The Crossmodal Congruency Effect, a Tool Incorporation Metric, Suffers from a Learning Effect with Repeated Exposures

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Abstract

The incorporation of a tool into a person's body representation is well established. Quantitative measures play an important role in assessing tool incorporation levels for tool use paradigms. The crossmodal congruency effect (CCE) is used to quantify tool incorporation without being susceptible to experimenter biases. The crossmodal congruency task is a visual-tactile interference task that is used to calculate the CCE score as a difference in response time for incongruent and congruent trials. Here we show that this metric is susceptible to a learning effect that causes attenuation of the CCE score due to repeated task exposure sessions. This study investigated the conditions under which CCE scores attenuated due to task overexposure and tested if a modified version of the crossmodal congruency task could reduce the learning effect. Our work also sought to examine if the attenuated CCE scores returned to baseline values after a period of time. Thirty subjects were tested up to a maximum of ten times and four of these subjects were retested after a four month delay period. We show that CCE score reduced as early as the second exposure with a 14.5% drop between first and second exposures ($p=0.027$). Importantly, we found evidence that a modified version of the crossmodal congruency task, in which each exposure was reduced from eight to four test blocks, reduced the drop between first and second exposure from an average of 14.5% to 6.5% without significantly increasing variability of the measurement. Additionally, we found that three out of four subjects that were retested after a four month period returned to near-baseline CCE scores. This study highlights the importance of limiting exposure to the crossmodal congruency task, and proposes a modified approach to improve the use of this psychophysical assessment in the future.

Introduction

There is an increasing interest concerning the multisensory representation of space in humans due to converging findings from a number of different disciplines. The crossmodal congruency task first introduced by Spence, Pavani, and Driver in 1998 is a visual-tactile interference task that has been successfully used to investigate multisensory representation of space in humans (1) (2). It has been used by researchers in a variety of experimental paradigms. It has been used to investigate deficits in the multisensory representation of space in brain-damaged patients (3). Investigation of crossmodal selective attention has been used to demonstrate the detrimental effects of age on the ability to ignore irrelevant sensory information when attending to relevant sensory information (4). Other studies have investigated changes in the representation of peripersonal space that are elicited by the prolonged use of hand-held tools (5) (6) (7). Further studies used this task to extend findings regarding physical and pointing tools to virtual robotic tools using techniques from haptics and virtual reality (8) (9) (10). Recently it has been used in conjunction with the rubber hand illusion paradigm to investigate realistic rubber hand incorporation into body schema (11). The crossmodal congruency effect (CCE) assessment has become a well-established quantitative metric of tool incorporation that extends to a variety of applications.

Typically, CCE study consists of a participant holding two foam blocks in either hand with vibrotactile targets and visual distractors embedded in the top and bottom of each foam block. A trial consists of a random and independent presentation of a single vibrotactile target paired with a single visual distractor from any of the four possible pairs of locations. Participants are instructed to make a speeded response regarding the elevation of the vibrotactile target (i.e. “up”, at the index finger verses “down”, at the thumb), while simultaneously ignoring visual distractors (2). Participants are typically slower at discriminating the elevation of vibrotactile targets when visual distractors are presented from an incongruent elevation (i.e. when vibrotactile target and visual distractors are presented from different elevations) as compared to a congruent elevation. The CCE score is calculated as a difference in the reaction time for congruent and incongruent trials and is used as a quantitative performance metric for multisensory representation of space. It has been demonstrated that CCE scores are typically higher when the spatial separation between visual distractor and vibrotactile targets is low (e.g. both locations on same block) compared to greater separation (e.g. locations on two different blocks held in different hands) (12) (1). CCE is a simple stereotypical behavioral task that provides a robust performance metric of tool incorporation.

Despite the widespread use of the crossmodal congruency task in a variety of experimental paradigms, important questions related to task exposure times remain unanswered. For example, in a majority of the studies the experimental protocol consists of multiple blocks of trials with experimental sessions lasting up to approximately 60 minutes. These time-intensive experimental sessions might result in extended learning of the task and adversely affect a participant’s CCE score. Also, there is no specific mention of a participant selection criterion based on their previous knowledge of the crossmodal congruency task. To our knowledge, there exist no studies to date that have investigated modulation of CCE score due to repeated task exposures. This study aims to answer three important questions: First, does the CCE score attenuate with repeated task exposure sessions? Second, can this attenuation of CCE score due to repeated task exposure sessions be reduced through a modified version of the crossmodal congruency task? Finally, does the attenuated CCE score return to baseline with the passage of time?

