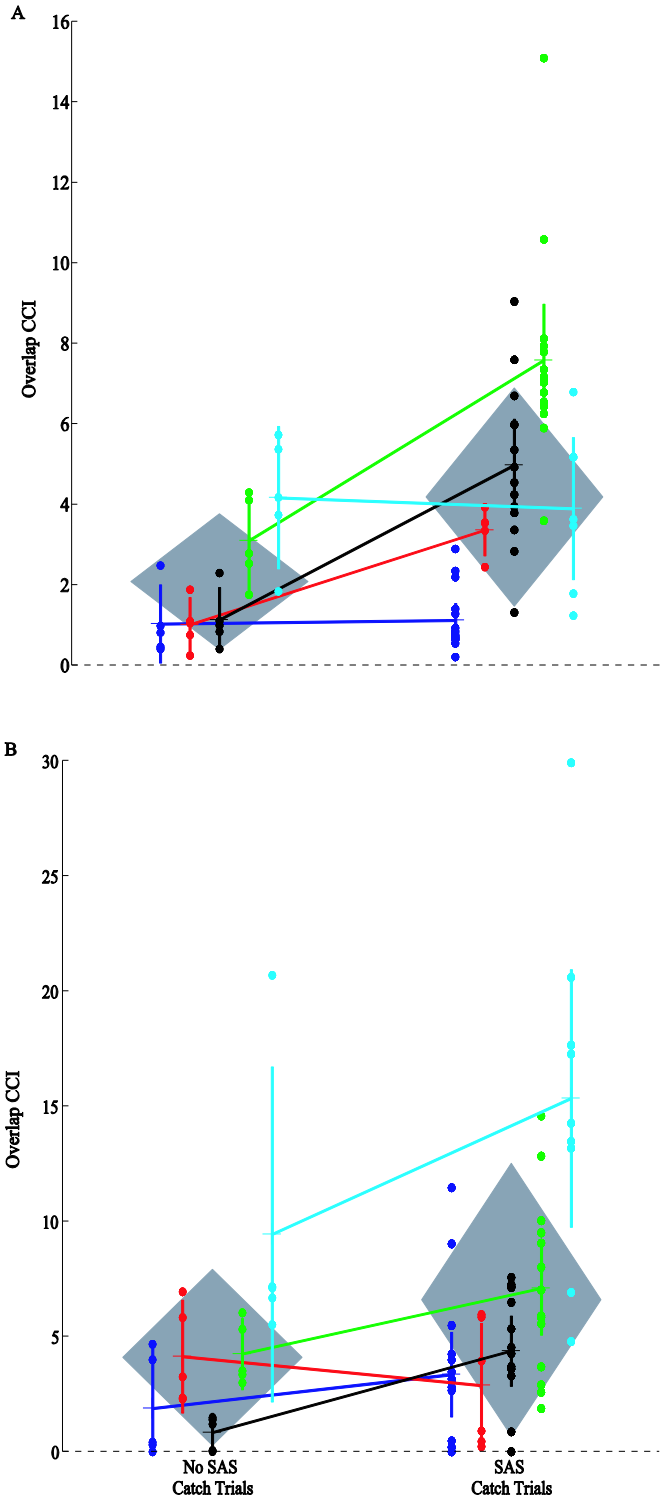

Figure 8: Overlap cocontraction indexes for (A) outward directed movements and (B) inward directed movements comparing No SAS catch trials and combined SAS catch trials. Cocontraction appeared to increase in some subjects when startled, but group means were not significantly different.

D. DISCUSSION (EXPERIMENT TWO)

By increasing the intensity of the startle stimulus and employing a system for which startle responses were detected through EMG, experiment two corrected the startle methods of experiment one. The acoustic startle stimulus proved to be effective in eliciting the early release of movement and causing a startle response marked by SCM activity. When movements were released by startle the magnitude of after-effects were reduced (SAS @ -0ms and -250ms timing conditions were found to be significantly different than the No SAS condition), but were not further modulated by the timing of SAS as expected. These results suggest that startle may disrupt the internal model formed during adaptive training. However, it appeared some subjects increased cocontraction with the presence of SAS, which may be seen as a confounding factor in this experiment.

One difference from this study and previous SAS investigations is that no differences in the size of after-effects were detected between the different SAS timing conditions. In a stepping preparation study, the magnitude of the stepping motor sequence, evoked by SAS, progressively increased as the timing of stimulation approached GO suggesting that the spatial and temporal characteristics of the movement progressively assemble over time [12]. As such, we expected that the build-up and release of an internal model would behave in a similar manner and therefor there would not be a reduction in the after-effects when startle was administered in synchronization with GO (i.e. 0ms). With no differences in the magnitudes of the after-effects across the three SAS timing conditions, it is possible that the preparation of movements following an adaptation task does not follow the same type of storage or build-up in the

feedforward program. Alternatively, it is possible the motor program was fully prepared well in advance to GO since the resolution of the response timing information was temporally certain [13]. Consequently, startle at different timing conditions would not release the feedforward program at different stages of assembly.

Another difference from this study and previous investigators were the noticeable differences in EMG profiles between startle and non-startle movements. To our knowledge, this is the first startle related study that measures cocontraction as a method to characterize EMG profiles. It has been shown that EMG characteristics, such as agonist-antagonist inter-onset time and agonist duration, are similar when startle is either present or absent, although agonist initial peak amplitude is known to increase when startled [4, 11]. Comparable EMG profiles, along with consistent kinematic profiles, between startle and non-startle movements lends to the belief that movements released by startle reflect the intent of the feedforward motor program rather than the superposition of a primitive startle reflex on top of a voluntary response. It is possible that cocontraction was part of the primitive response naturally triggered by subjects when startled or that stiffening the arm in response to startle was part of the intended feedforward model since a dynamic force-field was expected. Further analysis of the EMG profiles including measurements more consistent with other startle studies may help clarify the influence of SAS on movements.

The fact that there was a reduction in after-effects suggests startle may interfere with the release of the feedforward program. However, based on the observed differences in cocontraction, it is unclear if this degradation was caused by startle disrupting the recall of a

recently learned internal model or by startle augmenting the dynamics of the movement. Since stiffening the arm can facilitate a decrease in movement error when adapting to a dynamic perturbation, it is possible that the source of reduced after-effects was the change in dynamics that occurred when startled. To negate this potential experimental confound, it is possible to implement a kinematic based perturbation that requires a similar type of adaptation through learning an internal model, but independent of any dynamic changes startle may impose. In a subsequent experiment, we applied a visual distortion of the environment that intuitively cannot be confounded by cocontraction.

IV. EXPERIMENT THREE

A. INTRODUCTION (EXPERIMENT THREE)

Experiment three uses a similar adaptation paradigm and the existing SAS and robotic apparatus to test the original hypotheses, but instead of exposing subjects to a force-field, visual feedback of the handle position was distorted through a visual rotation of the cursor. This visual perturbation causes kinematic errors in the movement requiring subjects to modify the movement path to a different end position within the workspace. Thus, any changes to the dynamics of the movement that startle may impose cannot assist in reducing movement error, suggesting that the experiment cannot be confounded by cocontraction.

The results revealed that the after-effects of adaptation to a distorted visual field were reduced significantly when movements were released by startle at all three SAS timing conditions. Furthermore, subjects who exhibited an at least partial existence of a startle related response (i.e. early release of movement without accompanying SCM activity) also showed a reduction in after-effects but to a lesser degree than subjects with complete startle responses. Reduced after-effects suggest that startle disrupts the recall of a recently learned task.

