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ERP correlates of error processing during performance on the Halstead Category Test

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ABSTRACT

The Halstead Category Test (HCT) is a neuropsychological test that measures a person's ability to formulate and apply abstract principles. Performance must be adjusted based on feedback after each trial and errors are common until the underlying rules are discovered. Event-related potential (ERP) studies associated with the HCT are lacking. This paper demonstrates the use of a methodology inspired on Singular Spectrum Analysis (SSA) applied to EEG signals, to remove high amplitude ocular and movement artifacts during performance on the test. This filtering technique introduces no phase or latency distortions, with minimum loss of relevant EEG information. Importantly, the test was applied in its original clinical format, without introducing adaptations to ERP recordings. After signal treatment, the feedback-related negativity (FRN) wave, which is related to error-processing, was identified. This component peaked around 250ms, after feedback, in fronto-central electrodes. As expected, errors elicited more negative amplitudes than correct responses. Results are discussed in terms of the increased clinical potential that coupling ERP information with behavioral performance data can bring to the specificity of the HCT in diagnosing different types of impairment in frontal brain function.

1. Introduction

The Halstead Category Test (HCT) (DeFilippis and McCampbell, 1997; DeFilippis, 2002), which is part of the Halstead-Reitan Neuropsychological Battery, is a neuropsychological test routinely used to assess abstract reasoning, concept formation and problem solving abilities in a variety of clinical contexts and populations (Allen et al., 2007, 1999; Choca et al., 1997). The test consists of 208 items, divided into 7 subtests, and the total number of errors is the score most commonly used to assess performance, which has proven to be highly sensitive for identifying brain dysfunction (Choca et al., 1997). However, as studies seem to demonstrate that the HCT is a multidimensional instrument which assesses diverse cognitive executive abilities (Allen et al., 1999), the total error score has also received some criticism, due to its lack of specificity in identifying which particular abilities are impaired (Allen et al., 2007). For this reason, a number of studies have attempted to develop more elaborate approaches to scoring the HCT and created scales based on individual subtests (e.g., McNally et al., 2015; Minassian et al., 2003). Results suggest that by looking at the scores on the various subscales, the HCT is able to provide information about a variety of cognitive functions that are usually assessed by different instruments, which is useful in informing clinicians about different domains where further evaluation should be focused in case of impairment. Nonetheless, studies demonstrating that the scales are able to discriminate neurologically impaired patients and healthy individuals are still lacking (McNally et al., 2015). The informative potential of this test regarding brain dysfunction could be considerably increased if brain activity was registered concomitantly to test performance. To the best of our knowledge, no studies so far have examined brain activity through event-related potentials (ERPs) during performance on the HCT. ERPs are a high temporal resolution electrophysiological technique, which is particularly suited for studying the time course of brain processes.

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Therefore, ERP recordings during performance on the HCT could be helpful in increasing the diagnostic value of the test, providing a more direct link between test scores and underlying brain processes, and helping to disentangle the multitude of cognitive operations that are in play during HCT performance. This information could be used to better understand the brain processes and cognitive abilities that are impaired in association with a particular behavioral pattern, thus increasing the specificity of the test, an aspect of the HCT which has been pointed out as a limitation (Choca et al., 1997).

Although the electroencephalogram (EEG) can be easily recorded while participants perform on the HCT, the conditions are not ideal for the study of ERPs. Several characteristics of the test items differ from what is a classical ERP paradigm, namely the length of stimulus presentation, which in the HCT has no time limit and is typically long. This originates a high number of artifacts, both ocular and due to movement, since it is more difficult for the participant to exert self-control of these for the time of exposure. Another issue is the number of test items, which in total is 208, but which can be significantly reduced if specific analysis need to be carried out, namely analyzing only certain subtests, or separating correct from incorrect responses. Thus, it is necessary to employ a signal processing method that will allow for preservation of a high signal-to-noise ratio. The main aim of the present work was to demonstrate that it is possible to use the HCT in its current clinical format and simultaneously record an EEG for ERP analysis, in order to increase the informative value of the test in terms of identifying the underlying brain processes.

Another test commonly used in neuropsychological practice to assess executive function is the Wisconsin Card Sorting Test (WCST) (Heaton et al., 1993). Similarly to the HCT, the WCST is commonly regarded as a test of abstract reasoning and concept formation, and it is also generally adopted as an indicator of frontal lobe dysfunction. However, a lack of specificity to frontal damage has also been reported (e.g., Anderson et al., 1991), which has led to attempts to use ERPs as a brain activity measure to probe in detail the relation between brain dynamics and the cognitive processes underlying WCST performance (Barceló et al., 1997; Barceló, 2003). These studies have been successful in identifying frontal ERP components related to task performance, but also components that have a non-frontal origin (such as the P3b wave), which help clarify some reports of non-specificity of the WCST to prefrontal damage (Barceló and Rubia, 1998). However, these ERP studies have used a modified version of the WCST in order to adapt it to the recording of ERPs and to specifically allow the investigation of the electrophysiological dynamics related to attention set-shifting (Barceló, 2003). Our aim was to be able to explore the ERP correlates of performance on the HCT in its current clinical format, without introducing any adaptation to the task. In this way, we would be able to provide an additional tool that could be used in conjunction with behavioral performance. This would allow the use of standard norms and cut-off points for neuropsychological diagnosis, whilst simultaneously informing on the underlying brain dynamics, thus increasing the clinical potential of the test.

