Perceptual Decision Making Unfolds in a Processing Cascade Within and Across Brain Regions

Laura Gwilliams (leg5@nyu.edu)
New York University, Psychology,
6 Washington Place
New York, NY 10003, USA

Jean-Rémi King (jeanremi.king@gmail.com)
New York University, USA,
Frankfurt Institute for Advance Studies (FIAS),
Frankfurt, Germany

Abstract:

Perceptual decision making is proposed to consist of a sequence of processing stages. However, the neural computations involved at each stage mainly derive from spatially limited electrophysiology recordings or temporally unresolved functional Magnetic Resonance Imaging (fMRI). To shed light on these limitations, we apply linear multivariate pattern analyses (MVPA) to spatiotemporally resolved magneto-encephalography recordings (MEG). Seventeen participants discriminated between ambiguous visual symbols, constructed from 8-step morphs of letter/digit pairs. Stimulus features associated with each stage were orthogonalised by design: stimulus contrast (sensory), stimulus identity (evidence accumulation), stimulus ambiguity (difficulty) and response button (motor). Our results show that each of these variables can be sequentially decoded from the MEG signals generated by the visual, parietal and motor cortices respectively, and continue to be maintained in parallel thereafter. Importantly, the specific pattern of neural activity elicited by each variable continuously changed over time. Unlike discrete stage models, our results suggest that each stage is best accounted for by a cascade of neural computations within and across regions. These findings extend the results of previous studies and provide a macroscopic description of the elementary computations involved in perceptual decision making.

Keywords: perceptual decision making; MEG; MVPA; neural computations

Introduction

Transforming noisy environmental input (e.g. a pixelated frozen Skype screen) into a stable percept (e.g. recognising those pixels as one's boss) is a pervasive and seemingly effortless process; humans do it all the time without giving a second thought. The cognitive underpinnings of this ability, however, are far from trivial.

The field's current understanding is that perceptual decision making involves the continuous accumulation of sensory evidence until a decision threshold is reached, and a motor response is initiated (Gold & Shadlen, 2007). When the sensory input is ambiguous or noisy, evidence accrual – as represented by ramping neuronal activity in the parietal cortex – is slower, meaning that it takes longer to reach the decision threshold and initiate a response.

This process has been mapped onto at least three processing stages: sensory, accumulation and categorisation (Heekeren et al., 2008). The neural underpinnings of these processing stages have been investigated in humans using a range of techniques. For example, neural activation as recorded with fMRI has been found to track sensory evidence in a face-house categorisation task (Heekeren et al., 2006). Time-resolved techniques such as electro-encephalography (EEG) have been applied in similar discrimination tasks (Philiastides & Sajda, 2006), identifying two distinct response components. The first "early" response (~170 ms) is selective for faces and appears to track the initial sensory stage. A second "late" response (~300 ms) reflects decision difficulty.

Overall, the present empirical bases of perceptual decision making is therefore limited to 1) coarse macroscopic descriptions of brain activity or 2) precise but spatially-limited neuronal responses.

Method

Seventeen healthy adults completed a letter/digit discrimination task while MEG was recorded. A letter was formed by increasing (4:H) or decreasing (6:E) the contrast of a single solid bar. The stimulus was presented on-screen for 100 ms to either the left or right visual hemi-field. Participants had 2000 ms to identify the stimulus category via button press. Feedback was provided on unambiguous trials, and the next trial started 100-300 ms later.

Results and Discussion

Each processing stage was associated with a set of experimental variables. Sensory: presentation side (left/right), stimulus contrast (0-7), number of edges (5, 6, 7); Accumulation: behavioural selection (letter/digit), ambiguity (0-4); Motor: response side (left/right). For categorical and continuous variables, a regularised logistic and linear regression (l2) was fit, respectively, across all MEG sensors at each time sample separately. Accuracy and correlation scores were first computed within subjects, and then tested for significance across subjects with cluster-corrected statistics ($p < .05$).