B. METHODS (EXPERIMENT THREE)

1) Protocol

Eleven healthy adult subjects participated in this experiment that used a similar paradigm and task, but a visually distorted field replaced the force-field as the adaptation modality. Subjects performed a series of reaching movements all in the outward direction to a blue (radius = 18mm) target located 15cm from a fixed start position, indicated by an "x" on the screen. Each trial consisted of the appearance of a blue target followed by a low-level acoustic stimulus (83dB) after a fixed time period of 2.5 seconds to indicate the imperative GO. Subjects were instructed to release their movement in response to GO as early as possible and to execute the movement to the target as accurate as possible. Moving the cursor within the target resulted in a change in its color, denoting the end of the movement. Subjects were then instructed to move the handle back to the start position, at which time the target changed back to the original color, indicating the start of a new trial.

The visual distortion (VD) was arranged by rotating the visual field clockwise at an angle of 45 degrees about the start position (Three subjects received a counterclockwise rotation). In this field, for any movement away from the start position, the position of the cursor deviated at a 45 degree angle in the clockwise direction. Subjects consistently trained in the presence of the visually rotated field for 100 movements with the goal of making the cursor revert back to straight line movements. After training, subjects continued to move in the presence of the visually rotated field, but at several randomly selected intermittent trials (one in every 8

movements) subjects experienced either the unexpected removal of visual distortion or the unexpected removal of visual distortion with an SAS (occurring at -500, -250 or -0 ms prior to GO). Subjects were unaware that they would revert back to the null field until after the movement was initiated.

The numerical value of velocity based movement onset was displayed on the screen at the end of each movement to encourage subjects to decrease their response time to GO. Movement onset was defined as the time the handle velocity reached a threshold of .1m/s relative to the onset of GO.

Change in target color was used to provide feedback on movement time, defined as the amount of time that elapsed between movement onset and when the target was reached. The target turned green if the movement time was within the predetermined range of 450-700ms, consistent with typical movement times seen for 15cm movements [5]. In addition, the word "Speed", displayed in the top left-hand corner of the workspace, turned green if the peak speed of the movement was within the range of .7-1.1 m/s. Controlling movement time and speed is imperative in avoiding subjects that possibly engage in a technique to reduce speed in order to increase accuracy [21]. Failure to execute the movement within the respective ranges of either of these kinematic features resulted in a change in color of the visual feedback to red.

2) Analysis

Angular deviation from an ideal straight line movement to the target is the primary measure of movement error, since the after-effects of adaptation, seen when the CW visual rotation is unexpectedly removed, are a CCW bend of the movement path. Initial direction error is defined as the angle between the ideal straight line movement to the target and the vector formed from the point of velocity-based movement onset to 150ms along the path of the trajectory.

An early burst in neck muscle activity with a subsequent short latency release time was used to detect a startle response. To distinguish from other SCM activity, SCM onset within the time window of 30-100ms was used to determine if SCM activity was related to startle [3]. EMG-based movement onsets relative to the stimulus onset were considered to be early if they were outside the 95% confidence interval of the mean movement onsets of voluntary movements (last 25 trials in training phase). All SAS catch trials that exhibited startle related SCM activity with an accompanying early release of movement (ERM) were separated for analysis (SCM+/ERM+ group). Further analysis was performed on SAS trials where SCM activity was not detected, but did lead to an ERM (SCM-/ERM+ group). All trials that did not exhibit either an SCM response or an ERM were removed from the data set.

C. RESULTS (EXPERIMENT THREE)

We first examined the influence of startle on each subject (Fig. 9). It was quite evident that some subjects were more vulnerable to SAS as one group of subjects (n = 4) showed a startle response complete with an ERM and early burst in SCM activity based on the criteria described above (52 out of 60 trials). Another group of subjects (n = 5) displayed an early release of movement (43 out of 75 trials), but without accompanying SCM activity. It is possible that these subjects were less affected by startle, but had at least partial existence of a startle related response that lead to an accelerated release of movement. The SCM-/ERM+ group data was separated from the SCM+/ERM+ group for analysis.

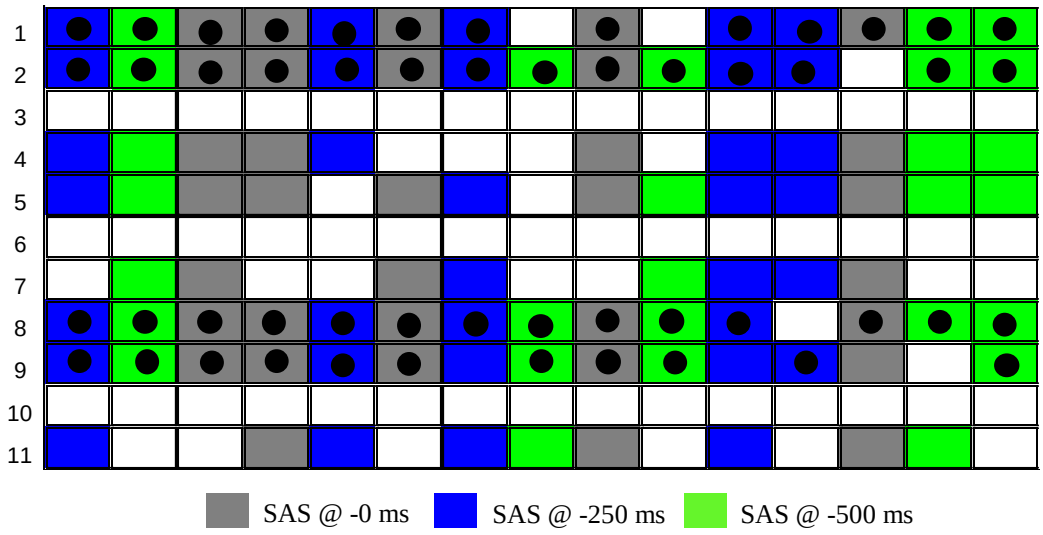

Figure 9: Individual participant data indicating SAS trials in which a startle response was detected. Each box represents a SAS trial. Shaded box indicates early release of movement (color indicates SAS timing condition). White box indicates absence of startle response. Black dots denote SCM response.

EMG-based movement onset times during SAS catch trials for the SCM+/ERM+ group and the SCM-/ERM+ group were separately compared to their respective No SAS voluntary movements (last 25 trials from the end of training). Differences across conditions are shown in Fig. 10 using a wings plot. For the SCM+/ERM+ group, the mean and standard error for voluntary movements and SAS catch trials were 143.57ms (±13.33ms) and 84.08ms (±9.59ms), respectively. A paired t-test revealed that when a complete startle response was detected, movement was released significantly earlier (~59ms) than voluntary responses; $t_{.05}(3) = 7.64$ $p = .0047$. For the SCM-/ERM+, the mean and standard error for voluntary movements and SAS catch trials were 131.77ms (±10.17ms) and 82.49ms (±6.28ms), respectively. A paired t-test revealed that movement onsets were released significantly earlier (~49ms) than voluntary responses; $t_{.05}(4) = 4.46$ $p = .011$.

