Startle Distinguishes Task Expertise

by

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ABSTRACT

Recently, it was demonstrated that startle-evoked-movements (SEMs) are present during individuated finger movements (index finger abduction), but only following intense training. This demonstrates that changes in motor planning, which occur through training (motor learning - a characteristic which can provide researchers and clinicians with information about overall rehabilitative effectiveness), can be analyzed with SEM. The objective here was to determine if SEM is a sensitive enough tool for differentiating expertise (task solidification) in a common everyday task (typing). If proven to be true, SEM may then be useful during rehabilitation for time-stamping when task-specific expertise has occurred, and possibly even when the sufficient dosage of motor training (although not tested here) has been delivered following impairment. It was hypothesized that SEM would be present for all fingers of an expert population, but no fingers of a non-expert population. A total of 9 expert (75.2 ± 9.8 WPM) and 8 non-expert typists, (41.6 ± 8.2 WPM) with right handed dominance and with no previous neurological or current upper extremity impairment were evaluated. SEM was robustly present (all $p < 0.05$) in all fingers of the experts (except the middle) and absent in all fingers of non-experts except the little (although less robust). Taken together, these results indicate that SEM is a measurable behavioral indicator of motor learning and that it is sensitive to task expertise, opening it for potential clinical utility.

DEDICATION

I would like to dedicate this to my mom and dad for their endless love, support, and inspiration. You have both taught me so much and have molded me into the person I am today. I would also like to thank and dedicate this to my sister, brother-in-law, grandparents, aunts, uncles, cousins, and all my friends for their love and support throughout this academic journey. You all have helped pushed me forward in your own unique way. Finally, I would like to thank all the professors at ASU (School of Biological and Health Systems Engineering) who have helped me get to this point.

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CHAPTER 1

While many are familiar with the classic startle response by which a loud sound causes a reflexive “flinching” of the body, a lesser known phenomenon is the ability of a startling stimulus to evoke the involuntarily release of a planned movement – a startle-evoked-movement (SEM- also referred to as startReact in the literature). SEM is a robust phenomenon observed across multiple joints (Carlsen, Chua, Inglis, Sanderson, & Franks, 2004b; Castellote & Valls-solé, 2015; Cressman, Carlsen, Chua, & Franks, 2006; Nonnekes, Oude Nijhuis, et al., 2014; Ossanna, 2017; Quezada Valladares, 2017; Wright, Carlsen, & MacKinnon, 2016) and patient populations: stroke (Honeycutt & Perreault, 2012, 2014; Honeycutt, Tresch, & Perreault, 2016; Marinovic, Brauer, Hayward, Carroll, & Riek, 2016; Rahimi & Honeycutt, 2017), Parkinson’s Disease (Fernandez-Del-Olmo et al., 2013; Nonnekes, Geurts, & Oude, 2014; Nonnekes, Kam, Nijhuis, & Geel, 2015; Thevathasan et al., 2011), Spinal Cord Injury (Baker & Perez, 2017), Cervical Dystonia (Serranová et al., 2012), and Hereditary Spastic Paraplegia (Nonnekes, Oude Nijhuis, et al., 2014). Furthermore, SEM generates movements that are tightly regulated and scaled to the temporal and spatial features of a task (Maslovat, Carlsen, Chua, & Franks, 2009; Maslovat, Carlsen, Ishimoto, Chua, & Franks, 2008) highlighting that it is a sophisticated tool to evaluate the motor planning process.

Provocatively, it was recently demonstrated that SEM may be a measurable behavioral indicator of motor learning. Index finger abduction – to date – is the only movement that has been shown to not be susceptible to SEM. This finding has been found by two independent groups (Carlsen, Chua, Inglis, Sanderson, & Franks, 2008; Honeycutt, Kharouta, & Perreault, 2013). However, after a 10-day training regimen, index finger abduction becomes susceptible to SEM suggesting that SEM can distinguish task expertise (Kirkpatrick & Honeycutt, 2015). Still, others who have evaluated tasks which are inherently susceptible to SEM, specifically elbow extension, show no difference in the ability to elicit SEM with practice (Maslovat et al., 2009, 2008; Maslovat, Hodges, Chua, & Franks, 2011). Therefore, it remains unclear if SEM is sensitive enough to differentiate task expertise.

The objective here was to evaluate SEM during a common task where expertise was easily quantified – typing. It was hypothesized that experts would show SEM in all fingers, while non-experts would have no SEM response. If this hypothesis is upheld, it would provide further evidence that SEM is a measurable behavioral indicator of motor learning – at least at the distal limb. Further, it would highlight that SEM, which is readily present during a wide array of proximal joint movements (elbow, wrist) of varying complexity (Marinovic & Tresilian, 2016; Maslovat, Carlsen, & Franks, 2012; Maslovat et al., 2011; Maslovat, Klapp, Jagacinski, & Franks, 2014), is present at the distal limb provided that the task is performed routinely by the individual. The following chapters discuss these findings with respect to how they shape the current understanding of how motor tasks are learned at the distal limb.

CHAPTER 2

METHODS

IRB and safety. This study was approved by Institutional Review Board STUDY00002440 under Arizona State University. Subjects were informed of all potential risks prior to participation in the study and verbal/written consent was obtained.

Subjects. Seventeen neurologically unimpaired, right-handed individuals (9 Male, 8 Female; Age: 20.7 ± 0.9 years) were utilized for this study. Subjects were categorized as expert or non-expert typists based on the result of a three-minute typing test. The average number of correct words typed per minute was used to account for speed and accuracy. A typing speed of 60 words per minute denoted an expert typist as per the TypingMaster Inc. classification. An unpaired t-test confirmed that the expert population (75.2 ± 9.8 WPM) scored higher on the test than the non-expert population (41.6 ± 8.2 WPM) ($t_{stat} = 7.44$, $P < 0.001$).

