Startle Stimuli Reduce the Internal Model Control in Discrete Movements

Zachary A. Wright, Mark W. Rogers, Colum D. MacKinnon, and James L. Patton

***Abstract* — A well known and major component of movement control is the feedforward component, also known as the internal model. This model predicts and compensates for expected forces seen during a movement, based on recent experience, so that a well-learned task such as reaching to a target can be executed in a smooth straight manner. It has recently been shown that the state of preparation of planned movements can be tested using a startling acoustic stimulus (SAS). SAS, presented 500, 250 or 0 ms before the expected "go" cue resulted in the early release of the movement trajectory associated with the after-effects of the force field training (i.e. the internal model). In a typical motor adaptation experiment with a robot-applied force field, we tested if a SAS stimulus influences the size of after-effects that are typically seen. We found that in all subjects the after-effect magnitudes were significantly reduced when movements were released by SAS, although this effect was not further modulated by the timing of SAS. Reduced after-effects reveal at least partial existence of learned preparatory control, and identify startle effects that could influence performance in tasks such as piloting, teleoperation, and sports.**

I. Introduction

Robot-applied force fields are used to study the adaptation and learning responses in humans and other animals. A typical force field experiment puts these concepts to test by exposing subjects to these forces. 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 [1]. When the forces are unexpectedly turned off and people return to the "normal" world, they make errors in their movements, called after-effects that are nearly symmetrical to the initial errors that occur when the subjects are first exposed to the forces [1]. Such after-effects reveal the learned *forward model* that predicts the dynamics of the movement before it even begins.

In another line of research it has recently been shown that the state of preparation of a planned movement can be probed with a startling acoustic stimulus (SAS). During simple reaction time tasks, the presentation of SAS up to 1400 ms prior to, or coincident with the imperative cue to initiate movement results in the rapid release of the planned movement with onset times of typically less than 100 ms [2, 3]. Moreover, the spatial and temporal characteristics of the movement sequence remain intact. Based on the early latency of onset of the movement, it has been proposed that SAS releases a pre-planned "*motor program*" from subcortical structures and occurs if the task is known before initial movement takes place [4]. We define the term "release" as the initiation of movement. The pre-planned "motor program" contains the framework for a future movement and is either releases voluntarily or involuntarily. This result is quite dramatic in programmed stepping response actions, where the SAS triggers not only a faster reaction time (sometimes premature to the "go" signal), but a more and more complete feedforward control program (involving appropriate preparatory weight shifting) as the time of the SAS stimulus timing approached the "go" cue [2]. Movement preparation apparently involves a progressive buildup of a feedforward motor program over time before the go signal. 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. What is not clear is whether adaptations to new environments, such as in the adaptation of reaching movements to force fields, involves the same type of progressive buildup of a feedforward motor program. To date, no study has used this paradigm to investigate the storage and release of the internal model formed after a force field training task.

This pilot study describes the use of healthy subjects and the existing robotic force field apparatus to test the hypothesis that SAS disrupts the release of movement trajectory consistent with the after-effects of force field training. Such disruption should reduce the size of after-effects. We further hypothesized that the magnitude of the released internal model would progressively increase as the timing of SAS approached in onset of the imperative "go" cue, related to the buildup and readiness of a possible feedforward motor program.

Manuscript received April 21, 2009. This work was supported in part by the U.S. Department of Education NIDRR program under Grant H133E0700 13 and the NIH under grant H133E0700 13.

J. L. Patton and Z. Wright are with the University of Illinois at Chicago, Illinois 60607 +01(312)413-7664 pattonj@uic.edu and the Rehabilitation Institute of Chicago.

C. MacKinnon is with Northwestern University Department of Physical Therapy and Human Movement Sciences.

M. Rogers is with the University of Maryland Department Of Physical Therapy & Rehabilitation Science.

See http://smpp.northwestern.edu/Robotics for more information on this research.

II. PROCEDURE

A. Apparatus

The experiment used a planar haptics/graphics manipulandum presented previously [5, 6], which combines a projected overlay display with robotic forces that can record limb movement and handle force (Fig. 1).