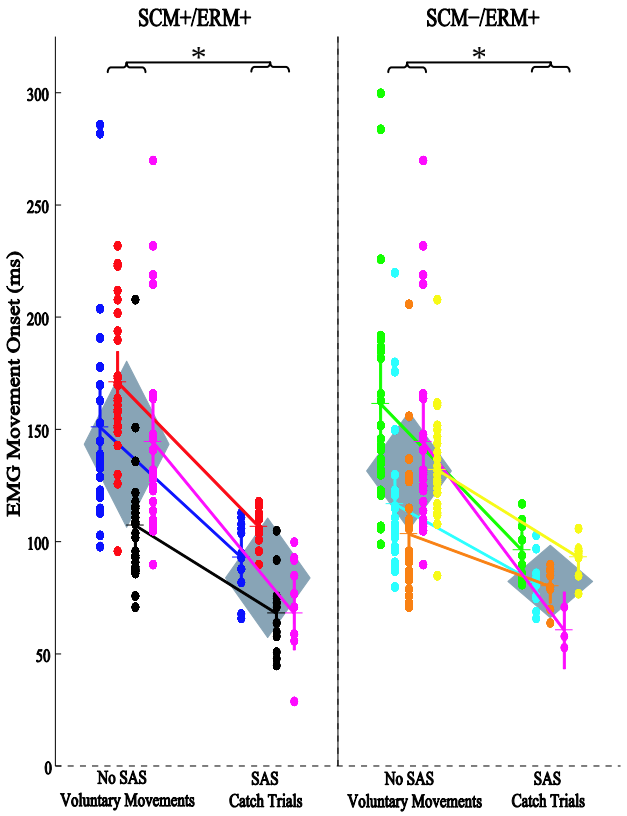

Figure 10: EMG-based movement onset times relative to stimulus onset of SAS catch trials for both startle response groups compared to voluntary movements. Line types and conventions are same. Statistical comparison of groups using a paired t-test revealed significant differences between voluntary movement onsets and SAS movement onsets of both startle response groups (shown by black lines connecting brackets and an asterisk at the top).

The patterns of movement trajectories for an adaptation study involving either visual rotation or force-field are similar. Baseline movements are nearly straight lines (Fig. 11A), initial exposure to a visually rotated field (in the clockwise direction) resulted in a deviation of the cursor in the CW direction (Fig. 11B), trajectories again approximated straight lines by the end of training (Fig. 11C), and trajectories were distorted in the CCW direction in the catch trials where the visually distorted field was unexpectedly removed, revealing after-effects of adaptation (Fig. 11D). Similar patterns were noticeable when subjects were startled.

We compared the magnitude of the after-effects between No SAS and SAS catch trials. Fig. 11D gives a visual of one subject's trajectories of the after-effects for when no startle stimulus was present (black) and when SAS was administered at the three different time points (SAS @ -500, -250, -0ms) relative to GO (green, blue, red, respectively) causing an early release of movement and SCM response. The dots represent the position along the path at the end point of the vector used to measure initial direction error (150ms into the movement). Angles between an ideal baseline trajectory and the after-effect trajectories appear smaller in the SAS conditions.

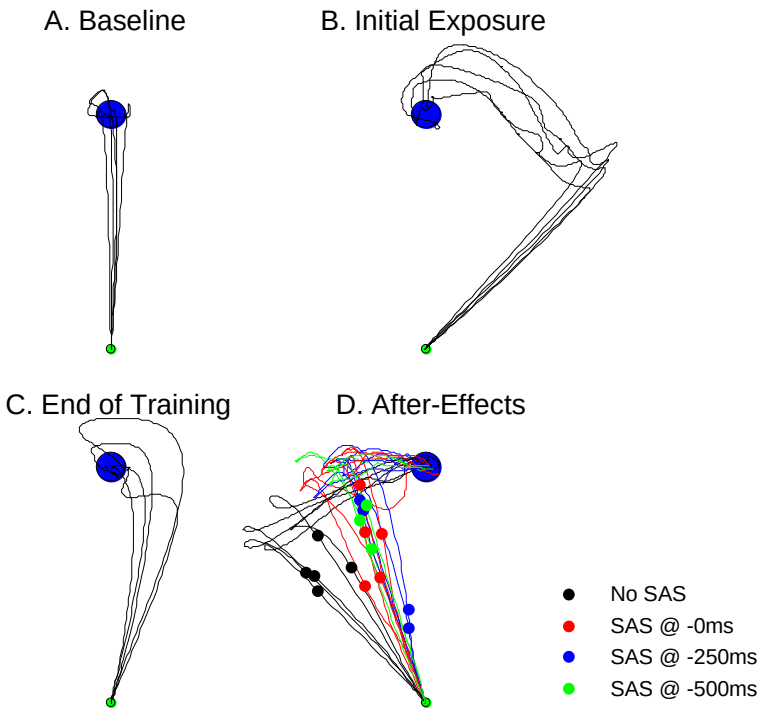

Figure 11: Typical trajectories during the different phases of the experiment. (A) Trajectories are initially straight during baseline movements. (B) Preliminary movement errors appear when VD is present. (C) After training, subjects begin to learn and revert back to straight line movements. (D) In the presence or absence of SAS, trajectories become mirror images of those seen in (B) after VD is removed. All trajectories shown are that of the cursor. Each color represents the No SAS condition or one of the 3 SAS timing conditions. The dots in (D) represent the position along the trajectory where movement error is measured (i.e. 150ms into the movement).

Subjects 9, 10 and 11 received a counterclockwise visual rotation to confirm that startle does not induce a change in the dynamics of the movement that is bias towards a particular direction. The CCW and CW rotations are expected to reveal after-effects in opposite directions when removed from the visual field and since all subjects performed the task with their right hand we would be able to determine if startle has the same effects on the size after-effects in both

directions. We did not observe significant differences between the two directions of visual rotation so the data was combined for analysis.

The group results of the SCM+/ERM+ group point to similar trends (Fig 12). The mean and standard error of movement errors for the No SAS catch trials was calculated to be 32.78° (±2.58°). The means and standard errors of movement errors for when SAS was administered at -500ms, -250ms and -0ms was calculated to be 13.75° (±3.76), 17.45° (±3.35°) and 18.03° (±3.60°), respectively. Differences across condition are shown in Fig. 12 using a wings plot. One-way Repeated Measures ANOVA revealed a main effect of task condition $F_{.05}(3,9) = 25.11$, $p = .0001$. Post hoc analysis using Tukey post hoc test (modified) showed that movement errors for the three SAS timing conditions were significantly different than the No SAS condition ($p < .05$), but did not differ significantly between SAS timing conditions. Similar to previous results (Experiment One and Experiment Two), the timing of SAS did not have any further effect on the magnitude of reduced after-effects.