Data acquisition. EMG data were collected at 3000 Hz with Ag/AgCl bipolar surface electrodes [MVAP Medical Supplies, Newbury Park, CA], two Bortec AMT-8 amplifiers (Bortec Biomedical Ltd., Canada), and a 16-bit data acquisition system (NI USB-6363, National Instrumentation, Austin, TX). The amplifiers (gain = 3000) had an internal bandpass filter set at 10-1000 Hz. To record finger extension and flexion, EMG was collected from the Abductor Pollicis Brevis (APB - thumb), Extensor Digitorium Communis (ED2-index, ED3- middle, ED4- ring), Extensor Digiti Minimi (EDM - little), and Flexor Digitorum Superficialis (F2/3- index/middle, F4-ring, F5-little) muscles using protocol established in the literature for evaluating individuated finger movements (Leijnse, Campbell-Kyureghyan, Spektor, & Quesada, 2008). To monitor startle, the right and left Sternocleidomastoid (RSCM, LSCM) muscles were recorded. Ground electrodes were placed over the right radial and ulnar styloid process. In addition to EMG, the keystroke was monitored using the change in voltage from the instrumented keyboard (Fig 1).

Task. At the beginning of each trial, the subject positioned their right hand on the home keys of the keyboard (i,j,k,l,;) with their wrist resting on the desk to minimize fatigue. Subjects were instructed to perform an individuated keystroke, of a specified key, following a series of auditory tones. The first tone, a soft acoustic stimulus of 80-dB, informed the subject to start planning the task (‘GET READY’). Between 2.5-3.5 seconds later, the subject was provided with a ‘GO’ cue of either a soft, 80-dB (66% of the time) or a randomized loud, 115-dB (33% of the time) acoustic stimulus. Each subject completed a total of 225 trials which were evenly distributed among the five keys. The order of keys was randomized into blocks of 15 trials during which the subject pressed a single key. To compare SEM to the classic startle response, the GET READY cue was substituted with the 115 dB GO cue for 5 trials (i.e. one for each key), while subjects were not in an active state of planning.

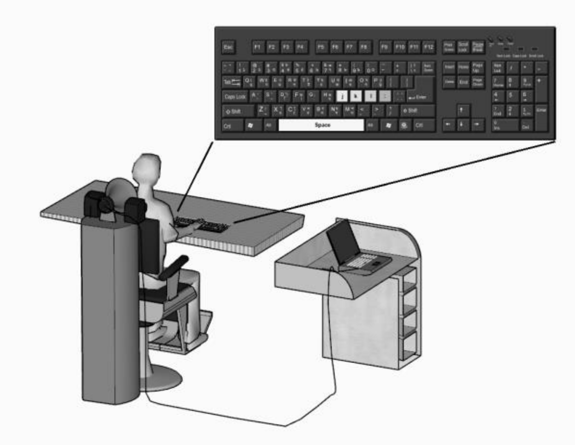

Figure 1. Experimental set-up.

Data processing. EMG data were rectified and smoothed in Matlab (R2017b) using a 10-point moving average. Muscle latency was automatically selected using a custom Matlab script that selected the first instance the signal achieved greater than three times the standard deviation of the background activity. Background activity was defined as the average of a 500 ms period prior to the GO cue. This selected onset was then visually inspected by a researcher blinded to all independent variables. Trials in which the user failed to press the key, pressed multiple keys, or pressed the key too late (i.e. EMG latency > 300ms, keystroke latency > 350ms) were eliminated from analysis (4.01% of trials). Additionally, one subject was eliminated from analysis as 63% of their trials had keystroke onsets later than 350ms.

SCM muscle activity was monitored to determine when a startle was present. Trials with activity in the SCM muscle prior to 120ms (Carlsen, Maslovat, Lam, Chua, & Franks, 2011) were designated Startle+ and those without activity or activity after 120ms were designated Startle-. SEM has occurred when the presence of startle influences movement onset latency. Specifically, if Startle+ trials have faster onset latencies than Startle- trials, SEM is present. If Startle+ trials do not differ from Startle- trials, the presence of startle does not influence the movement. Each key needed to have at least one Startle+ and one Startle- trial to be considered for analysis.

Statistical analysis. It was hypothesized that SEM would be present in expert typists but not in non-experts. To test this, Startle+ and Startle- onset latencies were compared using R statistical software (v3.4.2). A generalized linear mixed effects model (GLMM) that did not assume equal variance (Cohen, 1988) was utilized. Condition (Startle+ or Startle-) was the independent variable, and onset latencies (EMG and keyboard) were the dependent variables. Finally, subject was treated as a random factor. A confidence interval of 95% was used to classify statistical significance. To test for differences in the probability of startle (Count of Startle+ Trials / Count of Startle+ and Startle- Trials), a GLMM assuming equal variances, with population (expert and non-expert) and finger as independent variables was executed. All data in the results section is presented with marginalized means and standard errors.

CHAPTER 3

RESULTS

Startle influences onset latency in experts but not in non-experts (Fig 2, sample data - ring finger). Both the extensor (ED4) and flexor (F4) muscles have faster onsets in Startle+ trials (Fig 2, black) compared to Startle- trials (grey) resulting in a faster keystroke depression. Conversely in non-experts, Startle+ and Startle- trials show similar onset latencies in both extensor and flexor muscles as well as keystroke. These results suggest that the presence of startle influences typing movements in experts but not non-experts.

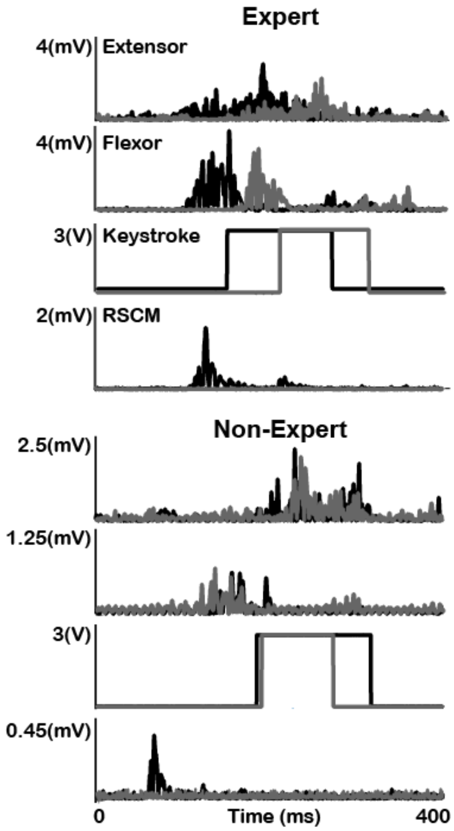

Figure 2. Sample data from the expert and non-expert populations**.** EMG and keystroke data for sample Startle+(black) and Startle-(gray) trials (ring finger) for an expert(top) and non-expert(bottom) typist. Earlier activation of the Startle+ trial indicates a SEM response (top).