Materials and Methods

CCE test implementation

In this experiment participants sat comfortably on a chair in front of a table in a dimly illuminated room. They wore over-ear noise-canceling headphones playing Brownian noise to mask background noise. Identical vibrotactile stimulation motors were placed on the thumb and index fingertips of the participant's right hand (see the Materials and Apparatus section for hardware details). Distractor light emitting diodes (LEDs) were placed on the thumb and index finger of the participant's right hand while a fixation LED was centered between the distractor LEDs using a plastic mounting strip. Fig 1 shows the system setup used for this experiment.

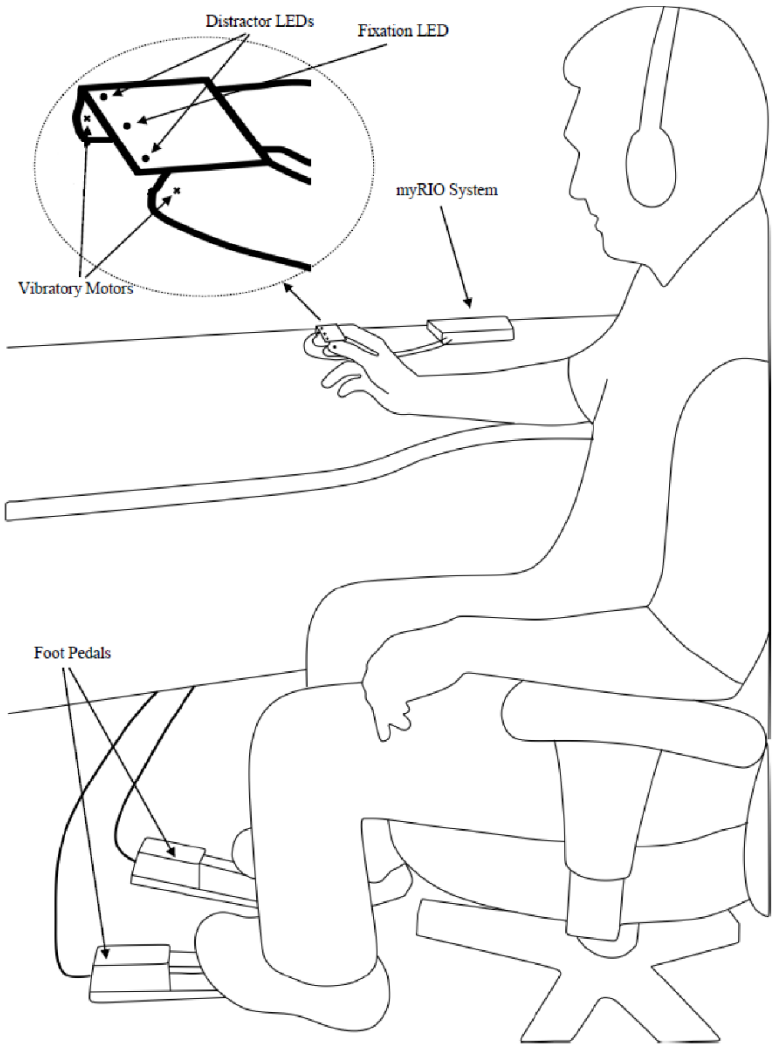

Fig 1. Overall system setup.

At the beginning of the experiment, participants were instructed to make a speeded response to vibrotactile targets that were presented randomly to either the thumb or index fingertip. Participants responded by pressing the left or right foot pedals to indicate stimulation of the thumb or index finger, respectively. Participants were explicitly instructed to respond as fast as possible, while making as few errors as possible. Participants were also informed that visual distractors would be presented simultaneously with the vibrotactile targets but they were completely irrelevant to the vibrotactile target discrimination task. They were specifically instructed to ignore visual distractors by keeping

their eyes open and fixating their vision on the central fixation LED. The fixation LED was presented 1000ms before the vibrotactile targets and visual distractors were simultaneously presented for 250ms. The experimental session was preceded by a practice session. The first block of the practice session consisted of presenting the fixation LED and vibrotactile targets only (i.e. no visual distractors were presented) so that participants could familiarize themselves with the vibrotactile target discrimination. The visual distractors were presented along with vibrotactile targets in the following two blocks of the practice session. This was followed by the experimental session during which 64 trials were presented to each participant during each block of trials. Either four or eight blocks of trials were presented depending upon which group subjects were randomly assigned to. Each trial ended when the participant responded by pressing one of the foot pedals or no response was made within 1500ms of target onset.

