BRAIN RESEARCH 1430 (2012) 62–67

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BRAIN RESEARCH

Research Report

Cognitive load impacts error evaluation within medial-frontal cortex

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ARTICLE INFO

Article history:
Accepted 17 October 2011
Available online 22 October 2011

Keywords:
Cognitive Load
Learning
Error-Related Negativity
Event-Related Brain Potentials

ABSTRACT

In the present experiment we investigated the impact of cognitive load on feedback evaluation by a learning system within medial-frontal cortex. Participants completed a task in which they had to use feedback to learn to accurately estimate the duration of one second. In two experimental conditions, we manipulated the cognitive load of the feedback stimuli (low load versus high load). Our results revealed that the amplitude of the feedback error-related negatvity (fERN), a component of the event-related brain potential (ERP) thought to index a learning system within medial-frontal, was reduced in the high load condition. Further, an analysis of the behavioural data revealed that in the high load condition participants made less effective adjustments to their estimates following error feedback. Taken together, our data suggest that the functional efficacy of the medial-frontal learning system is reduced as the cognitive load of feeback signals increase. Moreover, our data indicate that the effect of increased cognitive load is to increase the trial-to-trial temporal variability of feedback stimulus evaluation.

1. Introduction

There is little doubt that feedback evaluation plays an important role in human learning. Whether one is a child being scolded for inappropriate behavior or a university student getting a letter grade on a class essay, feedback in its various forms is critical for the reinforcement and modification of behavior (e.g., Thorndike, 1911). A recent theoretical account proposes that such learning is carried out by medial-frontal brain structures tasked with the evaluation of feedback and the optimization of behaviour, a system which includes anterior cingulate cortex, the basal ganglia, and the midbrain dopamine system (e.g., Holroyd and Coles, 2002; Holroyd et al., 2005). While a considerable amount of research has been focused on identifying the functional components and nature of the medial-frontal learning system (i.e., Gehring et al., 1993; Holroyd and Coles, 2002; Holroyd and Krigolson, 2007; Holroyd et al., 2005; Krigolson and Holroyd, 2006, 2007a, 2007b; Miltner et al., 1997), in contrast, much less emphasis has been placed on understanding the external factors which impact this system. Here we ask whether the nature of evaluative-based learning within the medial-frontal system is altered as the qualitative nature of feedback becomes more complex and challenging to interpret.

In particular, we examined the extent to which the medial-frontal learning system is affected by increasing the cognitive

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doi:10.1016/j.brainres.2011.10.028

load—or processing demands—of feedback signals. Our goal was to dissociate between two different but complimentary effects that might arise in feedback evaluation as the cognitive load of feedback signals increases. On the one hand, increasing cognitive load may reduce the overall depth or degree of feedback evaluation itself, an effect akin to shunting cognitive resources from feedback evaluation to signal interpretation. If true, removing resources from the feedback evaluation process might either slow the process as a whole, or perhaps even negate the functional efficacy of the medial-frontal system. On the other hand, increasing cognitive load may increase the temporal variance of feedback evaluation on a trial-by-trial basis – an effect which would also impact feedback evaluation, but may differentially impact the learning process. Our goal was to determine whether either or both of these effects may be at play as the cognitive load of feedback signals was increased.

Our experimental approach was based on asking participants to perform a simple time estimation task (c.f., Holroyd and Krigolson, 2007; Miltner et al., 1997) as we recorded the brain's electrical responses via event-related brain potentials (or ERPs). On each trial participants were required to estimate a one second duration. Following each estimate participants were given visual feedback as to the accuracy of their response. Between experimental conditions, we varied the load of the feedback signal, in the low load condition we used a visual stimulus indicating feedback valence, in the high load condition participants were required to add two numbers to determine the accuracy of their estimate. Within this context, our primary dependent measure was the amplitude of the feedback error-related negativity (fERN), an ERN component elicited by performance feedback (Miltner et al., 1997) thought to reflect feedback evaluation by the medial-frontal learning system (Holroyd and Coles, 2002). At issue was whether the fERN would show evidence of reduced amplitude under high cognitive load, and if so, whether this amplitude reduction was associated with decreased depth of signal evaluation, increased variability of evaluation timing, or both. To assess whether or not temporal variability was the source of a potential reduction in the fERN, we analyzed the latency of the P300 ERP component on a trial-to-trial basis. The logic here being that if there was increased temporal variability in the high load condition, then an analysis of the variability of the latency of the P300 would reflect this. Finally, we were interested in whether or not a potential reduction in fERN amplitude would parallel deficits in behavioural task performance. Here, we predicted that if increasing cognitive load did impact behavioural performance, then participants might be unable, or at least would have a reduced ability, to utilize error feedback to make adjustments to the subsequent estimate.