In the present work, we focused our analysis on the posterior P100 visual ERP component, which is elicited by visual stimuli independently of the task that the subject is doing (Luck, 2005) and is generally related to activity in extrastriate areas of the visual cortex (Pratt, 2011) and on the feedback-related negativity (FRN) wave, a frontocentral ERP component related to error processing (Miltner et al., 1997), which should be expected during performance on the HCT. This test consists of 208 items, divided into 7 subtests. The items consist of nonverbal stimuli representing geometric figures or designs, and the participant is asked to indicate the number between 1 and 4 that each stimulus suggests. After each response, visual feedback on whether the response was correct or incorrect is provided, which helps participants to adjust their strategy. The participant is informed that all items in a particular subtest have the same underlying abstract principle, and that this abstract principle may or may not change between subtests. Thus, an incorrect feedback after a response indicates the need to search for a different abstract principle. On the other hand, a correct feedback indicates that the same abstract principle should be maintained for the following items within that subtest. Every time a new subtest begins, the participant is informed that the underlying principle may be the same as in the last subtest or that it may change (McNally et al., 2015). Thus, this test measures concept learning, flexibility of thinking and ability to learn and apply new rules. Also, the test directly taps the ability to learn from experience, monitor the errors that are committed, and adjust one's response strategy as a function of feedback on the accuracy of a previous response, until a correct rule has been successfully identified which can be followed in the subsequent trials. Given the nature of the task, committing errors is common until the new rule is discovered.

An ERP component has been described, which follows the display of negative feedback, in tasks where errors are due to uncertainty regarding the correct response, and participants only become aware of the accuracy of their response after a feedback signal has been provided (Walsh and Anderson, 2012). This wave has been called feedback-related negativity (FRN). This component was first discovered in a time estimation task where participants had to push a button a second after a signal. A feedback stimulus told the participants whether the estimation was accurate or wrong, and a negative deflection appeared after negative feedback (Miltner et al., 1997). The FRN is measured maximally at midline fronto-central electrodes and is typically larger for erroneous responses than for correct responses, peaking between 200 and 250 ms after feedback. This component is believed to originate in a general purpose neural system for dealing with errors in different types of task, which contributes to the adjustment of ongoing behavior (Gehring and Willoughby, 2002; Miltner et al., 1997). Research has suggested that the FRN reflects the evaluation function of a neural system that determines whether an outcome was correct or incorrect relative to one's expectation (Gehring and Willoughby, 2002; Hajcak et al., 2006; Holroyd, 2004). Importantly, the FRN seems to reflect the processing of external cues about performance (Bernat et al., 2011). The most likely neural generator of the FRN has been localized in the dorsal area of the anterior circulate cortex (ACC), a brain region known to be involved in cognitive control and behavior regulation, and which is important for the ability to adapt behavior to different task demands and circumstances (Hauser et al., 2014; Walsh and Anderson, 2012).

As mentioned above, the Wisconsin Card Sorting Test (WCST) is another neuropsychological test commonly used to assess frontal lobe executive functions. Like the HCT, it also requires participants to infer sorting rules associated with simple geometrical stimuli (based on their color, shape, or number). Participants must adapt their responses based on the provided feedback regarding the accuracy of their responses (correct or incorrect feedback). A new discovered rule will be maintained for a number of trials, but after a while it will change again, requiring participants to discover the new sorting rule (Vilà-Balló et al., 2015). Studies using a modified version of the WCST, adapted to the recording of ERPs, have demonstrated the occurrence of the FRN component during performance on the test. In particular, (Kraus and Horowitz-Kraus, 2014) have shown that individuals with dyslexia exhibit decreased FRN amplitudes in the early phases of the task compared to normal readers, consistent with their difficulty in learning from previous mistakes. Another study, also using a modified ERP version of the WCST, has found larger FRN amplitude to positive feedback in a violent juvenile offender group compared to a control group, which suggested difficulty in using previous external feedback to accurately predict the negative outcomes of their behavior (Vilà-Balló et al., 2015). Thus, the FRN seems to be a reliable neurophysiological correlate of feedback-processing during performance on the WCST, a test that requires various executive abilities which are common to the HCT, as outlined above. Also consistent with these findings is evidence that performance on the WCST is positively correlated with metabolic activity in the cingulate region (Adams et al., 1995). So, since performance on the HCT also depends on the ability to monitor errors and adapt behavioral responses based on the success of previous