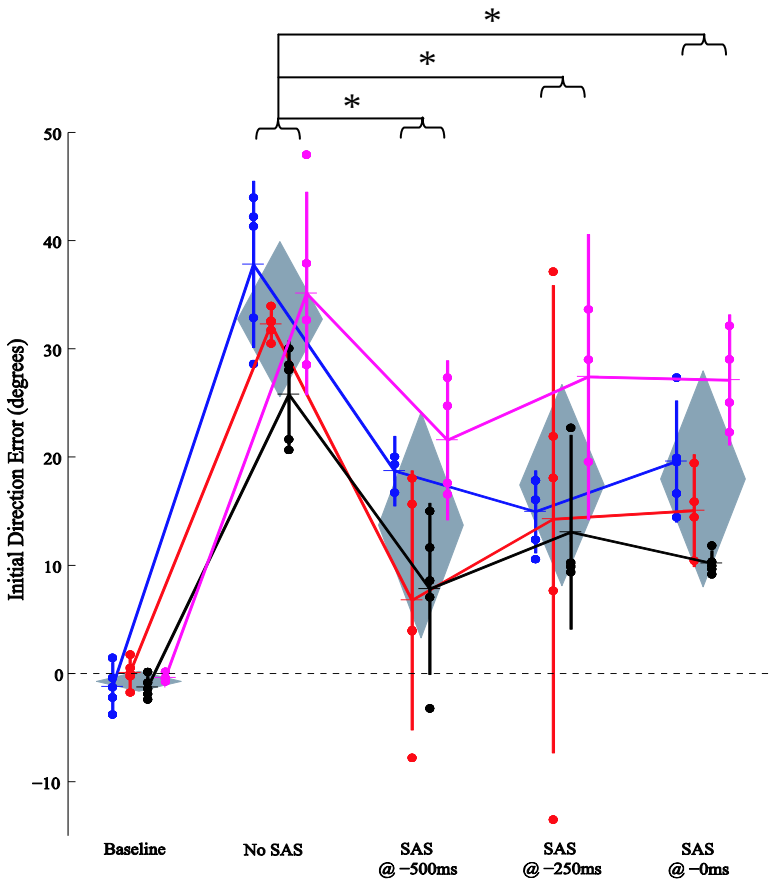

Figure 12: Movement errors for the SCM+/ERM+ group during catch trials for the cases of No SAS and SAS at several delays compared to baseline error (horizontal axis). The last subject (pink) received CCW rotation. Statistical comparison of groups using Tukey post-hoc tests revealed significant differences between No SAS and each of the three SAS conditions (shown by black lines connecting brackets and an asterisk at the top). Hence, SAS significantly reduced but did not eliminate after-effects.

We also compared the SAS catch trial movement errors of the SCM-/ERM+ group to No SAS catch trial movement errors. We found that, in the presence of SAS, after-effects were significantly reduced compared to No SAS catch trials. However, the reduction in after-effects was less drastic than the SCM+/ERM+ group. Differences across groups are shown in Fig. 13 using a wings plot. Since the three startle delays have not shown significant differences among each other, they were combined for analysis. Furthermore, each subject's movement errors were

normalized to the average movement error of their respective No SAS catch trials. For the SCM+/ERM+ group, the mean and standard error for the combined No SAS catch trials and combined SAS catch trials were 32.78° (±2.58°) and 16.22° (±3.40°). A paired t-test indicated that the magnitude of after-effects were significantly reduced with the presence of SAS; $t_{.05}(3) = 6.71$ $p = .0068$; For the SCM-/ERM+ group, the means and standard errors for No SAS catch trials and combined SAS catch trials were 34.79° (±3.83°) and 27.20° (±4.40°). Similarly, a paired t-test indicated that the magnitude of after-effects were significantly reduced with the presence of SAS, but to a lesser degree than the after-effects; $t_{.05}(4) = 3.61$ $p = .0225$). These results suggests that SAS causes a degradation of the movement trajectories consistent with after-effects, but the degree of such reduction may depend on the type of startle response.

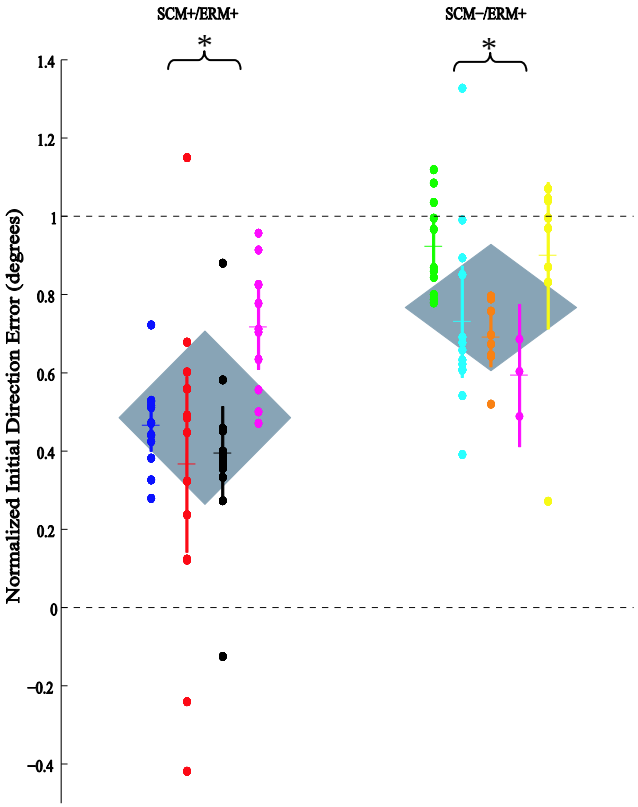

Figure 13: Movement errors for combined SAS catch trials normalized to the mean of No SAS catch trials for both startle response groups (horizontal axis). Group SAS means are considered significantly different than No SAS means if the upper bound of the group 95% confidence interval is less than 1(i.e. paired t-test). (Brackets with an asterisk indicate significance) The pink and yellow data represent subjects that received CCW rotation. Hence, SAS significantly reduced after-effects in both startle response groups.

D. Discussion (Experiment Three)

Experiment three relieved the concern that cocontraction posed in experiment two. In this experiment, subjects participated in a similar learning paradigm, but instead of using a force-field as the adaptation modality, subjects learned to make reaching movements within a visually distorted field. In contrast to adaptation to force-fields, movements when startled during the removal of a visual perturbation cannot be confounded by cocontraction, even if the act of

stiffening the arm is a natural part of the startle response or a conscious effort to stiffen the arm in order to overcome the forces exerted during the movement. Although, evidence of the convergence of hand trajectory kinematics similar to movement trajectories in the null field suggest that subjects do not follow this technique [6]. Since the end point of a movement (i.e. the location in space where the hand needs to end in order for the cursor to reach the target) within a force-field is in the same location as the target, the path of the movement converges with learning to an ideal straight line. Cocontracting muscles would occur about the intended path and consequently aide in reducing after-effects. Whereas, in the case of a visually rotated field, subjects have to learn a new end point (located 45 degrees counterclockwise from the target) in order for the cursor to reach the target and consequently move the hand along a different path other than the ideal straight line. Cocontraction during the removal of the visual field would occur about the new path instead of the required path. Thus, cocontraction intuitively cannot diminish after-effects unless startle adds torque towards a particular direction and not down the intended path direction. The fact that the use of CCW and CW visual rotations yielded similar results suggests that the possible natural response of cocontraction that appears when startle cannot be seen as confound when a visual rotation is the adaptation modality.

We found that, in all subjects that exhibited a startle response, the startle stimulus reduced after-effects, although, similar to previous experiments, the timing of SAS had no correlation with the magnitude of reduced after-effects. These results again suggest that startle disrupts the recall of a recently learned internal model, but is independent of the timing of SAS related to the build-up of a feedforward program. Although startle appears to have an influence on the magnitude of after-effects associated with catch trials (i.e. removal of VD), the paradigm

up to this point has neglected to allow us to examine the effects of startle on movements performed within the visually distorted field. In a follow-up experiment, we tested this idea on a separate set of subjects by including SAS not only in catch trials, but also in trials where the visually distorted field remained present (i.e. performance trials).