2. Results

2.1. Behavioral Data

As expected given our performance based manipulation on the size of the response window (see Experimental Procedure for more detail), mean accuracy did not differ between the low (49% +/− 4%) and high (49% +/− 4%) load conditions ($p>0.05$). Although accuracy in this task is not a good measure of performance, the size of the response window is as a larger response window suggests poorer performance. An analysis of the size of the response window revealed no effect for cognitive load, suggesting similar performance in low and high load conditions ($p>0.05$). However, in line with previous results, we did find that the size of the response window was larger for correct (130 ms +/− 6 ms) than for error trials (121 ms +/− 6 ms), $t(13)=4.757$, $p<0.001$. Finally, an analysis of the change in the estimate following error feedback demonstrated that changes in the estimate were larger following error feedback in the low load condition (231 ms +/− 13 ms) than in the high load condition (174 ms +/− 13 ms; $t(13)=2.227$, $p=0.044$). Further, in both the low load and high load conditions the change in the estimate following error feedback was larger than the change in the estimate following correct feedback (low load: $t(13)=4.682$, $p<0.001$; high load: $t(13)=5.175$, $p<0.001$).

2.2. ERP Data

The amplitude of the fERN was impacted by cognitive load (see Fig. 1). Specifically, we found that the amplitude of the fERN was more negative in the low load condition (−11.1 uV +/− 2.3 uV) than in the high load (−6.5 uV +/− 2.3 uV)($t(13)=-2.610$, $p=0.022$). The topography (see Fig. 2) and timing of the fERN in the low load condition was consistent with

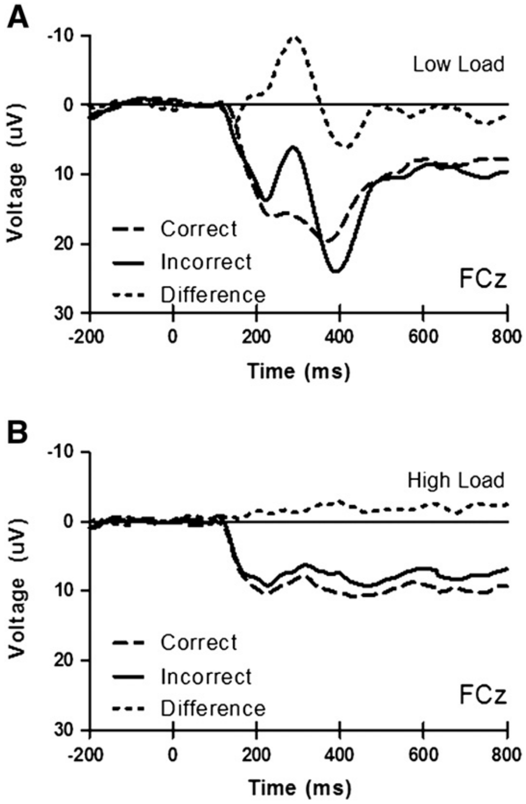

Fig. 1 – Grand average waveforms at channel FCz for correct and incorrect feedback for the a) low and b) high cognitive load conditions.