Participants

A total of 30 healthy participants were recruited from the local community (23 male, 7 female; aged 19 – 57 years, mean ± SD = 27.5 ± 7.8 years). All participants had normal or corrected to normal vision, no disorder of touch, 26 right hand dominant, 1 left hand dominant, 3 no particular hand dominance and were able to use both foot pedals. Participants were informed about the general purpose of the research and were given the opportunity to ask questions but they were not aware of specific goals of the research. Experiments were conducted under human ethics approval at the University of New Brunswick (Fredericton, NB, Canada) and the U.S. Department of the Navy's Human Research Protection Program. Written informed consent was obtained from each participant before conducting experiments and no compensation was provided for participating in the experiments.

Materials and apparatus

The experimental test platform was designed around the National Instruments (NI) myRIO embedded hardware system to achieve millisecond timing accuracy. The three digital outputs of the myRIO system were used to drive one 3mm green LED, termed the fixation LED, and two 3mm green LEDs named distractor LEDs. Two 308-107 Pico Vibe 8mm vibratory motors from Precision Microdrives were used as the vibrotactile targets for the thumb and index finger. The analog outputs of the myRIO system were used to drive STMicroelectronics L272 power operational amplifiers that drove the vibratory motors. The amplifiers were necessary to provide sufficient driving current to the vibratory motors. Two OnStage KSP100 keyboard sustain pedals were interfaced to the myRIO system through digital inputs to measure a participant's speeded responses to the vibrotactile targets. NI LabVIEW was used to develop the firmware for the myRIO system to randomly activate the visual distractors and vibrotactile targets at a fixed interval and measure the speeded response time. A desktop NI LabVIEW graphical user interface (GUI) was designed to interact with the myRIO embedded system, allowing the experimenter to set various experimental parameters such as vibratory stimulus amplitude, the number of trials and to specify the filename to record the timing results of speeded responses.

Experiment design

This experiment was designed to examine metric attenuation regarding three within-participant factors: number of exposure sessions (two exposures, five exposures and ten exposures), number of blocks per exposure (four blocks vs eight blocks), and the time between sessions (daily vs. four-month washout). The experimental session consisted of either four or eight blocks of 64 trials each. Each block lasted for approximately four minutes and a break period of two minutes was provided between consecutive blocks. The participants were randomly assigned to each of the five different groups named: eight blocks five sessions (8B-5S), eight blocks ten sessions (8B-10S), eight blocks two

sessions (8B-2S), four blocks ten sessions (4B-10S), and four blocks two sessions (4B-2S). Table 1 lists all the details for the different groups.

Table 1. Detailed information of five experimental conditions.

Group Name	8B-5S	8B-10S	8B-2S	4B-10S	4B-2S
Details	8 blocks per exposure, 5 exposure sessions	8 blocks per exposure, 10 exposure sessions	8 blocks per exposure, 2 exposure sessions	4 blocks per exposure, 10 exposure sessions	4 blocks per exposure, 2 exposure sessions
Number of participants	12	2	7	2	7

Analysis

Practice sessions that consisted of three blocks of ten trials preceded the experiment, and were not analyzed. The analysis was carried out by discarding trials with an incorrect response, trials with a premature response (i.e. reaction time less than 200ms), and trials with a delayed response (i.e. reaction time greater than 1500ms) as these conditions most likely occurred due to lapses in attention (1) (8). The remaining trials in each block were used to calculate the mean congruent and mean incongruent reaction times. The CCE score for each block was calculated by taking the difference between mean incongruent and congruent reaction times. The mean of the block CCE scores was used to calculate the CCE score for each participant for a particular exposure session.

Attenuation across sessions was evaluated using a paired sample t-test along with an exponential decay regression. Attenuation between 4-block participants and 8-block participants was assessed using a t-test. Variability of four vs. eight blocks within the same subjects was assessed by calculating the standard deviation and two sample f-test. Finally, mean CCE score data for original and washout data sessions for 8B-10S and 4B-10S participants was used to investigate if the attenuated CCE score can be washed out after a period of time.