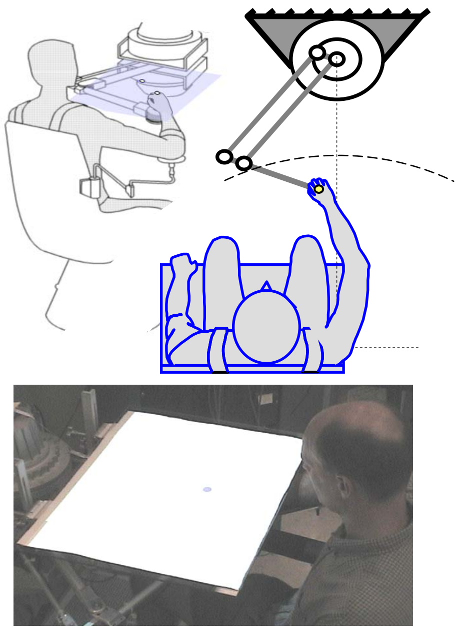

Fig. 1. Subject and manipulandum apparatus.

A computer-generated analog tone (1000 Hz, 50ms) was used to create an auditory startle stimulus. The tone was amplified to produce a stimulus with an intensity of 98 dB which was presented to the subject via headphones.

B. Protocol

Five Healthy adult subjects (Mean ± SD of age in years = 22 ± 2 years),freefrom neurological or musculoskeletal disorders and naïve to the learning paradigms participated in this study. Subjects grasped the handle of the robot and performed a series of reaching movements in two directions to visual targets. Each movement 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" cue, at which point the subjects were instructed to initiate a movement to the target as fast as possible. 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.

Subjects received an auditory startle stimulus in 20% of trials delivered at 500, 250 or 0 ms prior to the "go" cue (startle trials). Added to the 20%, some trials may present a visual "go" cue with no SAS. Also, a SAS was presented in between phases to gain knowledge on the subject's reaction when they are not asked to perform a task. The number of trials with the SAS was kept low to avoid habituation of the response.

Each subject participated in an experiment that has the following phases:

1. **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.
2. **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.
3. **Initial Exposure**: in a subset of 320 movements in all, on intermittent, randomly selected trials, (one in every 5 movements) subjects were exposed to either a SAS or exposed to the well-known "curl" force field [1]:

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

where F is the force vector applied to the limb and $\dot{x}$ is the 2-dimensional velocity vector of the hand. This field provides 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.

4. **Training**: a total of 200 movements were performed in all, where subjects consistently trained in the presence of the curl field.
5. **Evaluation**: 320 movements were performed with forces, but now several randomly selected intermittent trials (one in five 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 or the unexpected removal of forces with a SAS (occurring at -500, -250 and 0 ms prior to the "go" signal).

C. Analysis

Deviation from a straight line is the primary measure of movement error, since a "curl" force field results in a clockwise bend of the movement path. The after-effects of adaptation, seen when the force field is unexpectedly removed, are a counter-clockwise bend of the movement path. Hence initial direction error measurements were used to measure the degree at which after-effects deviate from a straight line, defined as the angle between the ideal straight line movement to the target and the vector formed from the starting point to the position at 25% of the distance to the target. The onset of movement was indicated when the handle velocity reached .6 m/s. The angle between baseline movements and after-effects at the onset of movement determined initial direction error. Performance and any deviation from a straight line were compared to that seen in Phase 3. Catch trials and their deviation from a straight line were compared with the performance of the same attempts on movements in Phase 2. One-Way ANOVA with Tukey post hoc comparisons was used to determine if the three SAS cases are statistically different than the non-startle case (α=0.05).

III. Results

As in other experiments of this type, baseline trajectories approximated straight lines (Fig. 2A), initial exposure to forces perturbed motions in a clockwise direction (Fig. 2B), motions again approximated straight lines by the end of training (Fig 2C), and trajectories were distorted in a counterclockwise direction in the catch trials where the forces were unexpectedly removed, revealing after-effects of adaptation (Fig. 2D). Similar patterns in the after-effects were also visible when the SAS was presented.