Group results confirm that the presence of startle influences typing movements in experts (except in the middle finger) indicating that SEM is present in this population (Fig 3). In experts, the onset latency of Startle+ trials was faster than Startle- trials in the thumb (APB: Δ = 9.11, P = 0.041, *Keystroke*: Δ = 13.98, P = 0.0004), index finger (*ED2*: Δ =14.01, P = 0.016; *F2*: Δ = 10.46, P = 0.013; *Keystroke*: Δ =11.86, P = 0.004), ring finger (*ED4*: Δ = 30.66, P = 0.005; *F4*: Δ = 17.62, P = 0.0047; *Keystroke*: Δ =19.61, P = 0.011), and the little finger (*EDM*: Δ = 21.02, P = 0.002; *F5*: Δ = 18.06, P = 0.0034; *Keystroke*: Δ = 16.39, P = 0.0007). However, Startle+ and Startle- onset latencies were not different in the middle finger (*ED3*: Δ = -2.34, P = 0.97; *F3*: Δ = 1.55, P = 0.79 *Keystroke*: Δ = 0.79, P = 0.63).

While startle influenced most fingers in experts, startle only influenced onset latencies of the little finger (and not robustly) in non-experts (Fig 3). Onset latencies of Startle+ trials were not different from Startle- trials in the thumb (*APB*: Δ = -0.13, P = 0.42; *Keystroke*: Δ = 9.99, P = 0.094), index (*ED2*: Δ = 10.30, P = 0.295; *F2*: Δ = 3.58, P = 0.204; *Keystroke*: Δ = 7.40, P = 0.30), middle (*ED3*: Δ = 10.61, P = 0.26; *F3*: Δ = 5.39, P = 0.24; *Keystroke*: Δ = 4.28, P = 0.43), and ring (*ED4*: Δ = -3.06, P = 0.46; *F4*: Δ = -2.00, P = 0.32; *Keystroke*: Δ = -5.37, P = 0.10). Startle+ and Startle- onset latencies were different for the little finger in the keystroke (Δ = 12.94, P = 0.03), but did not reach significance in the muscle responses (EDM: Δ = 15.75, P = 0.07; *F5*: Δ = 12.55, P = 0.23) indicating that SEM is present but not as robustly as experts.

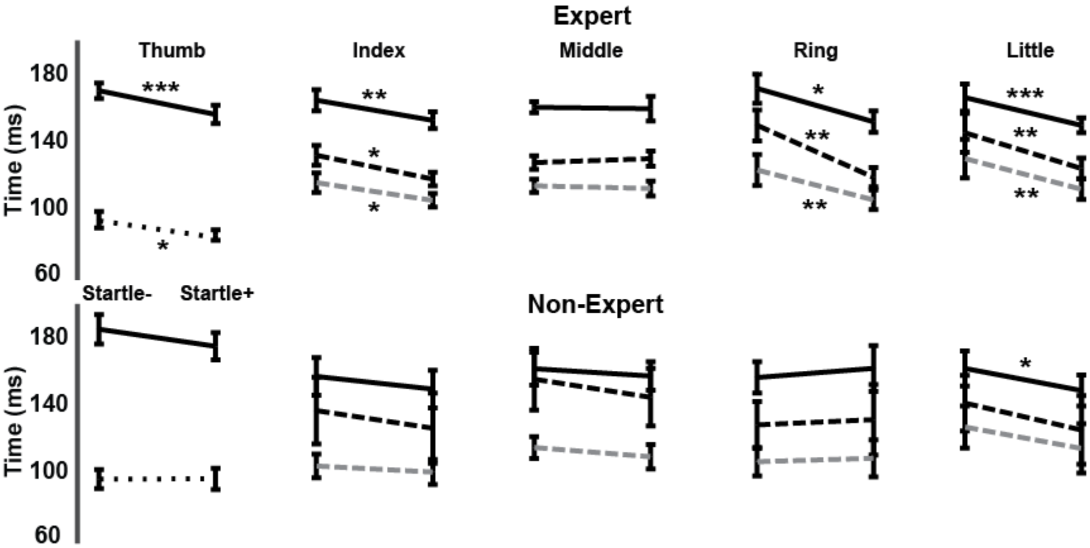

Figure 3. Startle+ and Startle- trials are compared between experts and non-experts. Onset Latency of the keystroke (solid black) as well as extensor (dashed black) and flexor (dashed gray) muscles in experts (top) and non-experts (bottom) are displayed for Startle+(right) and Startle-(left) trials. Stars represent a difference between Startle+ and Startle- (* = P < 0.05, ** = P < 0.01, and *** P< 0.001) indicating that the movement was susceptible to SEM.

Differences associated with startle between experts and non-experts were not the result of differences in the probability of startle. The probability of evoking startle was not statistically between populations ($F_{1,75} = 0.01$, $P = 0.92$) or between fingers ($F_{4,75} = 0.44$, $P = 0.78$). Additionally, there was no difference in interaction between fingers and population ($F_{4,75} = 0.13$, $P = 0.97$). The probability of startle for the expert and non-expert populations, when averaged between fingers, were 34.97 ± 4.93% and 36.62 ± 4.65% respectively. Finally, SEM distinguishes itself from the classic startle response. Of the 89 classic startle trials presented, only 9 exhibited a Startle+ response in the SCM muscle. Of those trials none exhibited movements that resembled SEM or startle (keystroke latencies < 170ms) in the monitored muscles of the distal limb.

CHAPTER 4

DISCUSSION

Summary. The objective of this study was to determine if SEM was sensitive enough to differentiate task expertise during a common everyday task – typing. It was hypothesized that SEM would be observed for all fingers of the expert population and none for the non-expert population. Indeed, it was found that SEM was robustly present in all fingers of experts (except the middle) and absent in all fingers of non-experts (except the little – though not robustly present). Taken together, these results indicate that SEM is a measurable behavior indicator of motor learning that is sensitive to task expertise. Further, while some have suggested that individuated finger movements were not susceptible to SEM, this work indicates that SEM is present during sophisticated and individuated movements of the hands provided that they are routinely performed. This provides the framework for future studies to analyze SEMs validity as a cost-effective, quick, and easily obtained measure for determining a performance plateau through training. This may prove to be useful during rehabilitation as it can be easily incorporated into current rehabilitative regimes, and may even be useful for time-stamping when the sufficient dosage of motor training has been delivered following impairment.

