An Electrophysiological Signature of Dynamic Urgency in Human Perceptual Decision Making

Ciara A. Devine (devineca@tcd.ie)
Trinity College Institute of Neuroscience, Trinity College Dublin

David P. McGovern (david.p.mcgovern@dcu.ie)
School of Psychology, Dublin City University

Jessica Dully (jdully@tcd.ie)
Trinity College Institute of Neuroscience, Trinity College Dublin

Emmet McNickle (mcnickle@tcd.ie)
Trinity College Institute of Neuroscience, Trinity College Dublin

Simon P. Kelly (simon.kelly@ucd.ie)
Deptartment of Electrical Engineering, University College Dublin

Redmond G. O' Connell (reoconne@tcd.ie)
Trinity College Institute of Neuroscience, Trinity College Dublin

Abstract:

In perceptual decision-making, dynamic urgency is a time-dependent, evidence-independent mechanism that imposes a gradual reduction in the amount of sensory evidence required to commit to a choice. Although the effects of urgency have been observed across the sensorimotor hierarchy during perceptual decision formation, a distinct neural signature of urgency has yet to be fully characterised in the human brain. Here we tested the hypothesis that the contingent negative variation (CNV), a frontocentral, negative-going potential that has been implicated in temporal processing, directly represents dynamic urgency in the human brain. To this end we analysed data from two experiments in which speed emphasis was manipulated while subjects performed perceptual discrimination tasks. We found that the CNV was more pronounced at baseline under speed pressure, reflecting a static urgency component and that it became more pronounced over time, reflecting a dynamic component. Moreover, we also found that the rate of build up of the CNV accelerated as time elapsed and was not driven by sensory evidence accumulation. Together these findings support the mechanistic characterisation of the CNV as a time-dependent, evidence independent urgency signal.

Keywords: Decision-Making; Electroencephalography (EEG); Urgency; Contingent negative Variation (CNV);

Introduction

Evidence from computational modeling ('Sequential Sampling' Framework) and neurophysiology indicates that perceptual choices are made by accumulating sensory evidence until a decision bound is crossed (Gold & Shadlen, 2007; Shadlen & Kiani, 2013). The height of the decision bound, which determines how much evidence is required in order to commit to a choice, can be adjusted strategically to reflect different levels of response caution (or 'urgency'). Although traditional sequential sampling models favour a fixed, time-invariant decision bound, recent modelling data suggests that response caution can also be modulated dynamically in certain contexts where behavioural optimisation depends on reducing the required amount of sensory evidence as a function of time (Drugowitsch et al., 2012; Frazier & Yu, 2007; Malhotra et al., 2018).

Neural data indicates that static and dynamic bound adjustments are implemented in the brain by a time-dependent, evidence-independent urgency component that directly affects the activity of neural decision signals that encode evidence accumulation (Churchland et al., 2008; Hanks et al., 2014; Murphy et al., 2016; Thura & Cisek, 2016; Steinemann et al., 2018). Moreover, in primate neurophysiology, a neural signature of urgency itself has been localized to neurons in the basal ganglia (Thura & Cisek, 2017). However, no such signal has yet been firmly isolated in the human brain.

One such potential signal could be the contingent negative variation (CNV), a slow fronto-central waveform of negative polarity that has been repeatedly linked to temporal and anticipatory processing (Kononowicz & van Rijn, 2011; Walter, 1964). The most compelling evidence for this hypothesis to date comes from a study by Boehm et al. (2014) in which they found that the amplitude of the early CNV (pre-decision onset) was more pronounced under speed emphasis and correlated with model-derived estimates of response caution. This suggests that the CNV represents static components of urgency. Here we sought to determine whether the CNV also exhibits the characteristics of dynamic urgency, namely a time-dependent, evidence-independent rate of build-up. To

this end we analysed data from two separate perceptual discrimination tasks in which speed emphasis was manipulated.

Methods

Exeriment 1: In experiment 1 thirty subjects aged 18-34 took part in a two-alternative contrast discrimination task. Subjects monitored two overlaid (left- and right-tilted) gratings (fig. 1), presented initially at 50% contrast. Following a delay of 400ms, one grating increased in contrast by either 10 or 16% (target) while the other decreased (non-target) by a corresponding amount. Subjects reported the direction of the grating whose contrast increased by clicking the appropriate (left/right) mouse button using their left/right thumb (response deadline = 1600ms). Stimuli were presented in blocks of 60 trials. In three blocks subjects were instructued to emphasise response speed while in another three blocks they were instructed to emphasise response accuracy. Each regime had a distinct reward system. Under the accuracy regime correct, error and missed responses were awarded 100, -60 and 0 points respectively. Under the speed regime, points awarded for correct responses diminished from the maximum of 100 at a rate of 75 points per second while points deducted for incorrect responses increased at a rate of 62.5 points per second. 116 points were deducted for misses. Feedback was given on a trial-by-trial and block-by-block basis.
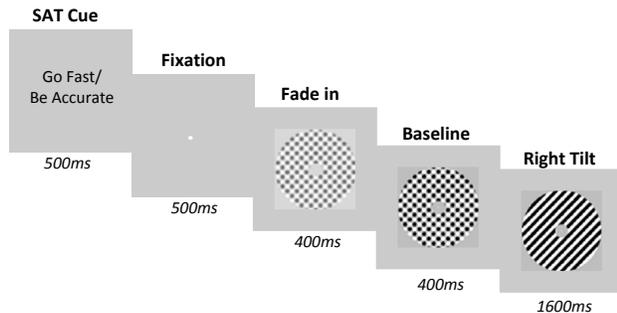
Figure1: Schematic depiction of a single trial in experiment 1.