V. EXPERIMENT FOUR

A. INTRODUCTION (EXPERIMENT FOUR)

As after-effects do reveal the existence of an internal model, one's performance within a perturbed environment also shows learning marked by the gradual decrease in movement error from initial exposure to the end of training (i.e. learning curve). For further confirmation on the idea that startle disrupts learning, in experiment four, we introduce a new paradigm that includes SAS during catch trials (i.e. removal of VD) and performance trials (i.e. presence of VD) at the end of training to test whether startle interferes with the performance of a learned task in the same fashion as after-effects. We hypothesize that SAS will also degrade performance of a newly learned internal model, thus causing an increase in movement error. The results of this experiment were presented at ICORR 2011 [45].

B. METHODS (EXPERIMENT FOUR)

1) Protocol

On a separate set of subjects (n = 9), we test a similar paradigm as experiment three that includes, in the evaluation phase, intermittent randomly placed trials in which movements in the presence of the visually distorted field are accompanied by SAS (@ -250ms, 0ms). In this paradigm, we are interested in catch trials (i.e. the removal of VD or the removal of VD with SAS @ -250ms, 0ms) and performance trials (i.e. presence of VD or presence of VD with SAS @ -250,-0ms). The SAS @ -500ms was excluded since the timing of SAS has not shown to be a

determinant on the size of reduced after-effects and in order to avoid habituation by minimizing the number of SAS trials.

One important step that we did not include in the paradigm of experiment two was startle trials while subjects attempted baseline reaching movement. This is an important piece of information that would allow us to gauge whether startle induces a change in movement path during straight line movements prior to training. Thus, some subjects were exposed to the startle stimulus (3 to 5 trials) during the initial exposure phase prior to training. The number of trials was kept low to avoid habituation in later phases of the experiment.

C. RESULTS (EXPERIMENT FOUR)

We first examined the influence of the startle stimulus on each subject (Fig. 14). This group of subjects appeared to be more vulnerable to the startle stimulus than previous experiments, which included 7 of the 9 subjects that exhibited a startle response, complete with an early release of movement and SCM response (104 out of 140 trials). Since there was a low number of trials that did not meet this criteria, the trials that did not exhibit a startle response were removed from the data set. This included the two subjects that seemed to be unaffected by startle. Furthermore, the two SAS timing conditions were combined for both SAS catch trials and SAS performance trials since previous experiments did not show differences in the magnitude of reduced after-effects with respect to the timing of SAS.

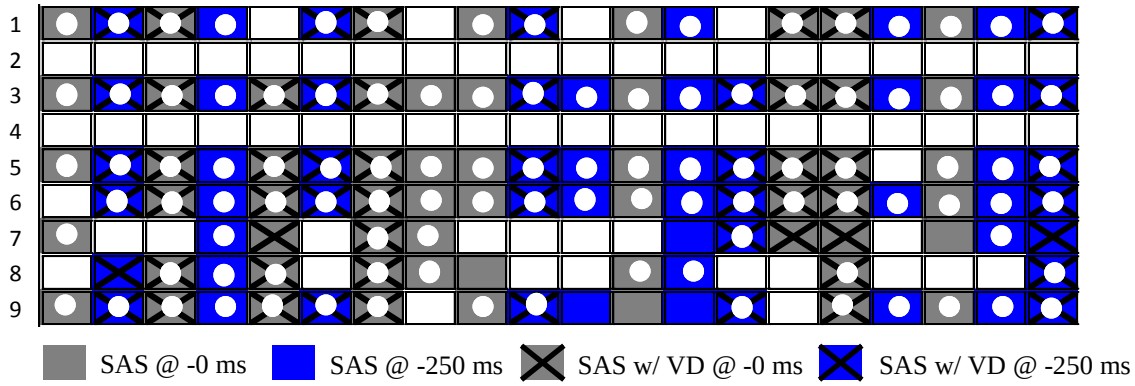

Figure 14: Individual participant data indicating SAS trials in which a startle response was detected. Each box represents a SAS trial. Shaded box indicates ERM for SAS catch trials. Shaded box with black "x" indicates ERM for SAS performance trials. Color indicates SAS timing condition. White dot denotes SCM response. White box indicates no startle response. Only shaded boxes with a white dot were included in analysis.

EMG-based movement onset times for the combined SAS catch trials and SAS performance trials were compared to No SAS voluntary movements - last 25 movements of training phase (Fig. 15). The mean and standard error for voluntary movement onsets and combined SAS movement onsets were 140.91ms (±11.19ms) and 87.874ms (±7.42ms), respectively. A paired t-test revealed that when a startle response was detected, movement was released significantly earlier (~53ms) than voluntary responses; $t_{.05}(6) = 8.69$ $p = .00013$.

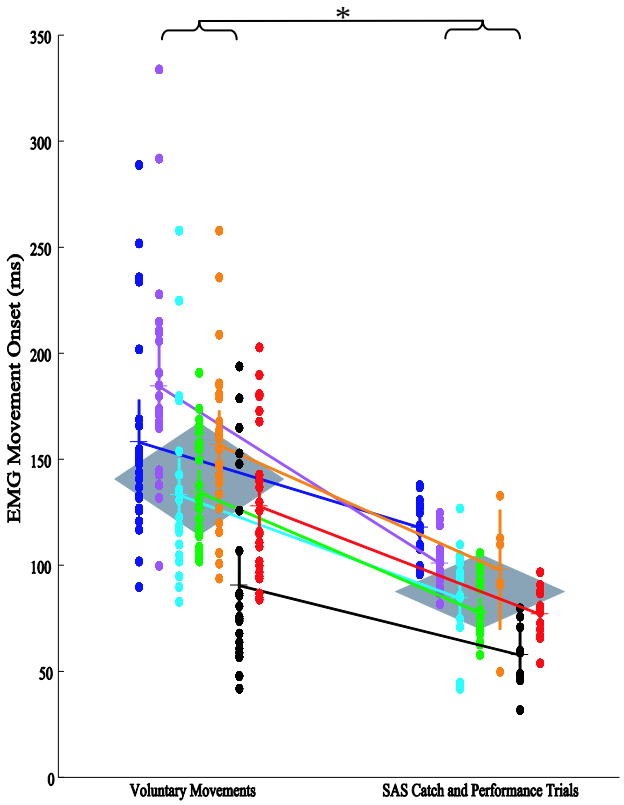

Figure 15: EMG-based movement onset times relative to stimulus onset for combined SAS catch trials and performance trials compared to voluntary movements. Only SAS trials with an ERM and SCM response are shown. Line types and conventions are same. Statistical comparison of groups using a paired t-test revealed significant differences between voluntary movements and movements released by SAS (shown by black lines connecting brackets with an asterisk at the top).

Using the same movement error measurement (initial direction error) as previous experiments, we compared the movement errors of SAS catch trials and SAS performance trials to No SAS catch trials and No SAS performance trials (last 5 trials at the end of training), respectively, using a paired t-test (α =.05). We found that SAS, not only reduces after-effects associated with the removal of VD, but also reduces performance while moving within a visually distorted field after training, causing an increase in movement error. Fig. 16 shows a wings plot

revealing a reduction of movement error in SAS catch trials and a reduction in performance with the presence of SAS. The movement error for SAS catch trials and SAS performance trials were normalized to the average movement error for no startle catch trials and the last five trials at the end of training, respectively. The means and standard errors in movement error for No SAS catch trials and SAS catch trials were 30.89° (± 2.69°) and 24.97° (± 3.42°), respectively. A paired t-test indicated that the magnitude of after-effects of the SAS catch trials were significantly reduced; $t_{.05}(6) = 4.04$ $p = .0068$. The means and standard errors in movement error for No SAS performance trials and SAS performance trials were 32.08° (± 3.40°) and 25.58° (± 3.58°), respectively. A paired t-test indicated that the magnitude of movement errors for SAS performance trials were significantly reduced; $t_{.05}(6) = 2.97$ $p = .0249$.