What is unique about the middle finger? An interesting, and initially surprising result, was the absence of SEM in the middle finger of experts. While SEM is robustly present across all other fingers in experts, the middle finger showed no evidence. This absence of SEM may correspond to its individuation relative to other digits. Specifically, the middle and ring fingers of the hand have the least individuation. There are 36 muscles used for manipulation of the thumb and fingers (5 digits), all of which act synergistically (Santello, Baud-Bovy, & Jörntell, 2013) in coordinated neuromuscular patterns (Schieber & Santello, 2004). This synergistic activation leads to a coupling of fingers when trying to perform individuated movements (Fish & Soechting, 1992; Hager-Ross & Schieber, 2000). For example, when attempting to flex a single finger, without movement of the others, movement of the adjacent fingers can be easily observed. The thumb and index finger have the greatest amount of individuation while the middle and ring have the lowest (Hager-Ross & Schieber, 2000).

The middle finger's low degree of independence during individuated typing movements may explain its lack of susceptibility to SEM. In right handed subjects, the magnitude of independence of the fingers does not differ between hands (Hager-Ross & Schieber, 2000). In other words, the neural control of the dominant hand ('trained') does not differ enough from that of the non-dominant hand ('less trained') to alter independence of the fingers. Therefore, one could infer that the lower degree of individuation for the middle and ring fingers is likely due to overall differences in neural control, and/or differences in the biomechanical interconnections (muscles and tendons) used for movement of these fingers (Hager-Ross & Schieber, 2000). Further, this lesser degree of individualization could lead one to believe that movements of the middle finger may utilize a more complex neuromuscular strategy, thereby leading to a lesser, or lack of, susceptibility to SEM. Unfortunately, this theory alone does not explain the robust SEM observed for the expert ring finger, however, the ring finger's overlapping neural correlates with the little finger may explain this anomaly (Hager-Ross & Schieber, 2000). Specifically, the little finger has demonstrated robust SEM in experts – and even SEM in non-experts (although less robust). Therefore, the neuromuscular control of the little finger may also correspond to movement of the ring finger, potentially explaining the ring finger’s susceptibility to SEM.

Current challenges with motor learning quantification and the utility of SEM. The analysis of motor learning, a process in which an individual improves at a task both spatially and temporally (Willingham, 1998), can provide researchers and clinicians alike with valuable feedback about rehabilitative effectiveness. A simple example of the motor learning process is the transition from a novice to an expert typist. As one trains, it no longer becomes difficult to type new and unique sentences with a high level of performance – measured by increased speed and decreased error (Chapman, 1919; Hill, 1934; Hill, Rejall, & Thorndike, 1913). However, it is often difficult to determine when the effects of motor learning reach plateau (i.e. when a task has been fully solidified through training) - a parameter which may be of interest to clinicians for determining when the proper dosage of task-specific training has been delivered to their patients. Specifically, this parameter (rehabilitative plateau) is important as patients are known to benefit from increasing the dosage of motor training - for a review see (Lang, Lohse, & Birkenmeier, 2015). Still, determining when rehabilitation training has reached its plateau remains unclear, with no established (adequate) method to quantify when to halt therapy.

One confounding factor is that people learn at different rates. For example, multiple groups have successfully quantified improvements in typing speed over time (Chapman, 1919; Hill, 1934; Hill et al., 1913), however a variety of learning curves, characterized by speed and accuracy, were observed (Chapman, 1919). Indeed, many individuals do not reach a plateau in performance after a substantial 180 hours of training (Chapman, 1919). Despite these difficulties, previous studies have tried to adequately quantify motor learning using characteristics such as: neurological changes in gray (Cannonieri, Bonilha, Fernandes, Cendes, & Li, 2007; Draganski et al., 2004; Driemeyer, Boyke, Gaser, Buchel, & May, 2008; Gaser & Schlaug, 2003) and white matter (Scholz, Klein, Behrens, & Johansen-berg, 2010; Taubert et al., 2010) regions of the brain, long-term task retention (Hill, 1934; Park, Dijkstra, & Sternad, 2013; Swift, 1905), and behavioral improvements in task performance. Unfortunately, these methods tend to be too expensive (neural imaging), too time consuming (long term-retention studies), and/or do not provide enough evidence that the task has been fully solidified (behavioral characteristics – further discussed below) to be effectively utilized in the clinic. Interestingly, behavioral improvements are commonly used to quantify rehabilitative success as they are easy to implement in the clinic, although they cannot easily determine when improvements have plateaued (Boissy, Bourbonnais, Carlotti, Gravel, & Arsenault, 1999; Lin et al., 2009). Specifically, measures such as grip strength, which are commonly used to quantify improvement during rehabilitation, (Sunderland, Tinson, Bradley, & Hewer, 1989) and have demonstrated a positive correlation with upper extremity function in chronic stroke survivors (Fugl-Meyer, upper extremity performance test for the elderly – TEMPA, etc.) (Boissy et al., 1999), do not necessarily correspond to a task specific plateau, rather to more generalize functional improvement. Additionally, when using clinical metrics such as the Action Research Arm Test to determine generalized functional improvements, a ceiling effect is often encountered (Lin et al., 2009) before the individual has reached a high level of expertise. These limitations for determining the time point in which the maximum benefits of task-specific training occur, demonstrate the occasional need for more complex metrics, such as the speed accuracy trade-off function (Fitts, 1954). Although these metrics provide useful information about a person’s overall level of functioning, they do not always provide the information needed to assess internalized motor learning without pairing them with neural imaging or long-term task retention. Due to these limitations in current measures of motor learning, new methods that can be easily and quickly implemented (like behavioral measures), but provide concrete detail about motor learning (like neural imaging), are critical for researchers and clinicians alike.

Recently, studies have started to fill this void by using the simple reaction time (RT) paradigm; however, these studies do not predict when a learning plateau occurs. More specifically, these studies are commonly focused on generalized changes in motor planning for tasks of varying complexity, (Eriksen, Pollack, & Montague, 1970; Henry & Rogers, 1960; Klapp, 1971, 1995, 2003; Klapp, Anderson, & Berrian, 1973; Sternberg, Monsell, Knoll, & Wright, 1978) rather than distinguishing overall expertise or a plateau in RT. Although these studies have provided insight into how individuals plan for task execution (motor drum theory – Henry and Rogers; motor chunking – Klapp), a more encouraging, and recent method for determining rehabilitative plateau is the pairing of simple RT with startle (SEM paradigm).

