Evaluating the partial contribution of the P3 event-related potential elicited by auditory oddball stimuli during the Stroop task

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Abstract— **The cognitive load of a precisely timed task, such as the Stroop task, may be measured through the use of event-related potentials (ERPs). To determine the time at which cognitive load is at its peak, oddball tones may be applied at various times surrounding a cognitive task. However, we need to determine whether the simultaneous presentation of auditory and visual stimuli would mask a potential change in P3 in an ERP-producing task. If the contribution of the Stroop stimulus is too large, then Stroop ERP with oddball stimuli occurring at different timepoints may not be directly comparable across the various timepoints due to the contribution of the Stroop ERP. The aim of this study was to measure the magnitude of the difference wave between that of simultaneously presented stimuli and that of linearly added stimuli of separate responses. Participants were fitted with a dry-sensor EEG cap and were presented with a series of Stroop and auditory stimuli. For some Stroop stimuli, auditory stimuli occurred simultaneously or in a close time proximity to the Stroop stimuli. We sought to estimate the linear contribution of the ERP from Stroop and oddball stimuli. We found that the magnitude of the difference waves were 3.07 ± 1.65 μV and 2.82 ± 1.34 μV for congruent and incongruent stimuli, respectively. As the average amplitude in the P3 region for both the congruent and incongruent difference waves was lower than the magnitude of the auditory oddball presented simultaneously with Stroop stimuli (12.13 ± 1.00 μV for congruent and 11.78 ± 1.05 μV for incongruent Stroop), we expect that the contribution of P3 auditory oddball would not mask a potential Stroop effect even if the timing of the auditory oddball stimuli were experimentally manipulated, a direction that we hope to explore in future work. In conclusion, we determine this paradigm is suitable for measuring cognitive load in precisely timed tasks.**

Clinical Relevance— **This study establishes the efficacy of presenting a Stroop task as a proxy for a cognitive challenge that could cause cognitive overload.**

I. Introduction

Momentary lapses of attention may be enough to cause accidents such as trips and falls during walking. This can be caused by high cognitive load, which refers to the total amount of mental resources needed to carry out a task successfully [1]. Individuals who need to focus more on their walking, such as lower limb prosthesis users, tend to have high rates of falling [2], which could be caused by higher cognitive loads. However, measurement of the time course (i.e., onset and offset, and fluctuations, if any) of cognitive load remains challenging. Fortunately, event-related potentials can be used to investigate effects on brain processing that occur upon changes in cognitive load.

An objective, non-invasive way to measure cognitive load is through the auditory oddball paradigm, which elicits the P3 event-related potential (ERP). The cognitive response to auditory stimuli, as measured by the amplitude of the P3 potential, may decrease if attention is directed away from the task [3]. Thus, P3 amplitude decreases as cognitive load increases. The P3 oddball effect may be explained by a two-process probabilistic model of knowledge, i.e., an initial bias in perception towards what is probable, and a later enhancement in perception of events that are unexpected [4].

The Stroop task can be used as a proxy for increase in cognitive load. Some well-studied components of Stroop ERP waveform include the P3, and N450 components, which have amplitudes that are sensitive to the congruency of the Stroop stimuli. These differences are seen maximally over the parietal cortex [5]. Some studies suggest the P3 amplitude may depend on ratio of congruent to incongruent stimuli throughout the experiment. For example, in one study that had a high congruent to incongruent Stroop ratio, the amplitude of the P3 potential was increased for incongruent compared to congruent Stroop [6]. This effect may be attributed to the improbability of the stimulus. In another study that had equal numbers of incongruent/congruent Stroop, P3 was decreased for incongruent Stroop compared to congruent [7]. This may be attributed to the increased difficulty of the incongruent Stroop. For a review, see [5].

Typical Stroop paradigms include a large number of Stroop words on a page, and the participant must say aloud all words in order, as fast as possible. As our purpose of including the Stroop task is to provide a brief increase in cognitive load, we modified the traditional Stroop paradigm to include only one word at a time. Additionally, we included auditory oddball stimuli as an evaluative tool that elicits the P3 event-related potential. By simultaneously applying auditory and Stroop stimuli, we hypothesized that we can separate the contribution of the P3 event-related potential and Stroop ERP. As the Stroop ERP components may appear at the same time as the ERP components of the auditory stimuli, we hope to determine the magnitude of this additive effect, if any.

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To examine the contribution of the Stroop task on the oddball ERP waveform, we can take the difference, known as the difference wave. Difference waves are commonly used to show differences between two conditions. Here we examine the difference wave in the P3 region, as this is the region of interest for measuring cognitive load.