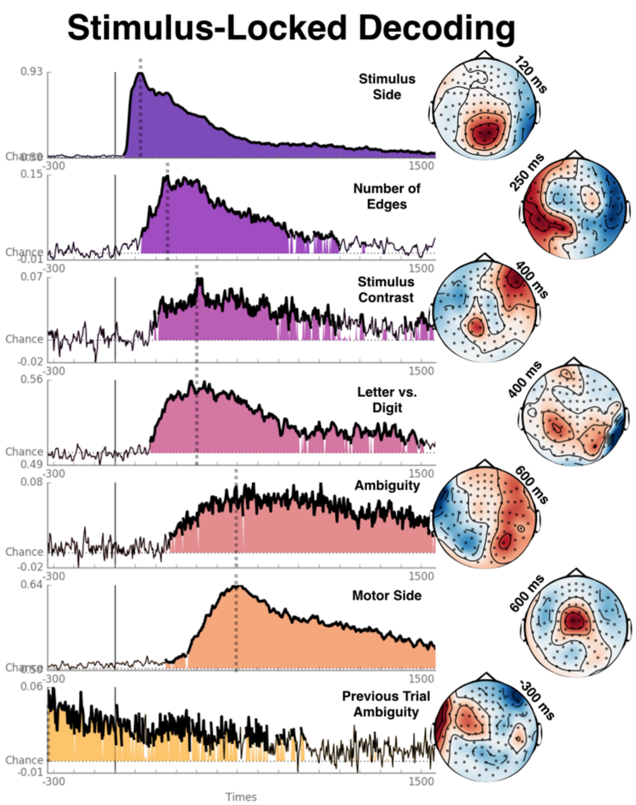

Figure 1: MEG decoding can track the cascade of processing stages involved in perceptual decision making. Decoding performance for each experimental variable as a function of time. Colored areas (left) correspond to decoding scores that are significantly above chance level across subjects ($p < .05$). Topographies (right) show MEG patterns at peak decoding performance (illustrated by a grey dashed line).

All variables could be decoded from the neural signal time-locked both to stimulus onset (Fig.1) and the onset of the motor response, following a sequence resembling a cascade of processing (McClelland, 1979), whereby lower-order features come online earlier, but are maintained parallel to higher-order features.

Furthermore, our results show that the perceptual representation varies as a function of sensory evidence and subjective reports. This provides a direct extension of Gold & Shadlen (2007)'s finding of ramping neural activity when using whole-brain analyses of human perceptual decision making.

Finally, and most importantly, source analysis revealed that the spatial patterns associated with evidence accumulation evolve not only across, but also within brain regions. This result suggests that a cascade of neural computations is performed on a single stimulus feature, even within a single brain region.

Conclusion

We elucidate the meso- and macro-scopic neural dynamics underlying perceptual decision making. Our results confirm multiple predictions of current theories (e.g. distinctions between sensory, evidence accumulation and motor stages) but also reveal unexpected patterns of neuronal activity that may call for a partial revision of discrete-stage models of perceptual decision making.

Acknowledgments

This work was supported by NYUAD Institute (G1001) (L.G). European Union's Horizon 2020 research and innovation program under the Marie Sklodowska-Curie Grant Agreement No. 660086, Bettencourt-Schueller Foundation and the Philippe Foundation (J-R.K).

References

Gold, J. I., & Shadlen, M. N. (2007). The neural basis of decision making. *Annu. Rev. Neurosci.*, *30*, 535-574.

Heekeren, H. R., Marrett, S., Ruff, D. A., Bandettini, P. A., & Ungerleider, L. G. (2006). Involvement of human left dorsolateral prefrontal cortex in perceptual decision making is independent of response modality. *Proceedings of the National Academy of Sciences*, *103*(26), 10023-10028.

Heekeren, H. R., Marrett, S., & Ungerleider, L. G. (2008). The neural systems that mediate human perceptual decision making. *Nature reviews neuroscience*, *9*(6), 467-479.

McClelland, J. L. (1979). On the time relations of mental processes: An examination of systems of processes in cascade. *Psychological review*, *86*(4), 287.

Philiastides, M. G., & Sajda, P. (2006). Temporal characterization of the neural correlates of perceptual decision making in the human brain. *Cerebral cortex*, *16*(4), 509-518.