SEMs can store and release functionally improved motor programs through training (Maslovat et al., 2009, 2008). This opens this experimental paradigm for use in testing the quality of motor planning through training - a character which is necessary for analysis of rehabilitative plateaus in the clinic. Specifically, Maslovat et. al. demonstrated shortened RTs in startle trials after training, relative to startle trials before training (Maslovat et al., 2012, 2011), but more importantly, improvements in the functional movement were maintained (Maslovat et al., 2009, 2008). As one trains and improves (increased endpoint accuracy and movement time) in a complex asymmetrical bimanual task, both voluntary and startle trials demonstrate the improvements (Maslovat et al., 2008). Additionally, with training of asynchronous bimanual movements, where the subject was informed to move one arm 100 ms earlier than the other, subjects were able to improve their goal in both startle and voluntary trials (Maslovat et al., 2009). This further demonstrates that SEMs are internalized functional motor programs as they maintain the behavioral improvements which occur through training. All together, these studies demonstrate that SEM may be a useful tool for analyzing the quality of motor learning, however have not yet demonstrated SEMs ability to distinguish differences in expertise, or more importantly, to determine a plateau in recovery.

Recently, Kirkpatrick et. al demonstrated that index finger abduction, a task which is not inherently susceptible to SEM (Carlsen et al., 2008; Honeycutt et al., 2013), is susceptible, but only following a 10-day training paradigm (Kirkpatrick & Honeycutt, 2015). This introduced the idea that SEM may be able to distinguish differences in motor planning through training, however it was still uncertain as to how this translates to a task that is more commonly executed in day-to-day life. This was expanded upon here by demonstrating that SEM is a sensitive enough tool for differentiating motor learning between populations (Fig. 3), or in other words, long-term task solidification (expertise) in a common everyday task - typing. With this knowledge, SEM can be utilized by many different groups, such as those testing a new rehabilitative strategy or those drawing general inferences about motor learning. Additionally, because the SEM paradigm is cost-effective, easily implemented, and non-invasive, it is a promising tool for clinical implementation. Specifically, future studies can look at the ability for SEM to time-stamp when a rehabilitative plateau has occurred, or more specifically, when SEM is observed on a motor learning curve. With this knowledge, SEM could then be used to quantify when the proper dosage of task specific training has been delivered to a patient.

Clinical relevance. Previously, it has been stated that individuated finger movements are not susceptible to SEM (Carlsen et al., 2008; Honeycutt et al., 2013). It has been suggested that this was due to differences in neural structures utilized to perform tasks at the distal limb; however, this work suggests that the lack of SEM in index finger abduction is related to task expertise. Therefore, all movements, even dexterous movements of the hand, may prove to be susceptible to SEM given that the motor plan necessary to complete the movement has been fully internalized. Interestingly, impaired movements have shown to be facilitated by startle, opening the possibility for SEM as a rehabilitative technique.

Over the past decade, SEM has shown utility in a variety of patient populations including stroke, Parkinson’s Disease (PD), spinal cord injury (SCI), Cervical Dystonia, and Hereditary Spastic Paraplegia (HSP). Specifically, starting in 2012, Honeycutt et. al demonstrated that stroke survivors, who had initially later RTs than an unimpaired control group (ballistic elbow flexion/extension), were able to move with EMG onset latencies resembling the unimpaired population through SEM (Honeycutt & Perreault, 2012, 2014). Interestingly, the overall functional movement (movement onset and movement accuracy) of stroke survivors (hand, elbow, and shoulder) has shown to be facilitated by SEM (Honeycutt & Perreault, 2012, 2014; Marinovic et al., 2016; Rahimi & Honeycutt, 2017) demonstrating its potential utility as a rehabilitative technique. To expand upon this, SEM has now been tested across various populations and movements: ankle dorsiflexion and wrist flexion were susceptible to SEM in those with HSP (Nonnekes, Oude Nijhuis, et al., 2014), power grips in those with SCI (Baker & Perez, 2017), and neck rotations in those with Cervical Dystonia (Serranová et al., 2012). Additionally, SEM has been able to differentiate those with freezing of gait from those with postural instability in PD (Nonnekes, Geurts, et al., 2014; Nonnekes et al., 2015), demonstrating the wide-ranging possibilities for utility of SEMs in patient populations.

Until recently (Kirkpatrick & Honeycutt, 2015; Quezada Valladares, 2017), movements of the fingers have been thought to lack SEM susceptibility (Carlsen et al., 2008; Honeycutt et al., 2013). It was demonstrated here that individuated finger movements are susceptible to SEM so long as they have been trained, opening SEM to therapy of a wider variety of movements.

Finally, it was demonstrated that SEM can identify overall task solidification as it is sensitive enough to distinguish expert typists from non-experts. When pairing this knowledge with the work by Kirkpatrick et. al – SEM can distinguish changes in motor planning through training – and the work by Maslovat et. al – SEMs are the storage of sophisticated motor plans that maintain functional improvements that occur with training – it is suggested that SEM is a tool that can assess the effectiveness of rehabilitation and task specific movement training. Specifically, it can be used to determine when a task has been solidified and possibly, in the future, when a rehabilitative plateau has likely been achieved.

Neural structures involved with motor learning. Task solidification and motor learning involves multiple layers of the nervous system. Multiple studies have analyzed neural differences following training (juggling and typing) and have found changes in gray (Cannonieri et al., 2007; Draganski et al., 2004; Driemeyer et al., 2008) and white (Scholz et al., 2010; Taubert et al., 2010) matter regions of the brain. Additionally, other studies have analyzed neurological differences between expert and non-expert musicians (musical keyboard) (Gaser & Schlaug, 2003; Hutchinson, Lee, Gaab, & Schlaug, 2018; Lee, Chen, & Schlaug, 2003; Schlaug, Jäncke, Huang, Staiger, & Steinmetz, 1995; Schmithorst & Wilke, 2002) and have also found differences associated with expertise in cortical regions (Gaser & Schlaug, 2003), subcortical regions (Lee et al., 2003; Schlaug et al., 1995; Schmithorst & Wilke, 2002), and cerebellar regions (Hutchinson et al., 2018; Schmithorst & Wilke, 2002) of the brain, suggesting that the cortex and the sub-cortex are likely both involved with motor learning.