To evaluate the cognitive load during a precisely timed task, in this experiment we apply an auditory oddball paradigm synchronized to the onset of the Stroop stimuli. To measure the change in cognitive load according to the relative timing of the onset of the cognitive task, in future work, we can vary the onset of the oddball tone relative to the onset of the Stroop stimulus. However, in using auditory and visual stimuli simultaneously, we first must ensure the potential additive effects do not mask the results. If the contribution of Stroop ERP is large in the P3 region then it may mask any potential changes in P3 amplitude for trials in which the auditory and Stroop tasks are presented simultaneously.

Previous Stroop paradigms present many Stroop stimuli, rather than one at a time, which results in a prolonged period of cognitive load. Here we evaluate a paradigm in which Stroop stimuli are presented individually, so as to increase the intensity of the temporal demand of the task. The purpose of this preliminary work is to determine whether this paradigm is appropriate for measuring the cognitive load of this precisely timed task. To this end, we measured the contribution of the Stroop task to the auditory P3 when the Stroop and auditory stimuli occur simultaneously.

II. Procedures

We recruited 17 subjects to participate in this experiment, in accordance with Northwestern IRB guidelines.

A. EEG Collection

EEG was collected from all subjects using the DSI-7 (Wearable Sensing) which has 7 dry-sensor electrodes (Pz, P3, P4, C3, C4, F3, and F4). The ground electrode was located at Fz. The reference was recorded from Linked Ears (average of left and right earlobes). Impedance was kept below 1 MΩ. The EEG sampling rate was 300 Hz. EEG was filtered offline at 0.5 Hz using a 2nd order zero-phase Butterworth high-pass filter. Each trial was segmented from -200 pre-stimulus to 1800 ms post stimulus using built-in functions from EEGLAB [8] and ERPLAB [9]. The baseline of -200 ms to 0 ms was subtracted from the rest of the trial. Independent components automated labeling (ICLabel) [10] was used to find the eye-related independent component(s), which were then used to detect blinks in artifactual trials. The remaining trials (95.6 %) were grouped according to stimulus type and aligned to the start of that stimulus onset. The data in the final figures were low-pass filtered at 30Hz using the built-in function `pop_filterp` in ERPLAB.

B. Stimulus paradigm

Participants viewed the stimulus paradigm while seated at a table with the laptop (Figure 1). Matlab custom scripts were used to create the stimulus paradigm with auditory and Stroop stimuli (Figure 2). Stroop stimuli were one of five possible words: RED, BLUE, GRAY, GREEN, and PINK. The font color was manipulated so that Stroop words were either congruent (e.g., BLUE with blue font) or incongruent (e.g., BLUE with green font) to their corresponding font color. Participants were asked to vocalize the color of the word, not the text, upon stimulus presentation. Visual and auditory stimuli were detected using a light sensor and audio input into the Trigger Hub (Wearable Sensing).

There were 10 consecutive auditory stimuli in each block. Target stimuli were high-pitched tones (1200 Hz) and non-target stimuli were low-pitched tones (900 Hz). Auditory stimuli appeared in a sequence of 5 non-target stimuli, then one oddball (target) stimulus, followed by 4 non-target stimuli. This was to keep the ratio of target to non-target stimuli low (~10%) to maximize the novelty of the oddball stimuli and thus the P3 amplitude.

There were 10 Stroop stimuli in each block. For each of the first 5 Stroop Auditory stimuli appeared just prior to (~ -1000 ms) each of the first 5 congruent Stroop stimuli in every block. The auditory stimulus associated with the 6th Stroop stimulus could have been applied just prior to, at the same time as, or just after the 6th Stroop stimulus. The 6th auditory stimulus was always a target (i.e., oddball) tone, highlighted in yellow in Figure 1. All other auditory tones were non-targets.

In total, there were 60 blocks with congruent Stroop stimuli only, 60 blocks with a combination of incongruent stimuli, and 60 blocks with auditory stimuli only.

C. Data Analysis

ERP were created by averaging all remaining trials after artifact removal. Mean amplitude was calculating from the grand average ERP waveform of the corresponding stimulus type in the region specified. The P3 region was defined as a 150 ms block surrounding the latency of the maximum amplitude of the P3 peak, which expected to be at approximately 300 ms based on literature values [3].

Figure 1. A participant completing the stimulus paradigm on a laptop while seated at a table. The light sensor connected to the Trigger Hub marks the onset of the Stroop stimuli. The wireless receiver transmits stimuli from the Trigger Hub to synchronize it to the EEG signal.