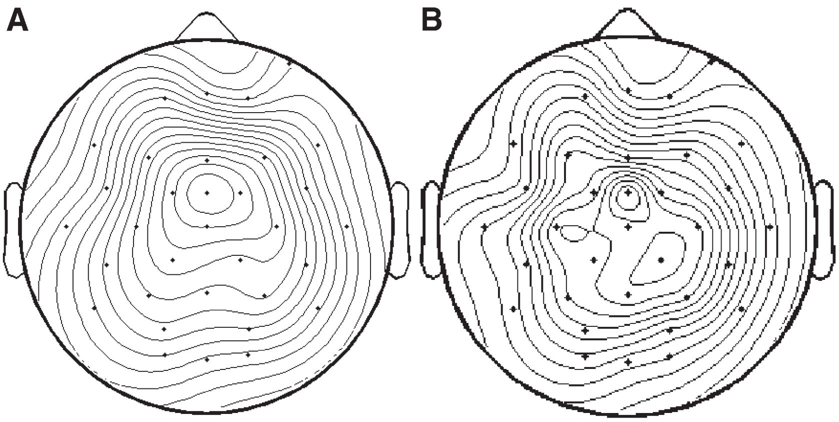

Fig. 2 – Topography of the fERN for a) low and b) high cognitive load feedback stimuli.

previous accounts of the fERN (i.e., Holroyd and Coles, 2002; Holroyd and Krigolson, 2007; Miltner et al., 1997). However, while the fERN in the high load condition had a topography consistent with previous accounts of the fERN, the peak latency in the high load condition (452 ms +/− 21 ms) occurred significantly later than the peak latency of the fERN in the low load condition (291 ms +/− 21 ms)($t(13) = 5.461$, $p < 0.001$).

To assess changes in the variability of feedback stimulus processing on a trial-to-trial basis, we calculated single trial amplitudes and latencies for the P300 ERP component for each trial for each experimental condition. We identified the P300 for each trial by finding the maximal voltage and it's latency 0 to 800 ms following feedback stimulus presentation at channel Pz for each trial, experimental condition, and participant. Our logic here was that the P300 is a large component, and thus reliably identifiable on a trial-to-trial basis (see Polich, 1986). We specifically picked the P300 component because it's latency reflects stimulus evaluation time (Duncan-Johnson, 1981; Kutas et al., 1977), and thus examining its latency would provide insight into the impact of increased congitive load on feedback evaluation. Our analysis revealed that there was no variability in the amplitude of the P300 associated with changes in cognitive load. However, our analysis revealed that increased cognitive load increased the variability of P300 latency, $t(13) = -9.612$, $p < 0.001$; see Fig. 3). Precisely, we found that the latency of the P300 on a trial-to-trial basis was more variable in the high load condition than in the low load condition.

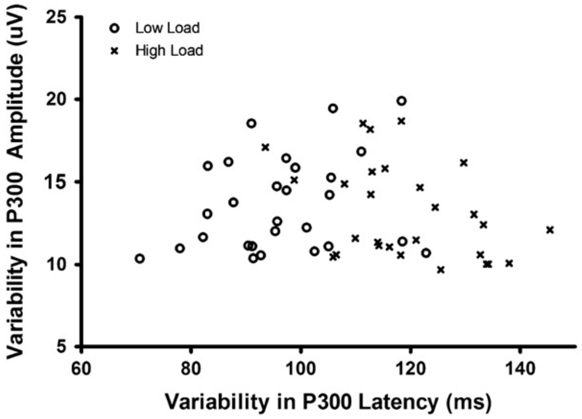

Fig. 3 – Single trial variability of P300 amplitude and latency for the feedback stimuli for each participant for the low and high cognitive load conditions.

3. Discussion

In the present experiment we assessed the impact of increasing cogntive load on feedback dependent learning. Our ERP results demonstrated that increased cognitive load resulted in a reduction in the amplitude of the fERN, an ERP component thought to index feedback evaluation by a learning system within medial-frontal cortex (Holroyd and Coles, 2002; Holroyd et al., 2005). Further, an examination of the behavioural data revealed that the magnitude of the change in participants' estimates following error feedback was larger following error feedback in the low load condition relative to the high load condition. In other words, we found that participants had a reduced cortical response to error feedback and were less effective at using error feedback to modify subsequent behaviour when cognitive load was increased (see Fig. 4). Several key issues follow.