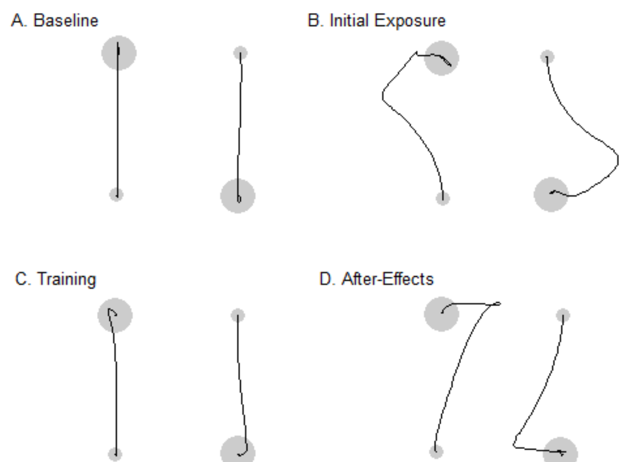

Fig. 2: Typical trajectories during the different phases of the experiment. (A) Trajectories are initially straight during baseline movements. (B) Preliminary movements are perturbed when a force field is applied. (C) After training, subjects begin to learn and revert back to straight line movements. (D) In the presence or absence of SAS, trajectories become mirror images of those seen in (C) after the force field is removed.

Although the patterns of the trajectories for the after-effects were similar for when an acoustic stimulus was present or absent, the magnitude of the after-effects for both cases were compared. Fig. 3 gives a visual view of one subject's trajectories of the after-effects for when no SAS was present and when SAS was administered at the three different time points relative to the "go" cue. Angles between the baseline trajectory and the after-effect trajectories were smaller in the SAS situation.

Group results point to similar trends (Fig 4). One-way ANOVA revealed that initial direction errors in both directions and for all subjects were partitioned into four independent groups (n = 200 movement errors). The mean of movement errors for the no startle case was calculated to be 16.79 degrees, with a standard error of ±.761. The means of movement errors for when SAS was administered at -500ms, -250ms and -0ms was calculated to be 13.07 degrees, 12.78 degrees and 11.86 degrees, respectively, with standard errors of ±.753, ± .761 and ±.768, respectively. There was a main effect of task condition ($F = 8.12$, $p < 4e\text{-}5$). Differences across condition are shown in Fig. 4 using a wings plot showing the means and error bars of movement errors for each subject for each situation.

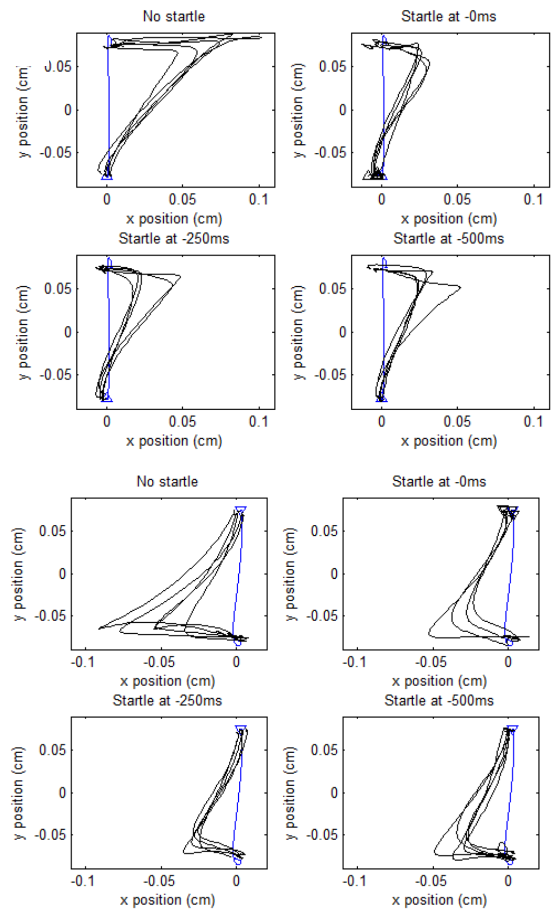

Fig. 3: Trajectories of one subject's after-effects for when SAS is absent and when SAS is present at -0ms, -250ms and -500ms relative to the "go" cue. Blue line indicates baseline trajectory. (A) Movement towards positive y-direction and (B) Movement towards negative y-direction as indicated by arrows.