Results

CCE score attenuation due to learning effect

The foundational question this study sought to answer was whether or not CCE score attenuated with over-exposure caused by multiple sessions. To answer this question, we tracked the CCE score of 12 subjects across five sessions using the conventional CCE method of 8-blocks. Fig 2 shows the mean CCE score for these 8B-5S participants, from which it is evident that attenuation is occurring. A paired sample t-test confirmed a 33% decrease in CCE score between the first and fifth exposure ($p = 0.011$).

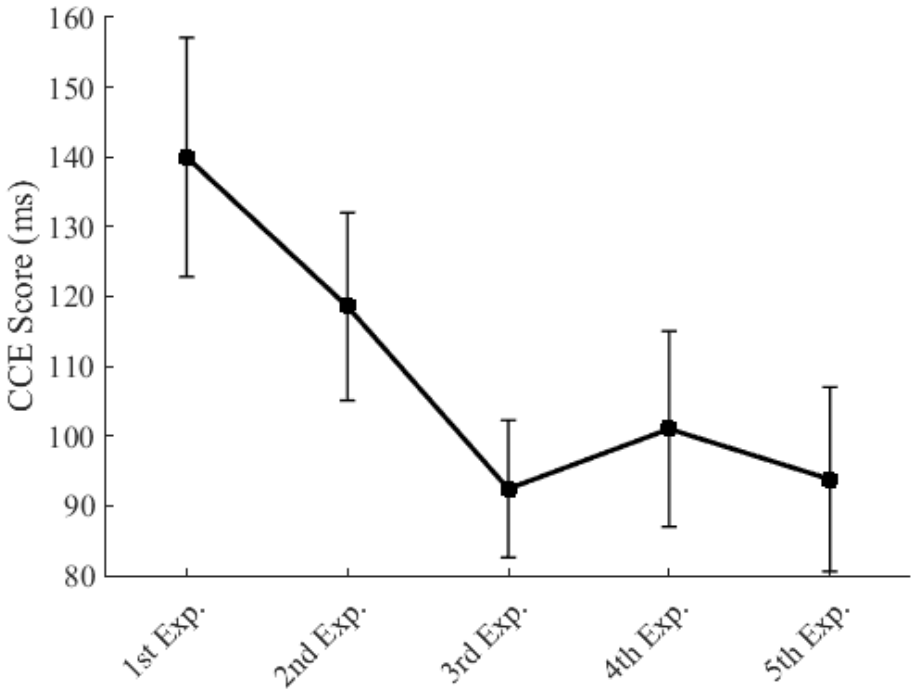

Fig 2. CCE score decreases with task exposure. Each data point represents the mean CCE score for 12 subjects along. Error bars show standard error.

To further characterize the observed learning effect, we tested two additional participants (8B-10S) for ten sessions (Fig 3). Both participants show attenuation of CCE score for ten sessions and the mean CCE score fit an exponential decay function having decay rate of -0.04 and $r^2 = 0.52$, suggesting a task learning effect.

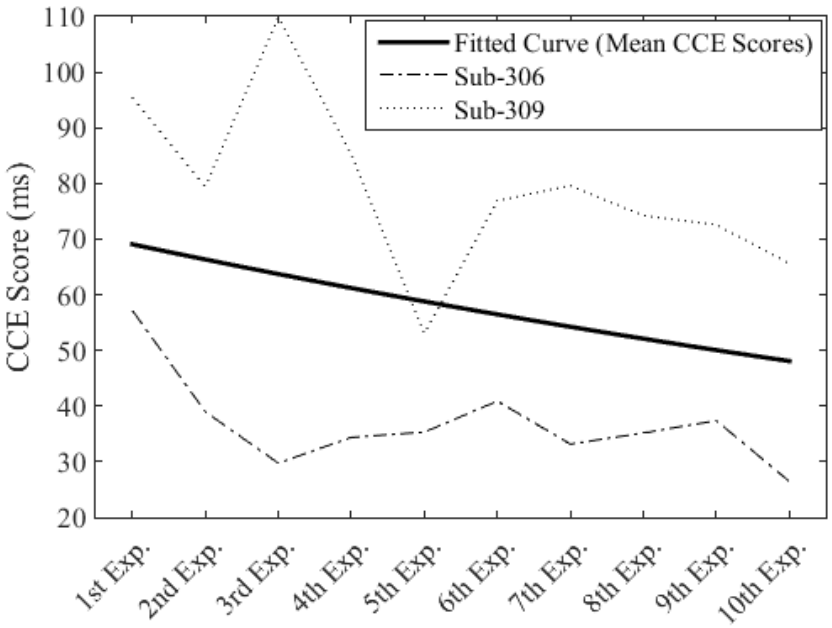

Fig 3. CCE score decreases over ten sessions.