Previous research has demonstrated that increasing cognitive load impairs task performance and/or neural responses to task relevant stimuli. For instance, in a recent study Nagamatsu et al. (2011) showed that increased cognitive load led to an increase in the amount of errors made by seniors performing a virtual reality street crossing task. Increasing load has also been shown to impact spatial attention. Specifically, Handy and Mangun (2000) demonstrated that increasing perceptual load reduced ERP responses associated with the allocation of spatial attention – a result the authors attributed to an increased demand for attentional resources. Here, we propose that increasing the cognitive load of feedback stimuli increased the demand for resources by the medial-frontal learning system, an increase which resulted in a reduced ability to process feedback. Further, we propose that this reduction in the ability of the medial-frontal system to process feedback led to a reduced ability to make subsequent feedback based adjustments to performance.

So what was the specific impact of increased cognitive load on the medial-frontal learning system? Recall that our single trial analysis of the P300 ERP component revealed that its latency was more variable in the high load condition. Given

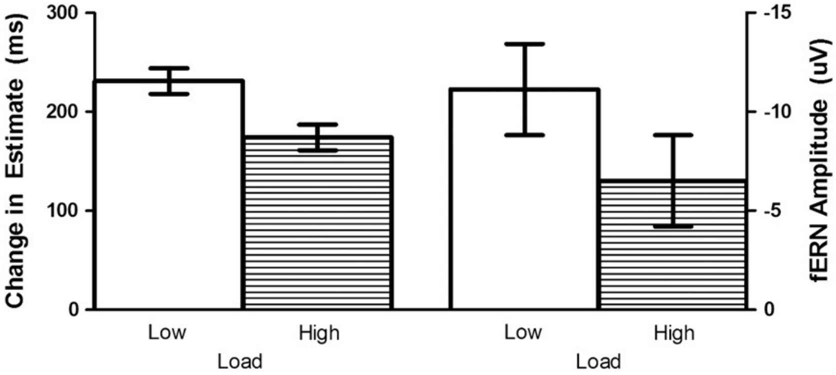

Fig. 4 – A comparison of the pattern of results for the changes in participants' estimates following error feedback and fERN amplitude. Error bars reflect within participant 95% confidence intervals.

that previous research posits that the P300 is indicative of stimulus evaluation time (Duncan-Johnson, 1981; Kutas et al., 1977), our data suggest that in the high load condition stimulus evaluation was more variable on a trial to trial basis. We believe that this increased variability in processing was brought about by an increased demand for feedback evaluation resources by the medial-frontal system in the high load condition. We suggest that the impact of the increased processing variability in the high load condition was an overall reduction in ability of the medial-frontal system to process and utilize error feedback.

A more obvious and visual result of the increased trial to trial processing variability was the "washed out" fERN in the grand average waveforms in the high load condition (see Fig. 1; see also Luck, 2005). However, recall that our behavioural data demonstrate that while participants were able to utilize error feedback to make adjustments to subseuqent behaviour in both the low and high load conditions, their ability to do so was reduced specifically in the high load condition. In other words, one cannot conclude from our data that the resulting increased processing variability in the high load condition – as indexed by the increased varibility in the latency of the P300 component in this condition - was simply to average out of the fERN in the grand average waveforms. Instead, our behavioural data combined with our ERP data suggest that increased cognitive load resulted in a reduced ability of the medial-frontal system to process feedback, and this reduction in feedback processing capability led to a reduction in behavioural task performance.