Interestingly, the group movement onset times appeared to be unchanged by startle (Fig 5). This indicates that the subjects did not launch their motions sooner as a consequence of the SAS stimulus. However, some subjects did show a significant but small reduction in onset time between the no startle and startle conditions (indicated by solid lines connecting the conditions.), which appears to increase again as the SAS time approaches the time of the "go" signal (-0ms). Hence, it is uncertain whether all time-related aspects reported to be associated with other startle response studies are clearly observed in this study.

IV. Discussion

We found that, in all subjects, the after-effect magnitudes were significantly reduced when movements were accompanied with a startle stimulus, but not entirely eliminated. However the time at which subjects initiated the movements appeared unchanged by either of the SAS timing conditions, indicating that the SAS may have not released their movements. The differences may be explained by the intensity of acoustic stimulus. In our study the intensity was lower (104 dB vs 110dB+ in other studies). It has been shown that this intensity can elicit a startle response and the early release of movement, but only when accompanied by a burst of muscle activity in neck muscles (most notably the sternocleidomastoid muscle) [7]. Since we did not record neck muscle activity, it is possible that not all trials actually produced a startling effect. The probability of eliciting a startle response becomes less at lower levels of stimulus intensity.

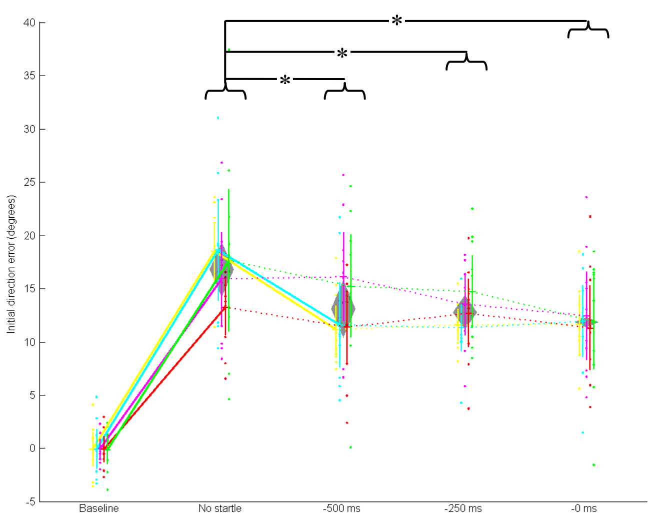

Fig. 4: Movement errors in the after effects catch trials (where forces are unexpectedly turned off) for the cases of no startle and startle at several delays (horizontal axis), compared to baseline error. Each subject is a color, each trial's data is a small dot, each subjects 95% confidence interval for that condition is indicated by a vertical bar, and each group mean and 95% confidence interval of the means is indicated by a diamond shaped shaded area. Individual significant differences between adjacent conditions within each subject are shown by solid colored lines if they are significant, and dashed if they are not significant. Statistical comparison of groups using Tukey post-hoc tests revealed significant differences between no startle and each of the three startle conditions (shown by black lines connecting brackets at the top). Hence, SAS significantly reduced but did not eliminate nor did it reverse the error seen in the after-effects trials.

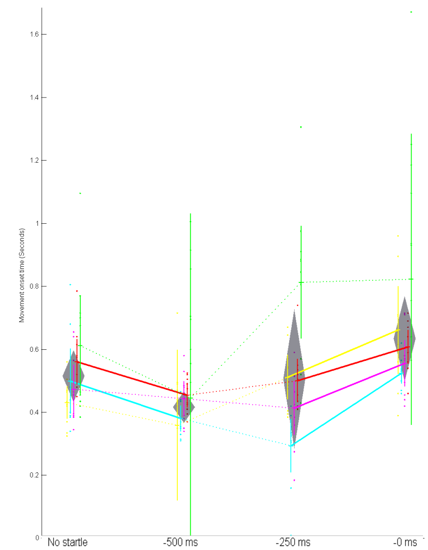

Fig. 5: Movement onset times for the 4 catch trial conditions. Line types and conventions are the same as in Fig 4.