There is clearly an attenuation of CCE score over multiple exposures but we wanted to see if there was a significant attenuation even as early as the second exposure. Fig 4 shows mean CCE score along with standard error for all the 8-block participants (i.e. 8B-5S, 8B-10S, and 8B-2S, total 21 subjects) for the first two task exposure sessions. A significant decrease of 14.5% is observed in the mean CCE score between first and second exposures and confirmed by paired sample t-test (p=0.027).

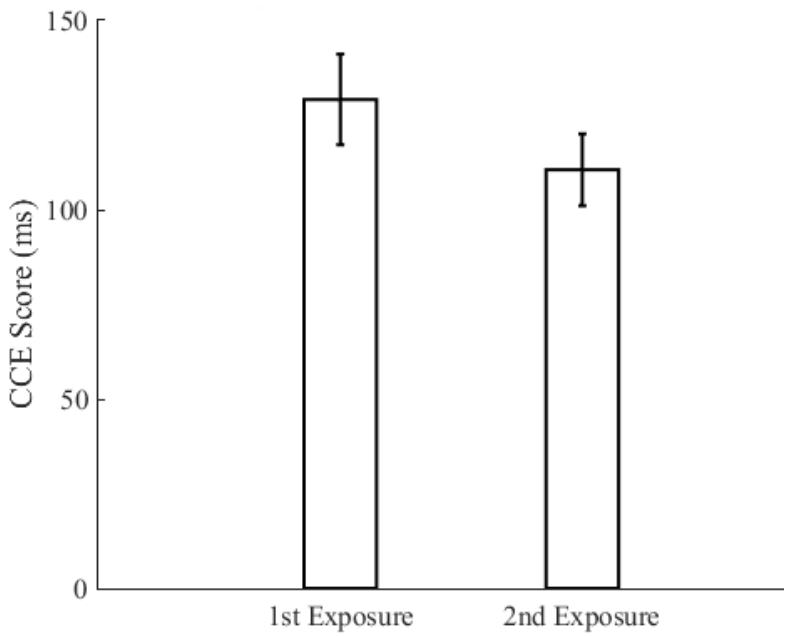

Fig 4. Mean CCE scores and standard error for 8-block participants. First and second exposure scores were significantly different (p = 0.027, paired t-test).

CCE score attenuation reduction using a modified crossmodal congruency task

Having concluded that CCE attenuation occurs, the second question that we wanted to address was whether we could reduce this attenuation without increasing variability of the metric. We explored if CCE attenuation could be reduced by limiting the duration of task exposure in each session to four blocks. There is a significant decrease of 14.5% between first and second exposure for 8-block participants (p=0.027) whereas for all 4-block participants paired sample t-test rejected the decrease of 6.5% between the first and second exposure (p=0.72). Limiting the exposure per session to half, reduced the CCE attenuation by approximately 55% between first and second exposure (Fig 5).