Interestingly, classic startle is known to be mediated by the brainstem, while utilizing the reticulospinal tract for its reflexive and defensive response (Landis & Hunt, 1939). Thereby, it has been suggested that SEM is driven through the same pathways as classic startle (Valls-Solé, Rothwell, Goulart, Cossu, & Muñoz, 1999), however, brainstem involvement during human motor planning/learning has been greatly understudied. Therefore, the validity of this hypothesis, that SEM is driven by the brainstem, (Valls-Solé et al., 1999) remains unclear. More specifically, some suggest that

SEM is driven by the reticulospinal tract, through the brainstem (Carlsen, 2002; Carlsen, Chua, Inglis, Sanderson, & Franks, 2004a; Carlsen et al., 2004b; Nonnekes, Oude Nijhuis, et al., 2014; Valls-Solé et al., 1999), while others suggest that SEM is driven by the cortex (Alibiglou & MacKinnon, 2012; Marinovic, Tresilian, de Rugy, Sidhu, & Riek, 2014; Stevenson et al., 2014), but may be mediated through pathways arising from subcortical regions allowing for the shortened RT. Although this study does not solve the ongoing debate, it suggests that the neurological changes, which occur through training, interact with or overlap with those involved during SEM. Therefore, in the future, SEM will likely prove to be a useful tool for analyzing neurological changes that occur through training.

REFERENCES

Alibiglou, L., & MacKinnon, C. D. (2012). The early release of planned movement by acoustic startle can be delayed by transcranial magnetic stimulation over the motor cortex. *The Journal of Physiology*, *590*(4), 919–936. https://doi.org/10.1113/jphysiol.2011.219592

Baker, S. N., & Perez, M. A. (2017). Reticulospinal Contributions to Gross Hand Function after Human Spinal Cord Injury. *The Journal of Neuroscience*, *37*(40), 3368–16. https://doi.org/10.1523/JNEUROSCI.3368-16.2017

Boissy, P., Bourbonnais, D., Carlotti, M. M., Gravel, D., & Arsenault, B. A. (1999). Maximal grip force in chronic stroke subjects and its relationship to global upper extremity function. *Clinical Rehabilitation*, *13*(4), 354–362. https://doi.org/10.1191/026921599676433080

Cannonieri, G. C., Bonilha, L., Fernandes, P. T., Cendes, F., & Li, L. M. (2007). Practice and perfect: Length of training and structural brain changes in experienced typists. *NeuroReport*, *18*(10), 1063–1066. https://doi.org/10.1097/WNR.0b013e3281a030e5

Carlsen, A. N. (2002). Altered Triggering of a Prepared Movement by a Startling Stimulus. *Journal of Neurophysiology*, *89*(4), 1857–1863. https://doi.org/10.1152/jn.00852.2002

Carlsen, A. N., Chua, R., Inglis, J. T., Sanderson, D. J., & Franks, I. M. (2004a). Can prepared responses be stored subcortically? *Experimental Brain Research*, *159*(3), 301–309. https://doi.org/10.1007/s00221-004-1924-z

Carlsen, A. N., Chua, R., Inglis, J. T., Sanderson, D. J., & Franks, I. M. (2004b). Prepared Movements are Elicited Early by Startle. *Journal of Motor Behavior*, *36*(3), 253–264.

Carlsen, A. N., Chua, R., Inglis, J. T., Sanderson, D. J., & Franks, I. M. (2008). Differential Effects of Startle on Reaction Time for Finger and Arm Movements. *Journal of Neurophysiology*, *101*(1), 306–314. https://doi.org/10.1152/jn.00878.2007

Carlsen, A. N., Maslovat, D., Lam, M. Y., Chua, R., & Franks, I. M. (2011). Considerations for the use of a startling acoustic stimulus in studies of motor preparation in humans. *Neuroscience and Biobehavioral Reviews*, *35*(3), 366–376. https://doi.org/10.1016/j.neubiorev.2010.04.009

Castellote, J. M., & Valls-solé, J. (2015). Clinical Neurophysiology The StartReact effect in tasks requiring end-point accuracy. *Clinical Neurophysiology*, *126*(10), 1879–1885. https://doi.org/10.1016/j.clinph.2015.01.028

Chapman, J. C. (1919). The learning curve in typewriting. *Journal of Applied Psychology*, *3*(3), 252–268.

Cohen, J. (1988). *Statistical Power Analysis for the Behavioral Sciences*.

Cressman, E. K., Carlsen, A. N., Chua, R., & Franks, I. M. (2006). Temporal uncertainty does not affect response latencies of movements produced during startle reactions. *Experimental Brain Research*, *171*(2), 278–282. https://doi.org/10.1007/s00221-006-0459-x

Draganski, B., Gaser, C., Busch, V., Schuierer, G., Bogdahn, U., & May, A. (2004). Changes in grey matter induced by training Newly honed juggling skills show up as a transient feature on a brain-imaging scan . *Nature*, *427*, 311–312.

Driemeyer, J., Boyke, J., Gaser, C., Buchel, C., & May, A. (2008). Changes in Gray Matter Induced by Learning — Revisited, *3*(7), 1–5. https://doi.org/10.1371/Citation

Eriksen, C. W., Pollack, M. D., & Montague, W. E. (1970). Implicit speech: Mechanism in perceptual encoding? *Journal of Experimental Psychology*, *84*(3), 502–507. https://doi.org/10.1037/h0029274

Fernandez-Del-Olmo, M., Bello, O., Lopez-Alonso, V., Marquez, G., Sanchez, J. A., Morenilla, L., & Valls-Solé, J. (2013). The effects of startle and non-startle auditory stimuli on wrist flexion movement in Parkinson’s disease. *Neuroscience Letters*, *548*, 56–60. https://doi.org/10.1016/j.neulet.2013.05.069

Fish, J., & Soechting, J. (1992). Synergistic finger movements in a skilled motor task. *Experimental Brain Research*, *91*(2), 327–334.

Fitts, M. (1954). The Information Capacity of the Human Motor System in Controlling the Amplitude of Movements. *Journal of Experimental Psychology*, *47*(3), 381–391.