Experiment 2: Thirty subjects aged 18-30 took part in a dot motion discrimination task. The stimulus in this task consisted of a cloud of randomly moving dots presented within a circular aperture (fig. 2). Following a delay of 680ms, a percentage of the dots (0%, 5%, 10%, 20%) began to move coherently in either a leftward or rightward direction. Subjects were required to report the direction of the coherent motion by clicking the appropriate (left/right) mouse button using their left/right thumb. Stimuli were presented in 6 blocks of 80 trials. The task consisted of three response regimes (2 blocks allocated to each). Under

speed emphasis the response deadline was 1200ms. Under free response the deadline was 1800ms. Under delayed response subjects were instructed to withhold their response until presented with a response cue. Feedback was presented on a trial-by-trial and block-by-block basis.
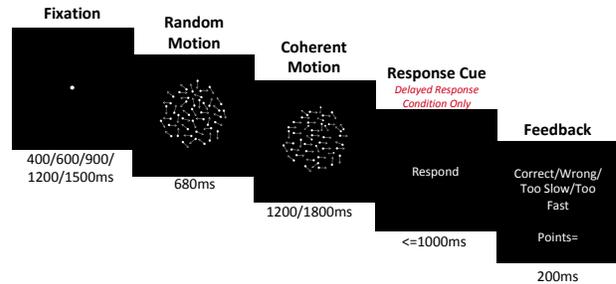
Figure 2: Schematic depiction of a single trial from experiment 2.

Electrophysiological Recording

In both experiments, continuous EEG data were recorded from 128 scalp electrodes. Continuous EEG data were low-pass filtered below 35 Hz, high-pass filtered above .05 Hz and detrended. For each subject we measured the CNV from a cluster of 4 electrodes centred around Fz/FCz.

Behavioural Results

In experiment 1, subjects responded faster but less accurately in the speed emphasis condition (fig. 3a; Accuracy: p<.05; fig. 3b; RT: p<.05). Likewise, in experiment 2, subjects also responded faster but less accurately when the response deadline was shorter (fig. 3c; Accuracy: p<.05; fig. 3d; RT: p<.05) Overall, across the two experiments, subjects responded more accurately and faster when presented with stronger sensory evidence (Exp1: Accuracy: p<.05; RT: p<.05; Exp2: Accuracy: p<.05; RT: p<.05).
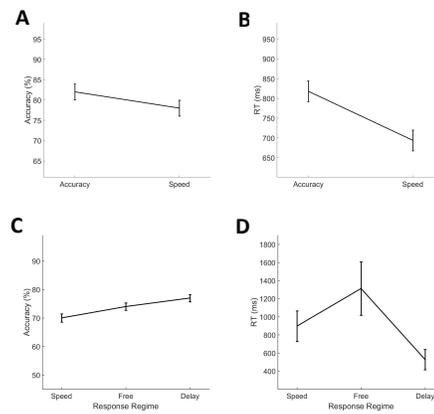
Figure 3: Behavioural performance plotted as a function of response regime for experiment 1 (A-B) and experiment 2 (C-D)

Static Urgency: Early CNV is More Pronounced under Speed Emphasis

To determine whether the CNV represents static components of urgency we examined its amplitude in a 100ms window centered on evidence onset. In line with Boehm et al. (2014), we found the early CNV to be more pronounced under speed emphasis in both experiment 1 (fig.4a; p<.05) and experiment 2 (fig.4b; p<.05).
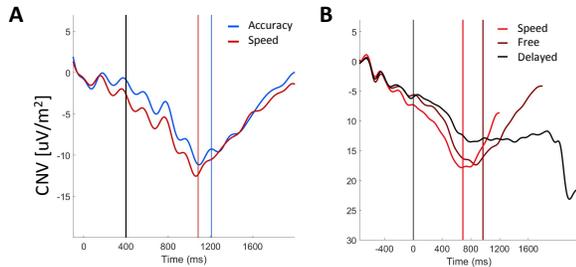
Figure 4: CNV waveform aligned to contrast change (A) and coherent motion (B). Vertical lines represent evidence onset (black; time point 0) and RT (coloured).