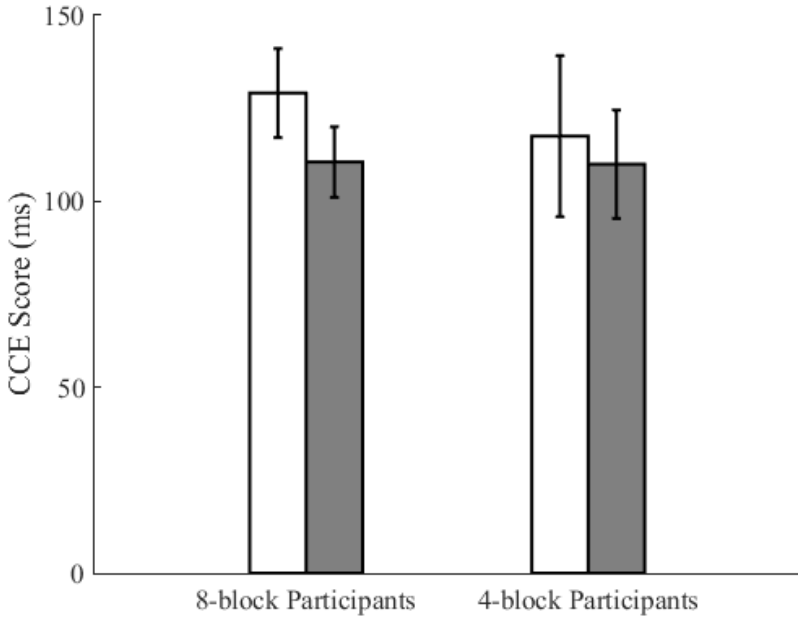

Fig 5. First exposure vs. second exposure mean CCE score for 8-block and 4-block participants. Means for 8-block (i.e. 8B-5S, 8B-10S, and 8B-2S) and 4-block participants (i.e. 4B-10S and 4B-2S) are shown with standard error. Light colored bars represent the first exposure session and dark colored bars represent the second exposure session.

There is a trend towards decrease in CCE score attenuation between first and second exposures due to limited task learning caused by reduced task exposure per session, but because this was achieved by collecting less data, it is possible that the modified procedure increased variability. In order to assess if variability was increased we analyzed the variability of CCE scores from all 8-block participants (21 participants) during their first-session, analyzing the variability of the first 4-blocks as well as all 8-blocks. Fig 6 shows CCE scores calculated from all eight and just the first four blocks of 8-block participants during their first exposure session. No increase in variability is confirmed by two-sample f-test which failed to reject the null hypothesis (p= 0.34) that the data for both sets had equal variance.

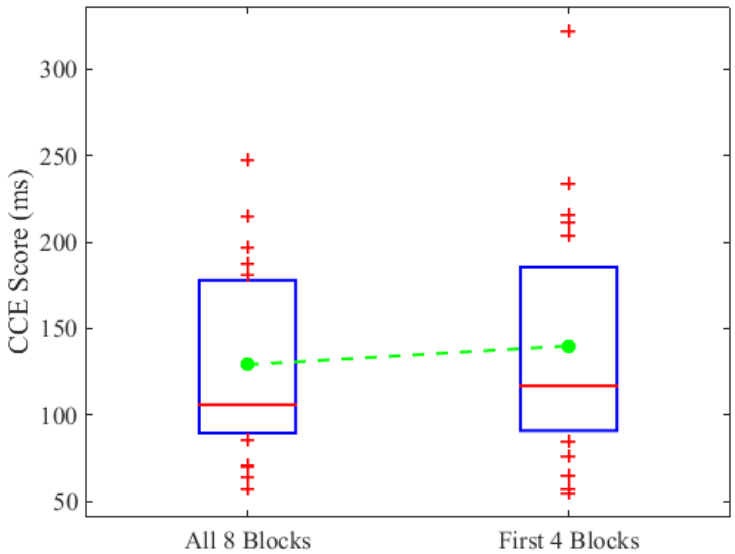

Fig 6. CCE scores calculated for all eight blocks and the first four blocks during the first exposure session for 8-block participants. Blue boxes represent the interquartile range, median CCE score is represented by solid red lines and dashed green line represents mean CCE score.

Attenuated CCE score washout after a passage of time

The final question we sought to address was whether subjects would return to their baseline CCE scores after a washout period. Four participants that completed ten sessions (i.e. 8B-10S and 4B-10S) were retested after a gap of four months. Three out of four participants returned to near-baseline CCE score on the follow-up tests (Fig 7). One participant showed a decrease of 66% in the CCE score between the first sessions of the original and washout data collections. This particular participant also showed a decrease of 45% in the CCE score between the first and second exposure during the original data collection. The very rapid attenuation of CCE score experienced by this subject indicates a much more rapid adaptation to the crossmodal congruency task than other participants. As a result, it is believed that this subject rapidly adapted to the task during the first exposure of the washout collection and therefore did not return to near-baseline CCE score.