As alternative interpretation for our findings is that the increased variability in the latency of the P300 reflects increased variability in an additional stimulus processing step in the high load condition. Indeed, it seems reasonable to conclude that the nature of the feedback stimuli used in the high load condition required an additional processing step – the mental arithmetic needed to determine feedback valence. Supporting this, recall that we found that the latency of the fERN was longer in the high load condition relative to the low load condition, a result which in turn suggests that more time was needed for feedback stimulus evaluation in the high load condition. Thus, the reduction in fERN amplitude that we observed might not be related to a reduction in the functional efficacy of the medial-frontal system as noted above, but instead is simply related to increased variablity in the additional processing step required in the high load condition. While it is unclear why this would be the case, one might hypothesize that the increased varibility in the additional processing step in the high load condition impaired the medial-frontal systems ability to form stimulus-reward relationships thus explaining the decreased behavioural performance that we observed in this condition.

3.1. *Conclusions*

In the present study we found that increased cognitive load resulted in a reduction in the amplitude of the fERN and participants' ability to make behavioural adjustments following error feedback. In other words, increased cognitive load reduced the efficacy of the medial-frontal learning system (Holroyd and Coles, 2002; Holroyd et al., 2005). We believe that the effect of increased cognitive load was to increase the variability in the trial to trial timecourse of feedback stimulus evaluation, the result of which was an increased demand for feedback processing resources by the medial-frontal system. Further, we suggest this increased demand for feedback processing resources was not without effect, but that the increased resource demand brought about by increased cognitive load resulted in an overall reduction in the medial-frontal system's ability to process feedback and implement subsequent behavioural adjustments.

4. Experimental Procedure

4.1. *Participants*

Fifteen undergraduate students (7 male, 8 female; aged 18 to 30 years) with no known neurological impairments and with normal or corrected-to-normal vision participated in the experiment. All of the participants were volunteers who received extra-credit in undergraduate psychology courses at the University of British Columbia for their participation. The participants provided informed consent approved by Research Services at the University of British Columbia, and the study was conducted in accordance with the ethical standards prescribed in the original (1964) and subsequent revisions of the Declaration of Helsinki.

4.2. *Apparatus and Procedure*

The participants' task was to estimate the duration of one second. Each trial began with the presentation of a centrally positioned fixation cross on a computer monitor that remained onscreen for the duration of the trial. To reduce the number of ocular artifacts, participants were instructed to keep their eyes on the fixation cross at all times. Five hundred milliseconds after the fixation cross was presented, participants heard an auditory cue (1500 Hz, 65 dB, 50 ms duration). Following the cue, participants waited until they thought one second had elapsed, and then responded by pressing a button on a standard USB response pad. A feedback stimulus (see below) indicating the accuracy of the participant's estimate appeared 600 ms following the response, and remained onscreen for 1000 ms. Following the offset of the feedback stimulus, a blank screen was presented for either 1400, 1500, or 1600 ms (equivalent probability of each).

An estimate was considered correct if the participant's response was within a time window centered on 1000 ms. On the first trial of the experiment, the time window was +/– 100 ms. As such, a participant's estimate on the first trial was correct if their response occurred 900 to 1100 ms after the auditory cue. If the participants' response was outside of the window, the estimate was incorrect. Following each trial, the size of the time window decreased by 10 ms if the previous estimate was correct, and increased by 10 ms if the previous estimate was incorrect. The purpose of this manipulation was to ensure that participants' accuracy was approximately 50% over the course of the experiment in order to avoid contamination of the amplitude of the feedback error-related negativity by stimulus frequency effects (i.e., modulation of the N200 and P300, c.f., Holroyd and Krigolson, 2007; Holroyd et al., 2008).

The key experimental manipulation involved varying the cognitive load of the feedback stimuli presented to participants in two experimental conditions: low load and high load. In the low load condition the feedback stimuli comprised a check mark "✔" for correct trials and a "✖" for incorrect trials. We believe these stimuli reflected a low level of cognitive load given ease of processing and the considerable exposure participants had to these stimuli, and their meaning, prior to the experiment. In the high load condition, the feedback stimuli comprised two numbers (either "1" , "2", "3", "4"). Feedback valence was determined by adding the numbers - if the numbers summed to an even number the estimate was correct and if the numbers summed to an odd number the estimate was incorrect. In the high load condition, we believed the mental arithmetic required to determine feedback meaning required cognitive effort, and thus reflected a higher load on the system. Participants completed two blocks of 200 trials, one for each experimental condition. The order of the experimental blocks was randomly counterbalanced across participants. Participants relaxed during self-paced rest periods between each block.