Dynamic Urgency: The CNV Grows at a Time Dependent Rate

To determine whether the CNV exhibits time dependent build up, we first examined its amplitude prior to response (-300 to -200ms) as a function of RT (6 RT bins). As expected of a dynamic urgency signal, the CNV became more pronounced over time as the response deadline approached, irrespective of response regime, in both experiment 1 (fig. 5a; p<.05) and experiment 2 (fig. 5b; p<.05). Moreover, the slope of the pre-response CNV steepened as a function of RT, irrespective of response regime, in experiment 1 (fig. 5c; p<.05) and experiment 2 (fig. 5d; p<.05) suggesting that this signal accelerates over time.
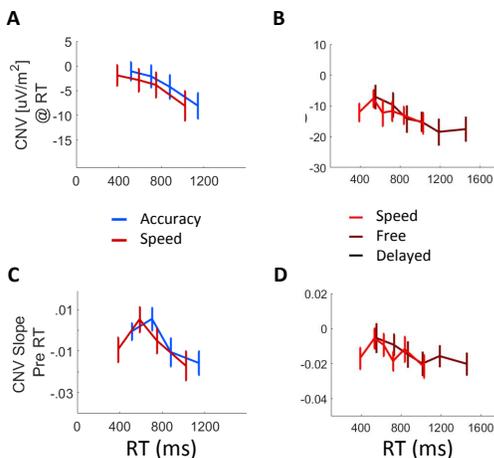
Figure 5: Pre-response CNV amplitudes (A-B) and slopes (C-D) plotted as a function of RT and response regime for experiments 1 (A;C) and 2 (B; D).

Dynamic Urgency: The CNV Grows at an Evidence Independent Rate

To determine whether the CNV exhibits evidence-independent build-up, we measured its slope prior to response (-450 to -150ms) as a function of sensory evidence strength. In experiment 1 the pre-response CNV slope was no different between higher and lower contrast trials (fig. 6a; p>.05). In experiment 2, although the pre-response CNV slope did scale with evidence strength, it did so in the reverse manner to that of an 'evidence accumulation' signal. Specifically, the CNV was steeper when motion coherence was weaker (fig. 6b; p<.05). However, this may be explained by the prevalence of slower responses on weaker evidence trials, which, as shown above, incur an acceleration in the growth of the CNV.
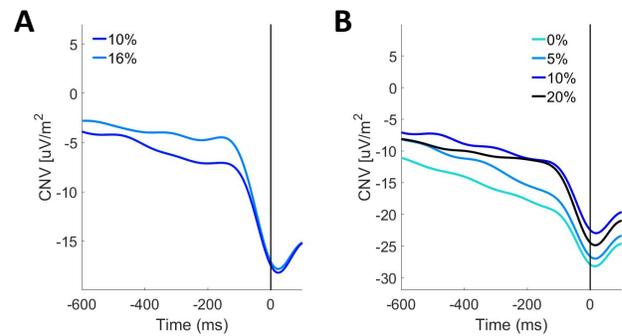
Figure 6: CNV aligned to response plotted as a function of sensory evidence strength in experiment 1 (A) and experiment 2 (B).

Discussion

The findings presented here support the novel characterisation of the CNV as a neural signature of dynamic urgency. Our findings show that, in addition to being more pronounced at baseline under speed emphasis (see also Boehm et al., 2014), the CNV grows in a time-dependent manner that is not driven by sensory evidence accumulation. Moreover, our results show that the rate of growth of the CNV increases over time, consistent with an acceleration of urgency as the response deadline draws closer.

These results have a number of key implications. Firstly, the characterisation of the CNV as a neural signature of urgency provides the unprecedented opportunity for researchers in perceptual decision making to directly study this key component of the decision process. Secondly, the ability to measure dynamic urgency at the neural level provides a means to adjudicate between different models of perceptual decision making that make different assumptions about the mechanisms underpinning response caution. Thirdly, the measurement of the CNV may be used as a tool for constraining parameters in those models pertaining to urgency in order to achieve better fits to

behavioural data. Fourthly, our findings provide a novel, mechanistically- grounded functional account of the CNV situated within the sequential sampling framework that attributes to it a central role in the decision making process.

Future Directions

It should be noted that further work remains to be done in order to fully consolidate the explanatory account of the CNV presented here. Specifically, further analyses will attempt to establish a direct correlation between the CNV and model-derived estimates of urgency using sequential sampling modelling, similar to efforts reported by Boehm et al. (2014) in which the early CNV amplitude was correlated with model-derived estimates of response caution. Moreover, following previous work (e.g. Murphy et al., 2016; Steinemann et al., 2018), further analyses will be undertaken in order to examine the effects of urgency on the decision process by measuring distinct neural signatures of domain-general and effector-selective decision formation.

Acknowledgements

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