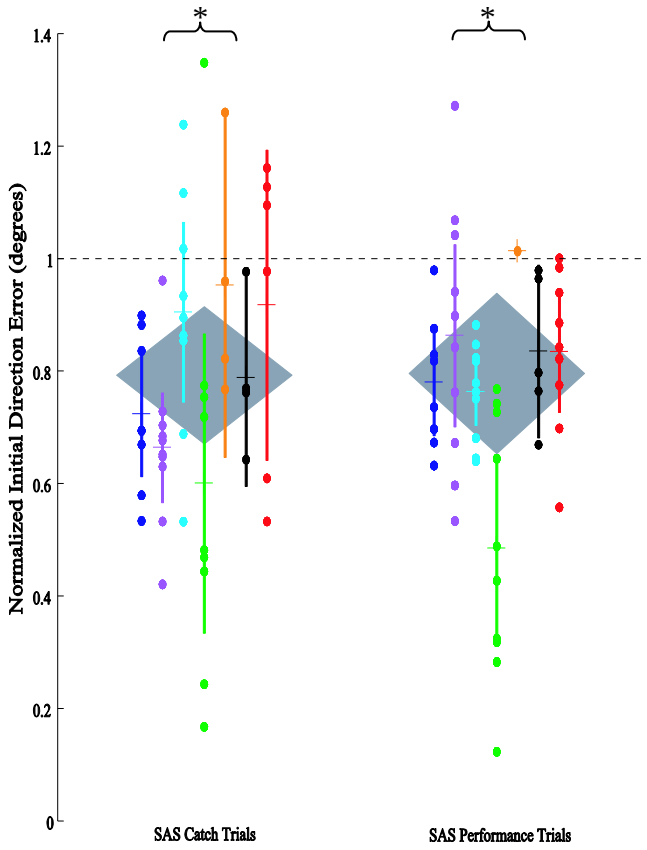

Figure 16: Movement errors in SAS catch trials and SAS performance trials normalized to mean No SAS catch trials and mean performance at the end of training, respectively. Group means are considered significantly different if the upper bound of the group 95% confidence interval is less than 1 (i.e. paired t-test). (Brackets with an asterisk inidicate significance) SAS significantly reduced after-effects in catch trials and reduced performance.

Another important question is whether startle has an influence on baseline movement trajectories. We compared the movement errors of voluntary baseline movements to SAS baseline movements performed prior to training (Fig. 17). A paired t-test revealed that startle did not have a significant effect on movement trajectories during baseline movements; $t_{.05}(4) = .920$ $p = .410$. Since startle caused errors on both sides of an ideal baseline movement (IDE equal to 0), although more variable, suggests that startle did not add torque to the dynamics of the movement.

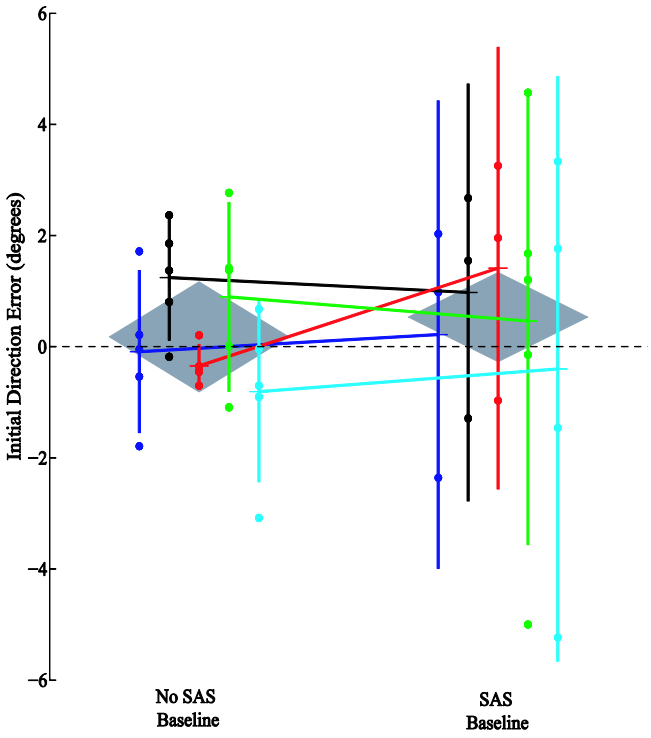

Figure 17: Movement errors in voluntary baseline attempts compared to SAS baseline movements. Startle did not have a significant effect on subject's ability to make straight line movements prior to training.

D. Discussion (Experiment Four)

The purpose of experiment four was to determine if the effects of startle on learning which were previously revealed by startling subjects during the removal of a force-field (experiment one and two) and a visually distorted field (experiment three) can also be shown by startling subjects while they move within the visually distorted field. Thus, the paradigm included startle in both catch trials (i.e. removal of VD) and performance trials (i.e. presence of VD). We found that, in all subjects that exhibited a startle response, startle (1) reduces the magnitudes of after-effects and (2) decreases performance.

We compared the movement errors in startle performance trials to each subject's respective performance within the visually distorted field at the end of training (e.g. last 5 trials) which included a total of 100 movements. This amount of training should have been a sufficient amount to allow subjects to learn, although previous studies have shown that subjects have difficulty fully learning to make the required movement (e.g. ideal straight line) when exposed to a visually distorted field [8]. It is possible that subject's movement errors could have converged closer towards zero with more practice. The fact that startle reduces performance of a learned task in a similar fashion as it reduces after-effects provides further evidence that startle disrupts the recall of a newly learned internal model.

Within this paradigm we also introduced startle in baseline trials prior to training to determine if startle has an influence one's ability to make straight line movements. The number of startle trials was kept low and not every subject received the startle stimulus in order to avoid habituation seen the previous experiments. The results revealed that, in subject's that exhibited a startle response, although the movement errors during SAS Baseline trials were more variable, they were not significantly different from the movement errors in No SAS baseline trials. The magnitude of the movement errors during SAS baseline trials were relatively smaller compared to the movement errors seen when they were initially exposed to the VD field. Also, the fact that movement errors occurred on both sides of an ideal straight line indicates that these movements were not biased to a particular direction resulting from startle. Thus, startle did not add additional torque to the dynamics of the movement in one direction and seemingly did not reduce performance during baseline trajectories.

VI. GENERAL DISCUSSION

This thesis presented results on the effects of startle on the storage and release of a recently learned internal model formed through operating a machine in the presence of a challenging (1) dynamic force-field (2) rotation of visual feedback. We found that in all subjects that exhibited a startle response, SAS (1) reduced after-effect magnitudes (2) reduced performance of the learned task. However, the magnitude of reduced after-effects was not further modulated by the timing of SAS. Such degradation in learned control suggests that startle may disrupt, but not totally diminish, the internal model that arises in adaptive training. To the best of our knowledge, these results are the first to probe the effects of startle framed in the context of robot and sensory adaptation.