Gaser, C., & Schlaug, G. (2003). Brain structures differ between musicians and non-musicians. *The Journal of Neuroscience*, *23*(27), 9240–9245. https://doi.org/23/27/9240 [pii]

Hager-Ross, C., & Schieber, M. H. (2000). Quantifying the Independence of Human Finger Movements: Comparisons of Digits, Hands, and Movement Frequencies. *J. Neurosci.*, *20*(22), 8542–8550. https://doi.org/20/22/8542 [pii]\par

Henry, F. ., & Rogers, D. . (1960). Increased response latency for complicated movements and a “memory drum” thory of neuromotor reaction. *Research Quarterly*, *31*, 448–458.

Hill, L. B. (1934). A Quarter Century of Delayed Recall. *The Journal of Genetic Psychology*, *44*, 231–238.

Hill, L. B., Rejall, A. E., & Thorndike, E. . (1913). Practice in the case of typewriting. *The Journal of Genetic Psychology*, *20*(4), 516–529.

Honeycutt, C. F., Kharouta, M., & Perreault, E. J. (2013). Evidence for reticulospinal contributions to coordinated finger movements in humans. *Journal of Neurophysiology*, *110*(7), 1476–1483. https://doi.org/10.1152/jn.00866.2012

Honeycutt, C. F., & Perreault, E. J. (2012). Planning of Ballistic Movement following Stroke: Insights from the Startle Reflex. *PLoS ONE, 7*(8). https://doi.org/10.1371/journal.pone.0043097

Honeycutt, C. F., & Perreault, E. J. (2014). Deficits in startle-evoked arm movements increase with impairment following stroke. *Clinical Neurophysiology*, *125*(8), 1682–1688. https://doi.org/10.1002/nbm.3066.Non-invasive

Honeycutt, C. F., Tresch, U. A., & Perreault, E. J. (2016). Startling acoustic stimuli can evoke fast hand extension movements in stroke survivors. *Clinical Neurophysiology, 126*(1), 160–164. https://doi.org/10.1016/j.clinph.2014.05.025.Startling

Hutchinson, S., Lee, L. H., Gaab, N., & Schlaug, G. (2018). Cerebellar Volume in Musicians, *i*(February), 1–27.

Kirkpatrick, N., & Honeycutt, C. F. (2015). *Evidence for a transition in usage of cortical and subcortical structures during the learning process of human hand movement. Society for Neuroscience*.

Klapp, S. T. (1971). Implicit speech inferred from response latencies in same-different decisions. *Journal of Experimental Psychology*, *91*(2), 262–267. https://doi.org/10.1037/h0031852

Klapp, S. T. (1995). Motor response programming during simple choice reaction time: The role of practice. *Journal of Experimental Psychology: Human Perception and Performance*, *21*(5), 1015–1027. https://doi.org/10.1037/0096-1523.21.5.1015

Klapp, S. T. (2003). Reaction time analysis of two types of motor preperation for speech articulation: Action as a sequence of chunks. *Journal of M*, *35*(2), 135–150. https://doi.org/10.1177/017084068800900203

Klapp, S. T., Anderson, W. G., & Berrian, R. W. (1973). Implicit Speech in Reading, Reconsidered. *Journal of Experimental Psychology*, *100*(2), 368–374.

Landis, C., & Hunt, W. A. (1939). *The Startle Pattern*. *Farrar & Rinehart*. New York, NY: Farrar & Rinehart. Retrieved from http://scholar.google.de/scholar?hl=de&q=Landis+C%2C+Hunt+WA.+The+startle+pattern.+New+York%3A+Farrar+and+Rinehart+Inc%3B+1939.&btnG=&lr=#2

Lang, C. E., Lohse, K. R., & Birkenmeier, R. L. (2015). Dose and timing in neurorehabilitation: Prescribing motor therapy after stroke. *Current Opinion in Neurology*, *28*(6), 549–555. https://doi.org/10.1097/WCO.0000000000000256.Dose

Lee, D. J., Chen, Y., & Schlaug, G. (2003). Corpus callosum : musician and gender effects. *Group*, *14*(2), 205–209. https://doi.org/10.1097/01.wnr.0000053761.76853.41

Leijnse, J. N. A. L., Campbell-Kyureghyan, N. H., Spektor, D., & Quesada, P. M. (2008). Assessment of Individual Finger Muscle Activity in the Extensor Digitorum Communis by Surface EMG. *Journal of Neurophysiology*, *100*(6), 3225–3235. https://doi.org/10.1152/jn.90570.2008

Lin, J., Hsu, M., Sheu, C., Wu, T., Lin, R., Chen, C., & Hsieh, C. (2009). Psychometric Comparisons of 4 Measures for Assessing. *American Physical Therapy Association*, *89*, 840–850.

Marinovic, W., Brauer, S. G., Hayward, K. S., Carroll, T. J., & Riek, S. (2016). Electric and acoustic stimulation during movement preparation can facilitate movement execution in healthy participants and stroke survivors. *Neuroscience Letters*, *618*, 134–138. https://doi.org/10.1016/j.neulet.2016.03.009

Marinovic, W., & Tresilian, J. R. (2016). Triggering prepared actions by sudden sounds: Reassessing the evidence for a single mechanism. *Acta Physiologica*, *217*(1), 13–32. https://doi.org/10.1111/apha.12627

Marinovic, W., Tresilian, J. R., de Rugy, A., Sidhu, S., & Riek, S. (2014). Corticospinal modulation induced by sounds depends on action preparedness. *Journal of Physiology*, *592*(1), 153–169. https://doi.org/10.1113/jphysiol.2013.254581

Maslovat, D., Carlsen, A. N., Chua, R., & Franks, I. M. (2009). Response preparation changes during practice of an asynchronous bimanual movement. *Experimental Brain Research*, *195*, 383–392. https://doi.org/10.1007/s00221-009-1801-x

Maslovat, D., Carlsen, A. N., & Franks, I. M. (2012). Subcortical motor circuit excitability during simple and choice reaction time. *Behavioral Neuroscience*, *126*(3), 499–503. https://doi.org/10.1037/a0028285

Maslovat, D., Carlsen, A. N., Ishimoto, R., Chua, R., & Franks, I. M. (2008). Response preparation changes following practice of an asymmetrical bimanual movement. *Experimental Brain Research*, *190*, 239–249. https://doi.org/10.1007/s00221-009-1801-x

Maslovat, D., Hodges, N. J., Chua, R., & Franks, I. M. (2011). Motor preparation and the effects of practice: evidence from startle. *Behavioral Neuroscience*, *125*(2), 226–240.