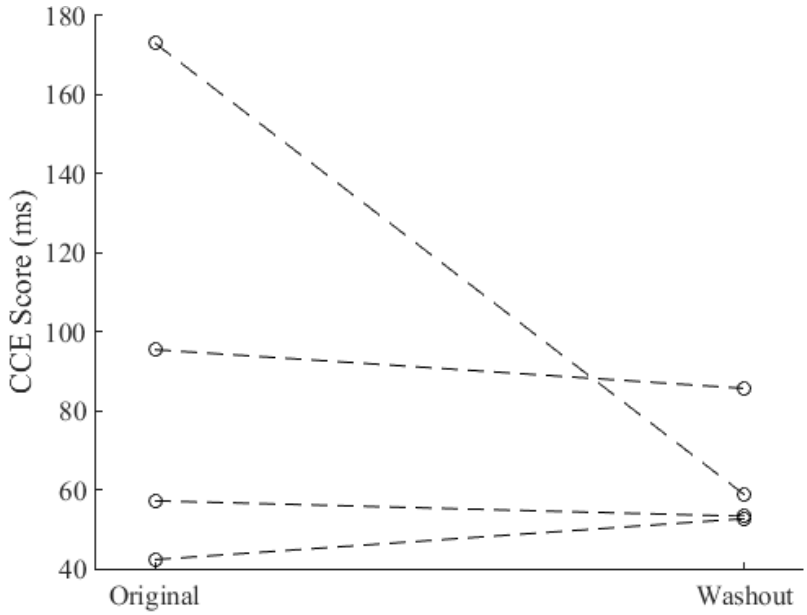

Fig 7. Original vs. washout first exposure CCE score for 8B-10S and 4B-10S participants.

Discussion

The CCE is a well-established quantitative measure of tool incorporation that extends to a variety of applications such as measuring the incorporation of novel sensory feedback modalities. However, many of these applications require repeated testing – for example, testing the same subject under different sensory feedback conditions to see which one enables the best tool incorporation. This study sought to assess whether the CCE could be tested multiple times in the same subject without partially extinguishing the effect. We found that CCE did indeed attenuate over time, as early as the second exposure, and that this attenuation appeared to continue over time with an exponential decay.

This attenuation may occur as the subject becomes familiar with the CCE task, and "learns the exam". In particular, they may begin to map an internal model of the foot pedal location to the vibration stimulus. Anecdotally, this became clear to us when one subject commented that "When the feedback is in the opposite location to the light, I sometimes find myself thinking about which pedal to press only to realize I've already pressed the correct pedal". There is accordingly a sweet spot between obtaining a reliable measurement of CCE, and over-exposure to the measurement apparatus.

We accordingly investigated whether reduced exposure even within a single session would limit metric attenuation without increasing variability. We found that halving the number of blocks from

eight to four did not significantly increase variability, but did result in a 55% decrease in attenuation. Although this reduced attenuation was not statistically significant, it was a clear trend, and it is founded on a logical foundation that reduced exposure reduces attenuation, which in turn is a reasonable extension of our broader, statistically supported finding, across sessions. Reducing the number of blocks per session has the added benefit of reducing fatigue, improving the ability of subjects to concentrate over the duration of the study, and shortening the length of the session to approximately 30 minutes (which in turn makes it viable to test a greater number of subjects or for use in a clinical setting). Using a modified version of the CCE with only four blocks of 64 trials has many potential gains, with no apparent deficits.

Finally, our study suggested that CCE scores did return to near-baseline results after a substantial washout period for the majority of subjects. It does accordingly seem possible that subjects can be retested (for example, before/after a take-home clinical trial), as long as the wash-out period is substantial.

To our knowledge, this is the first study that investigated and showed the modulation of CCE score due to task overexposure. Moving forward there are some limitations of this study that need to be addressed. One limitation was that participant mental and physical fatigue was not tracked or controlled so as to account for its effect on CCE score modulation. Although the crossmodal congruency task for individual participants was conducted during the same time of the day, no strict guidelines were used to ensure that participants were not mentally or physically fatigued before task exposure.

The presented work can be extended to further investigate the findings described in this paper. For example, in this work participants that were exposed to ten sessions were retested after a gap of four months to investigate participant reusability. The minimum time period needed for attenuated CCE score to return to the baseline value needs to be investigated. Additionally, modulation of CCE score due to mental and physical fatigue can be investigated by creating mental and physical fatigue in a laboratory controlled environment and comparing CCE results.

Conclusion

In this work we have shown that CCE scores attenuated due to a learning effect caused by task overexposure and that this attenuation can be reduced by using a modified implementation. We also showed that participants returned to near-baseline CCE scores after a gap in testing confirming participant reusability over time.

Acknowledgments

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