Experiment one may have used stimuli that were not strong enough to elicit a definite startle according to criteria laid out by previous research, yet the results provided initial evidence that such stimuli may have an influence on the preparation of movements associated with adaptive control. There was no effect on the timing of response initiation, yet there appeared to be a reduction in the magnitude of after-effects, consistent with the trials in experiment 2 where startle was more certain. It is unclear whether startle caused the degradation in after-effects or if subjects associated startle with catch trials, which would have allowed them to voluntarily reduce movement error. The delayed response times could have given subjects enough time to prepare a voluntary response that compensated for the removal of the force-field. However, it is possible that startle distracted the preparation of the learned model, and that the effects of such disturbance still persisted when subjects initiated a voluntary response. This idea that startle may

have a lingering effect on the recall of learned control, even on subsequent movements, could be explained by the fact that the nervous system has difficulty mixing complex neural processes with outside disturbances.

Experiment two repaired the problems in the elicitation and detection of a startle response. Since strengthening the startle stimulus led to the early release of movement involuntarily, it is unlikely that subjects had the ability to voluntarily alter their pre-planned movements. Instead, we presumed that startle disrupted the release of movement trajectories consistent with after-effects. However, measurements of cocontraction revealed that startle may have inflicted a change in the arm dynamics. This was seen as a potential confound in the experiment because cocontraction could explain the reduced after-effects.

Experiment three resolved this problem with cocontraction by using a visually distorted environment as the mode of adaptation. As expected, we found that the after-effects of adaptation were reduced when movements were released early by startle and the extent of such effects of startle appeared to be larger on subjects that had a more pronounced physiological response to the stimulus (i.e. SCM activity). As after-effects reflect the formation of an internal model, performance within a perturbed environment is also a way to gauge the extent of learning. Thus, since startle does disrupt the recall of a recently learned internal model, as evidence of reduced after-effects, it seems logical that startle also reduces the performance of a learned task.

As mentioned, one of the differences from this study and previous SAS investigations is that we failed to detect disparity in after-effect magnitudes among the different SAS timing conditions. Related to the build-up of a prepared response, we expected a more robust response when startle was administered in synchronization with the GO [12]. Due to the intricacies of the neural processes associated with the performance of a recently learned task, it is possible that preparation following an adaptation task is also more complex and, as a consequence, does not require the same early build-up seen in simple one degree of freedom tasks. In this experiment, the time at which subjects began to prepare movements was uncertain. Since the timing information for when subjects were to release movements was fixed, recent research suggests that movements are fully prepared well in advance to GO [13]. However, due to the length of the experiment, the beginning of preparation may have been delayed as subjects learned to respond faster relative to GO. Consequently, it is unclear if the various SAS timing conditions released the feedforward program during different stages of assembly. Manipulating the response timing information such that the initial moment of movement preparation can be identified with relative certainty may help clarify the time course and assembly of prepared movements following an adaptation task.

One possible explanation for the reduction in after-effects across all SAS timing is that the neural processes associated with learning are more susceptible to interferences such as startle. Many studies have revealed how fragile internal models are to interferences and have identified factors that may disrupt learning or short term and long term retention of internal models [6, 46]. For example, switching between two conflicting internal models or a temporal lapse between practice sessions can lead to degradation in performance of the learned model. This study

exposed subjects to startle while they were still in the early stages of learning. Robustness to such effects (extinction) may be a way to gauge the extent of learning. Not all subjects were vulnerable to startle, so one may speculate that those who were either not easily startled or were perhaps further along in their learning process had a more consolidated and robust performance as a consequence. It remains to be seen whether startle is more prevalent during the fragile early stages of learning where consolidation of a learned task in memory has not yet taken place. More practice over an extended period of time (days or weeks) may help clarify if startle still has an effect on a learned task that is more consolidated in memory.

One hypothesis is that after-effects are a consequence of a conscious level of programming requiring high-level planning. However, in order for startle to elicit an early release of movement, it is believed that the underlying feedforward mechanisms must be stored in the brainstem and other subcortical regions [4]. The defining requirement for a response to be elicited early by startle is preprogramming which in return requires a movement task that allows for preparation to take place in advance. In the particular case of reaching movements to targets used in these experiments the task was known in advance to GO. As such, preprogramming of the learned response was expected, yet, the after-effects were shown to reduce in the event of startle. Since startle did lead to early responses and since startle reduced but did not eliminate the recall of learned control, we suggest that multiple neural centers (cortical and subcortical) are involved in such learning. Consequently, because the effects of adaptation still remain evident after startle, there may be another center other than the brainstem that may be involved with managing fine motor control. This part of the brain may act as a control center by refining the components of the feedforward motor program during the early stages of learning. The

foundation of the feedforward motor program may reside in subcortical structures making it capable of being released by startle. This supports the concept of the society of mind, in which the brain is actually not one unit but multiple units that work in concert to function [47].

This study was an important step to understanding both startle and its relationship to the recall of feedforward control. The approach might also simply heighten motivation and/or attention not just in recall but also in the learning process itself, making more errors more noticeable. This study provides evidence that can point to future studies that attempt to exploit the natural adaptive tendencies in the nervous system for teaching new motor functions. These results can impact training areas that rely on intricate motor learning strategies, such as piloting, teleoperation, sports, and rehabilitation. Furthermore, this study can impact areas that involve frequent high-noise or abrupt distracting stimulations, such as military, construction and traffic.

CITED LITERATURE

1. Carlsen, AN, Chua, R, Inglis, JT, Sanderson, D, and Franks, I (2004) Prepared movements are elicited early by startle. Journal of Motor Behavior 36:253-264.

2. Valls-Solé J, Solé A, Vallderiola F, Munoz E, Gonzalez LE, Tolosa ES (1995) Reaction time and acoustic startle in normal subjects. Neuroscience Letters 195:97-100.

3. Carlsen AN (2010) Considerations for the use of a startling acoustic stimulus in studies of motor preparation in humans. Neuroscience Biobehaviorial Review doi:10.1016/j.neubiorev.2010.04.009.

4. Valls-Solé J, Rothwell JC, Goulart F, Cossu G, and Munoz E (1999) Patterned ballistic movements triggered by a startle in healthy humans. Journal of Physiology 516:931-8.

5. Kawato M (1999) Internal models for motor control and trajectory planning. Current Opinion in Neurobiology 9:718-727.

6. Gandolfo F, Mussa-Ivaldi FA, and Bizzi E (1996) Motor learning by field approximation. Proceedings of the National Academy of Sciences of the United States of America 93:3843-6.

7. Shadmehr R and Mussa-Ivaldi FA (1994) Adaptive representation of dynamics during learning of a motor task. Journal of Neuroscience 14:3208-3224.

8. Wei Y, Bajaj P, Scheidt R, and Patton J (2005) Visual Error Augmentation for Enhancing Motor Learning and Rehabilitative Relearning. IEEE International Conference on Rehabilitation Robotics

9. Flanagan JR and Rao AK (1995) Trajectory adaptation to a nonlinear visuomotor transformation: evidence motion planning in visually perceived space. Journal of Neurophysiology 74:2174-8.

10. Patton J, Wie Y, Scharver C, Kenyon R, and Scheidt R (2006) Motivating rehabilitation by distorting reality. BioRob 2006 The first IEEE/RAR-EMBS International Conference on Biomedical Robotics and Biomechatronics, Pisa, Tuscany, Italy, February 20-22, 2006.