4.3. *Data Acquisition*

Accuracy (correct, incorrect) and the magnitude of each estimate (ms) were recorded for each trial by the experimental program as behavioral measures of performance. The electroencephalogram (EEG) was recorded from 40 electrode locations using ActiView software. The electrodes were mounted in a fitted cap with a standard 10–20 layout and were referenced to a two electrode feedback loop (common mode sense to driven right leg). The vertical and horizontal electrooculograms were recorded from electrodes placed above and below the right eye and on the outer canthi of the left and right eyes, respectively. Electrode offsets were kept below +/– 25 mV at all times. The EEG data were sampled at 512 Hz and amplified with an Active Two system (Biosemi B. V., Amsterdam, Netherlands).

4.4. *Data Analysis*

We calculated mean accuracy (%) and mean size of the response window (ms) for correct and error trials for each experimental condition and participant as measures of task performance (c.f., Holroyd and Krigolson, 2007). We also calculated the percent change in the estimate for the trial following error feedback (%) for each experimental condition and participant, the logic with this measure being that we anticipated participants would make changes to their estimate following error feedback to improve subsequent performance (c.f., Holroyd and Krigolson, 2007).

The EEG analysis was done as follows. First, the EEG data were filtered offline through a (0.1 Hz – 25 Hz passband) phase shift free Butterworth filter and re-referenced to an average mastoid reference. Next, epochs for each experimental condition (low, high) and feedback valence (correct, incorrect) were extracted from the continuous EEG (200 ms before feedback stimulus onset to 800 ms after feedback stimulus onset). Following this, the ocular artifacts in each epoch were corrected using the algorithm described by Gratton, Coles and Donchin (1983) and each epoch was baseline corrected using the mean voltage for the 200 ms preceding feedback stimulus onset. Epochs were then examined for artifacts and removed from the data set if there was a change in voltage on any channel that exceeded 35 μVs between adjacent sampling points or a difference of more than 150 μVs between the maxima and minima of the epoch. On average, less than 10% of the data were discarded per participant, with one participant's data being completely removed from further analysis due an excessive number of artifacts (more than 80% of the trials were lost).

ERP waveforms were created by averaging the EEG epochs for each experimental condition (low, high) and feedback valence (correct, incorrect) for each participant. To isolate differences between correct and incorrect waveforms for each experimental condition, "difference waves" were created by subtracting the correct ERP waveform from the incorrect ERP waveform for each participant (Holroyd and Krigolson, 2007; Holroyd et al., 2008; Luck, 2005). The fERN was quantified as the most negative deflection on the difference waveform 0 to 800 ms following feedback stimulus onset at channel FCz. We focused our analysis on channel FCz given previous work (Holroyd and Krigolson, 2007; Holroyd et al., 2005, 2008; Krigolson et al., 2008, 2009) and an examination of the fERN topographies that supported our decision (see Fig. 2). The reasoning behind our quantification of the fERN was as follows - if the processing of correct and incorrect feedback did not differ cognitively, at least in terms of effects observable in the

ERP data, then the peak analysis of the difference waveforms would not statistically differ from zero (the fERN in each condition passed this test, p's < 0.05). Extending from this, if cognitive load did not impact fERN, then the peak analysis of the difference waveforms would not differ between experimental conditions.

All analyses were done with EEGLAB (Delorme and Makeig, 1994) and custom code written in the Matlab programming environment. Paired samples t-tests were used to examine all effects of interest. An alpha level of 0.05 was assumed for all statistical tests; only significant statistical effects are reported. All error measures reflect 95% within participant confidence intervals (Loftus and Masson, 1994; Masson and Loftus, 2003).

5. Acknowledgements

The first and last authour would like to thank the National Sciences and Engineering Research Council of Canada and the Michael Smith Foundation for Health Research for funding this research.

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