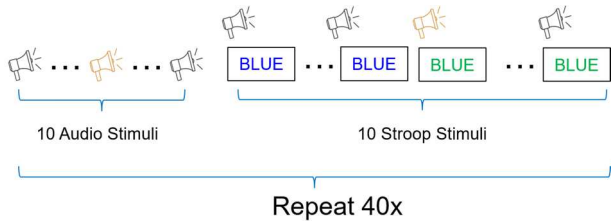

Figure 2. Stimulus paradigm showing audio and visual stimuli during Congruent and Incongruent Stoop tasks. The highlighted speaker icon indicates the auditory tone played simultaneously with the onset of the 6th Stroop task.

III. Results

Figure 3A shows the amplitude of the P3 potential for incongruent stimuli, congruent stimuli, oddball tones only, and the simultaneous presentation of Stroop and oddball tones. Figure 3B shows the mean P3 values for each of the plots in Figure 3A. For Stroop stimuli occurring simultaneously with the auditory oddball, the average value in the P3 region (225 to 375 ms) was 9.07 ± 1.77 µV for congruent and 8.95 ± 1.40 µV for incongruent Stroop stimuli. For auditory oddball stimuli only (3C), the amplitude is 6.36 ± 0.75 µV in the P3 region. The peak seen in the P3 region indicated the oddball effect was present. For Stroop stimuli presented alone, the mean values in the P3 region are -0.972 ± 1.08 µV for congruent stimuli (3D) and 1.03 ± 1.32 µV for incongruent stimuli (3E).

Figure 4 shows the ERP Waveforms and difference waves of congruent and incongruent Stroop stimuli and auditory oddball stimuli. The P3 region (225 ms to 375 ms) is highlighted in yellow. Congruent Stroop only (4A) has a mean value of 6.36 ± 0.75 µV in the P3 region. The incongruent Stroop stimuli only (4B) has a similar waveform to that of the congruent Stroop and mean value (5.42 ± 0.53 µV) in the P3 region. Both congruent and incongruent Stroop stimuli alone have amplitudes that are similar to that of the oddball stimuli (4C) mean P3 value (6.36 ± 0.75 µV).

Plots 4D and 4E show the linear combination of oddball + Stroop stimuli. Figure 4D shows the auditory oddball ERP waveform linearly added to the congruent Stroop ERP waveform. The average value in the P3 region is 12.13 ± 1.00 µV. Figure 4E shows the auditory oddball ERP waveform linearly added to the incongruent Stroop ERP waveform. The average value in the P3 region is 11.78 ± 1.05 µV. Note that these are artificially combined waveforms.

Figures 4F and 4G show the ERP from simultaneously presented Stroop and oddball stimuli. 4F shows the oddball and congruent Stroop stimuli when they occurred simultaneously. The average value in the P3 region is 9.06 ± 1.77 µV, which is lower than that of the linearly added trials. Figure 4G Shows the ERP waveform from oddball and incongruent Stroop occurring simultaneously. The average value in the P3 region is 8.95 ± 1.40 µV, which is lower than that of the linearly and artificially added trials.

Figures 4H and 4I are the difference waves to show the linear contribution of oddball and Stroop stimuli. Figure 4H shows the difference wave from (D) minus (F). In Figure 4H, the mean amplitude in the P3 region is 3.07 ± 1.65 µV. Figure 4I shows the difference wave from (E) minus (G). The mean amplitude in the P3 region is 2.82 ± 1.34 µV.

IV. Discussion

The aim of this preliminary study was to measure the magnitude of the difference wave between simultaneously presented and linearly added stimuli. If the contribution of the auditory stimulus were too large, then it may not be feasible to use Stroop ERP with audio stimuli occurring at different timepoints. To ensure the oddball P3 is not masked by the ERP from the Stroop stimuli, we looked at the linear contributions of the Stroop and Oddball stimuli compared to that of the stimuli appearing simultaneously.

The contribution of the auditory stimulus can be seen in Figure 4. The mean values in the P3 region for the linear combination of auditory stimuli and Stroop stimuli (12.13 ± 1.00 µV for congruent Stroop (4D) and 11.78 ± 1.05 µV for incongruent Stroop (4E)) are less than the contribution of auditory P3 estimated from the difference waves (3.07 ± 1.65 µV and 2.82 ± 1.34 µV for congruent (4H) and incongruent (4I) stimuli, respectively). This is approximately half the value of the oddball auditory waveform, suggesting that our approach may be a promising technique create a momentary change in cognitive load that can be probed using an auditory oddball paradigm.