11. Carlsen AN, Chua R, Inglis JT, Sanderson DJ, and Franks IM (2004) Can prepared responses be stored subcortically? Experimental Brain Research 159:301-9.

12. MacKinnon CD, Bissig D, Chiusano J, Miller E, Rudnick L, Jager C, Zhang Y, Mille M L, and Rogers MW (2007) Preparation of anticipatory postural adjustments prior to stepping. Journal of Neurophysiology 97:4368-79.

13. Carlsen AN and Mackinnon CD (2010) Motor preparation is modulated by the resolution of the response timing information. Brain Research 1322:38-49.

CITED LITERATURE (continued)

14. Lackner JR and DiZio P (1996) Motor function in microgravity: movement in weightlessness. Journal of Neural Biology 6:744-750.

15. McIntyre J, Zago M, Berthoz A and Lacquaniti F (2001) Does the brain model Newton's laws? National Neuroscience 4:693–694.

16. Lackner JR and DiZio P (1994) Rapid adaptation to Coriolis force perturbations of arm trajectory. Journal of Neurophysiology 74:1787-1792.

17. Sainburg RL and Kalakanis D (2000) Differences in control of limb dynamics during dominant and nondominant arm reaching. Journal of Neurophysiology 83:2661-2675.

18. Held R and Schlank M (1959) Adaptation to disarranged hand-eye coordination in the distance-dimension. American Journal of Psychology 72: 603-5.

19. Flash T and Hogan N (1985) The coordination of movements: an experimentally confirmed mathematical model. Journal of Neuroscience 5:1688-1703.

20. Morasso P (1981) Spatial control of arm movements. Experimental Brain Research 42:223-227.

21. Fitts PM and Peterson JR (1964) Information capacity of discrete motor responses. Journal of Experimental Psychology 67(2):103–112.

22. Milner TE and Cloutier C (1993) Compensation for mechanically unstable loading in voluntary wrist movements. Experimental Brain Research 94:522-532.

23. van Emmerick REA (1992) Kinematic adaptations to perturbations as a function of practice in rhythmic drawing movements. Journal Motor Behavior 24:117-131.

24. Landis C and Hunt WA (1940) The Startle Pattern. Journal of Psycho-Analysis 21:168.

25. Davis M, Gendelman DS, Tischler MD, Gendelman PM (1982) A primary acoustic startle circuit: lesion and stimulation studies. Journal of Neuroscience 2:791-805.

26. Brown P, Day BL, Rothwell JC, Thompson PD and Marsden CD (1991b) The effect of posture on the normal and pathological auditory startle reflex. Journal of Neurology Neurosurgery and Psychiatry 54:892—897.

27. Yoemans JS and Frankland PW (1996) The acoustic startle reflex: neurons and connections. Brain Research Reviews 21:301-314.

28. Cui R and Mackinnon CD (2009) The effect of temporal accuracy constraints on movement-related potentials. Experimental Brain Research 94:477-88.

CITED LITERATURE (continued)

29. Thickbroom GW, Byrnes ML, Sacco P, Ghosh S, Morris IT and Mastaglia FL (2000) The role of the supplementary motor area in externally timed movement: the influence of predictability of movement timing. Brain Research 874:233-241.

30. Carlsen AN, Chua R, Inglis JT, Sanderson DJ and Franks IM (2003) Startle Response is dishabituated during a reaction time task. Experimental Brain Research 152:510-518.

31. Valls-Solé J, Valldeoriola F, Tolosa E and Nobbe F (1997) Habituation of the auditory startle reaction is reduced during preparation for execution of a motor task in normal human. Brain Research 751:155-159.

32. Brebner JMT and Welford AT (1980) Introduction: An historical background sketch. In A.T. Welford (Ed.), *Reaction Times*, pp. 1-23.

33. Kumru H, Urra X, Compta Y, Castellote JM, Turbau J, Valls-Solé J (2006) Excitability of subcortical motor circuits in Go/noGo and forced choice reaction time tasks. Neuroscience Letters 406:66–70.

34. Carlsen AN, Chua R, Dakin CJ, Sanderson DJ, Inglis JT, Franks IM (2008a) Startle reveals an absence of advance motor programming in a Go/No-go task. Neuroscience Letters 434:61–65.

35. Klapp ST (1996) Reaction time analysis of central motor control. In Zelaznik HN (ed), Advances in Motor Learning and Control, Human Kinetics, Champaign, pp. 13-35.

36. Carlsen AN, Chua R, Summers JJ, Inglis JT, Sanderson DJ, Franks IM (2009b) Precues enable multiple response preprogramming: evidence from startle. Psychophysiology 46:241–251.

37. Maslovat D, Carlsen AN, Chua R, Franks IM (2009) Response preparation changes during practice of an asynchronous bimanual movement. *Experimental Brain Research* 195:383-392.

38. Thickbroom GW, Byrnes ML, Sacco P, Ghosh S, Morris IT and Mastaglia FL (2000) The role of the supplementary motor area in externally timed movement: the influence of predictability of movement timing. Brain Research 874:233–241.

39. Carlsen AN, Dakin CJ, Chua R, and Franks IM (2007) Startle produces early response latencies that are distinct from stimulus intensity effects. Experimental Brain Research 176:199-205.

40. Wright ZA, Rogers MW, MacKinnon CD and Patton JL (2009) Startle stimuli reduce the internal model control in discrete movements. IEEE Engineering in Medicine and Biology Conference (EMBC), Minneapolis, MN USA.

CITED LITERATURE (continued)

39. Carlsen AN, Dakin CJ, Chua R, and Franks IM (2007) Startle produces early response latencies that are distinct from stimulus intensity effects. Experimental Brain Research 176:199-205.

40. Wright ZA, Rogers MW, MacKinnon CD and Patton JL (2009) Startle stimuli reduce the internal model control in discrete movements. IEEE - Engineering in Medicine and Biology Conference (EMBC), Minneapolis, MN USA.

41. Patton JL and Mussa-Ivaldi FA (2002) Linear Combinations of Nonlinear Models for Predicting Human-Machine Interface Forces. Biological Cybernetics 86:73-87.

42. Burgess JK, Haner R, and Patton JL (2007) Generalization of Motor Adaptation Skills from Bimanual-Grasp to Individual Limbs. IEEE Transactions on Neural Engineering and Rehabilitation, vol. 15.

43. Howell, David. *Fundamental Statistics for the Behavioral Sciences.* 7th ed. Stamford: Cengage Learning, 2010. Print.

44. Frost G, Dowling J, Dyson K and Bar-Or (1997) Cocontraction in three age groups of children during treadmill locomotion. Journal Electromyography Kinesiology 7:179-186.

45. Wright ZA, Patton JL, Ravichandran V (2011) Startle Reduces Recall of a Recently Learned Internal Model. IEEE International Conference on Rehabilitation Robotics, Zurch, CH.

46. Brashers-Krug T, Shadmehr R, Bizzi E (1996) Consolidation in human motor memory. Nature 382:252–255.

47. Minsky M, The Society of Mind ISBN 0-671-65713-5. Simon and Schuster, New York. March 15, 1988.

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Wright, Z.A., Patton, J.L., Ravichandran, V.: Startle Reduced Recall of Recently Learned Internal Model. IEEE International Conference on Rehabilitation Robotic (ICORR) Zurich, CH, 2011.