Maslovat, D., Klapp, S. T., Jagacinski, R. J., & Franks, I. M. (2014). Control of Response Timing Occurs During the Simple Reaction Time Interval but On-Line for Choice Reaction Time. *Journal of Experimental Psychology*, *40*(5), 2005–2021.

Nonnekes, J., Geurts, A. C. H., & Oude, L. B. (2014). Reduced StartReact effect and freezing of gait in Parkinson's disease : two of a kind ?, 943–950. https://doi.org/10.1007/s00415-014-7304-0

Nonnekes, J., Kam, D. De, Nijhuis, L. B. O., & Geel, K. Van. (2015). StartReact Effects Support Different Pathophysiological Mechanisms Underlying Freezing of Gait and Postural Instability in Parkinson ' s Disease, 1–17. https://doi.org/10.1371/journal.pone.0122064

Nonnekes, J., Oude Nijhuis, L. B., de Niet, M., de Bot, S. T., Pasman, J. W., van de Warrenburg, B. P. C., … Geurts, A. C. H. (2014). StartReact Restores Reaction Time in HSP: Evidence for Subcortical Release of a Motor Program. *Journal of Neuroscience*, *34*(1), 275–281. https://doi.org/10.1523/JNEUROSCI.2948-13.2014

Ossanna, M. (2017). *Startle-evoked movement in multi-jointed, two-dimensional reaching tasks*. *Harrington Bioengineering Program, & Barrett, The Honors College.* https://doi.org/10.1038/bjc.2016.418

Park, S.-W., Dijkstra, T. M. H., & Sternad, D. (2013). Learning to never forget—time scales and specificity of long-term memory of a motor skill. *Frontiers in Computational Neuroscience*, *7*(September), 1–13. https://doi.org/10.3389/fncom.2013.00111

Quezada Valladares, M. J. (2017). *Startle can evoke individuated movements of the fingers ; implications for neural control María José Quezada Valladares*. *Harrington Bioengineering Program, & Barrett, The Honors College.*

Rahimi, M., & Honeycutt, C. F. (2017). Does startle enhance unrestricted, 2D reaching movement in stroke survivors? Society for Neuroscience Abstract.

Santello, M., Baud-Bovy, G., & Jörntell, H. (2013). Neural bases of hand synergies. *Frontiers in Computational Neuroscience*, *7*(April), 1–15. https://doi.org/10.3389/fncom.2013.00023

Schieber, M. H., & Santello, M. (2004). Neural Control of Movement Hand function : peripheral and central constraints on performance, 2293–2300. https://doi.org/10.1152/japplphysiol.01063.2003

Schlaug, G., Jäncke, L., Huang, Y., Staiger, J. F., & Steinmetz, H. (1995). Increased corpus callosum size in musicians. *Neuropsychologia*, *33*(8), 1047–1055. https://doi.org/10.1016/0028-3932(95)00045-5

Schmithorst, V. J., & Wilke, M. (2002). Differences in white matter architecture between musicians and non-musicians: A diffusion tensor imaging study. *Neuroscience Letters*, *321*(1–2), 57–60. https://doi.org/10.1016/S0304-3940(02)00054-X

Scholz, J., Klein, M. C., Behrens, T. E. J., & Johansen-berg, H. (2010). Training induces changes in white matter architecture. *Nat Neurosci*, *12*(11), 1370–1371. https://doi.org/10.1038/nn.2412.Training

Serranová, T., Jech, R., Martí, M. J., Modreanu, R., Valldeoriola, F., Sieger, T., … Valls-Solé, J. (2012). A Loud Auditory Stimulus Overcomes Voluntary Movement Limitation in Cervical Dystonia. *PLoS ONE*, *7*(10), 1–9. https://doi.org/10.1371/journal.pone.0046586

Sternberg, S., Monsell, S., Knoll, R. L., & Wright, C. E. (1978). *The latency and duration of rapid movement sequences: Comparisons of speech and typewriting*. *Information Processing in Motor Control Learning* (Vol. 3). ACADEMIC PRESS, INC. https://doi.org/10.1016/B978-0-12-665960-3.50011-6

Stevenson, A. J. T., Chiu, C., Maslovat, D., Chua, R., Gick, B., Blouin, J. S., & Franks, I. M. (2014). Cortical involvement in the StartReact effect. *Neuroscience*, *269*(604), 21–34. https://doi.org/10.1016/j.neuroscience.2014.03.041

Sunderland, A., Tinson, D., Bradley, L., & Hewer, R. L. (1989). Arm function after stroke . An evaluation of grip strength as a measure of recovery and a prognostic indicator. *Journal of Neurology*, *52*, 1267–1272.

Swift, J. E. (1905). Relearning a Skillful Act: An Experimental Study in Neuro-Muscular Memory, *XVI*.

Taubert, M., Draganski, B., Anwander, A., Muller, K., Horstmann, A., Villringer, A., & Ragert, P. (2010). Dynamic Properties of Human Brain Structure: Learning-Related Changes in Cortical Areas and Associated Fiber Connections. *Journal of Neuroscience*, *30*(35), 11670–11677. https://doi.org/10.1523/JNEUROSCI.2567-10.2010

Thevathasan, W., Pogosyan, A., Hyam, J. A., Jenkinson, N., Bogdanovic, M., Coyne, T. J., … Brown, P. (2011). A block to pre-prepared movement in gait freezing, relieved by pedunculopontine nucleus stimulation. *Brain*, *134*, 2085–2095. https://doi.org/10.1093/brain/awr131

Valls-Solé, J., Rothwell, J. C., Goulart, F., Cossu, G., & Muñoz, E. (1999). Patterned ballistic movements triggered by a startle in healthy humans. *Journal of Physiology*, *516*(3), 931–938. https://doi.org/10.1111/j.1469-7793.1999.0931u.x

Willingham, D. (1998). A Neuropsychological Theory of Motor Skill Learning. *Psychological Review*, *105*(3), 558–584. Retrieved from http://psycnet.apa.org/journals/rev/105/3/558.pdf

Wright, Z. A., Carlsen, A. N., & MacKinnon, C. D. (2016). Degraded expression of learned feedforward control in movements released by startle. *Experimental Brain Research*, *233*(8), 2291–2300. https://doi.org/10.1007/s00221-015-4298-5.Degraded