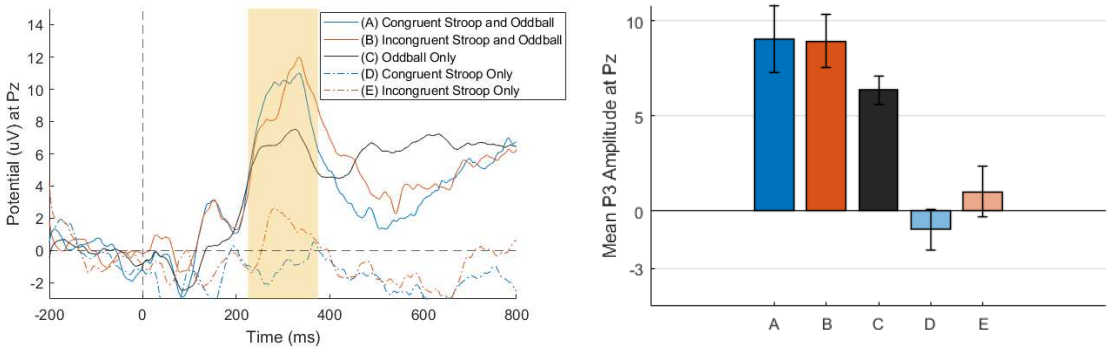

Figure 3. (Left) ERP Waveforms showing simultaneously presented oddball stimuli with (A) congruent and (B) incongruent Stroop stimuli, (C) oddball stimuli only, (D) congruent Stroop stimuli only, and (E) incongruent Stroop stimuli only. The P3 region (225 to 375 ms) is highlighted in yellow. (Right) Mean amplitude in the P3 region (225 to 375 ms).

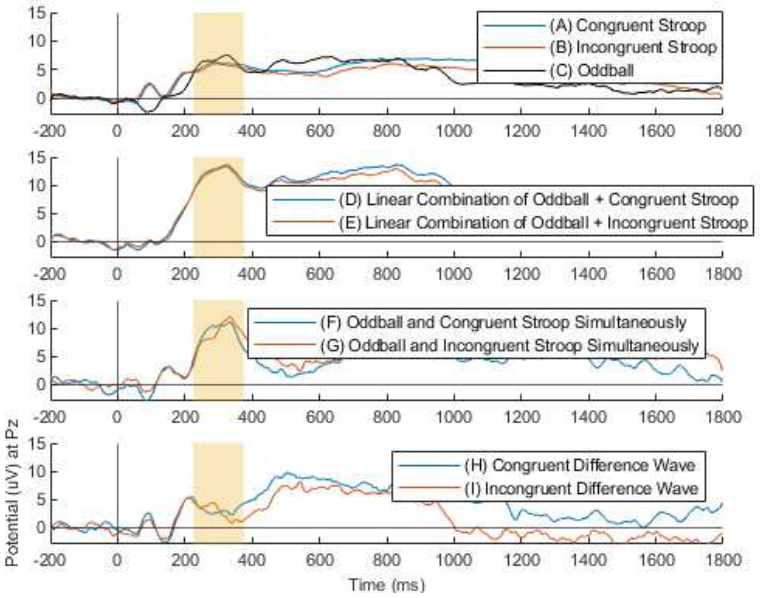

Figure 4. ERP Waveforms and difference waves showing the contribution of congruent and incongruent Stroop stimuli and auditory oddball stimuli. The P3 region (225 ms to 375 ms) is highlighted in yellow. Plot (A) shows congruent stroop only, plot (B) shows incongruent Stroop only, and (C) shows oddball stimuli only. (D) shows the linear combination of oddball + congruent Stroop stimuli. Plot (E) shows the linear combination of oddball + incongruent Stroop. (F) Shows the ERP waveform from oddball and congruent Stroop occurring simultaneously. (E) Shows the ERP waveform from oddball and incongruent Stroop occurring simultaneously. Plot (H) shows the difference wave from (D) minus (F). Plot (I) shows the difference wave from (E) minus (G).

Looking at the ERP from the oddball stimuli presented simultaneously with the incongruent and congruent Stroop tasks, it appears that there is no difference between the peaks in the P3 region. This is expected, as we would not expect a change in cognitive load to be apparent immediately at the onset of the Stroop, and may take some time to be detected using an ERP. Our future work will attempt to quantify the time-course of when the change and cognitive load can be probed.

V. Conclusion

This study determined that this stimulus paradigm is suitable for measuring cognitive load. In future work, we hope to examine attentional requirements of precisely timed cognitive tasks. To determine the time at which cognitive load is at its peak, we may be able to apply oddball tones at various times surrounding a cognitive task such as the Stroop task. In future work, in lieu of the Stroop task, we may be able to apply this method during real-world tasks such as difficult transitions for individuals using assistive devices.

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