Another difference from this study and previous SAS investigations is that no differences in the after-effect trajectory were detected between the different SAS timing conditions. In a stepping preparation study [2], the magnitude of the SAS effect increased as the timing of stimulation approached the imperative "go" cue. We expected that there would be more of a reduction in the after-effects when startle is administered in synchronization with the "go" signal because it would allow for less time for the activation of the internal model that compensates for the forces. With no differences in the magnitudes of the after-effects across the three SAS timing conditions, it suggests that the preparation for movements in a simple reaction time task may differ from preparation following an adaptation task. There may not be the same type of build-up in the feedforward model in adaptive training that is seen in time reaction tasks where movements are prepared.

The reduction in the size of the after-effects suggests that startle may disrupt, but not totally diminish, the internal model that arises in adaptive training. The part of the brain that manages fine motor control through the acquisition of the internal model, seemingly the cerebellum, may be disrupted by the startle stimulus. This could cause an incomplete merging of the neuronal processes that control movement, leaving out or creating a temporal lag in the internal model that is built through adapting and learning to move in the presence of forces. Such disruption would cause degradation of the after-effects and presumably in learning.

V. Conclusion

To our knowledge, this study is the first of its type to probe the influence of the startle response on the adaptive training seen in adaptation to external forces. More data from more subjects possibly tested at more startle times and higher stimulation intensities may help clarify the influence of SAS on reaction (onset) time, but the fact that there is at least some influence on the measures of this study indicates that some portion of this feedforward control resulting from adaptation is influenced by startle. Such results may impact military and other human-machine performance tasks such as piloting, teleoperation, and sports training. Such tasks rely on feedforward control strategies from adaptive training and could be disrupted by loud noises and other some forms of startle stimuli.

ACKNOWLEDGMENT

We thank Santiago Acosta, Vess Djoev and Assaf Pressman for their excellent technical assistance.

REFERENCES

[1] F. Gandolfo, F. A. Mussa-Ivaldi, and E. Bizzi, "Motor learning by field approximation," *Proceedings of the National Academy of Sciences of the United States of America*, vol. 93, pp. 3843-6, 1996.

[2] C. D. MacKinnon, D. Bissig, J. Chiusano, E. Miller, L. Rudnick, C. Jager, Y. Zhang, M. L. Mille, and M. W. Rogers, "Preparation of anticipatory postural adjustments prior to stepping," *J Neurophysiol*, vol. 97, pp. 4368-79, 2007.

[3] J. Valls-Sole, J. C. Rothwell, F. Goulart, G. Cossu, and E. Munoz, "Patterned ballistic movements triggered by a startle in healthy humans," *Journal of Physiology*, vol. 516, pp. 931-8, 1999.

[4] A. N. Carlsen, R. Chua, J. T. Inglis, D. J. Sanderson, and I. M. Franks, "Can prepared responses be stored subcortically?," *Exp Brain Res*, vol. 159, pp. 301-9, 2004.

[5] J. K. Burgess, R. Haner, and J. L. Patton, "Generalization of Motor Adaptation Skills from Bimanual-Grasp to Individual Limbs," *IEEE transactions on Neural Engineering and Rehabilitation*, vol. 15, 2007.

[6] J. L. Patton and F. A. Mussa-Ivaldi, "Linear Combinations of Nonlinear Models for Predicting Human-Machine Interface Forces," *Biological Cybernetics*, vol. 86, pp. 73-87, 2002.

[7] A. N. Carlsen, C. J. Dakin, R. Chua, and I. M. Franks, "Startle produces early response latencies that are distinct from stimulus intensity effects," *Exp Brain Res*, vol. 176, pp. 199-205, 2007.