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Final Progress Report – Bial Foundation

Predicting your decision while you make up your mind – an intra-cranial human study of the neural underpinning of decision-making

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Adult human beings typically experience their decisions and actions to be up to them in a meaningful manner. They decide, for example, whether to donate money to charity or use it for vacation, and they are therefore held morally responsible for the consequences of their decisions. However, some relatively recent neuroscientific studies by Libet and others claimed to challenge that notion, demonstrating predictive information in the brain about upcoming decisions before the person reported having consciously decided (Fried, Mukamel, & Kreiman, 2011; Haggard & Eimer, 1999; Libet, Gleason, Wright, & Pearl, 1983; Soon, Brass, Heinze, & Haynes, 2008; Soon, He, Bode, & Haynes, 2013). Therefore, some have claimed, it is unconscious brain activity that initiates action in humans, and the accompanying conscious decision may be ineffective, or irrelevant, to the production of action. If this interpretation is true, our introspective experience of free will may be no more than an alluring illusion (Harris, 2012; Libet, 1985; Maoz & Yaffe, 2013; Mele, 2006, 2009; Roskies, 2010; Sinnott-Armstrong & Nadel, 2011; Wegner, 2002).

However, these experiments have also come under conceptual and empirical criticism. Importantly, the type of decisions that were studied in them – i.e., arbitrarily raising the left or right hand at a time of the subject's choice for no reason or purpose and with no consequence to the subject – are highly artificial. In everyday situations, outside the lab, humans generally act for a purpose and according to reasons, and their decisions tend to have consequences. In that vein, it would be ludicrous to take someone to court for having raised her left hand rather than her right hand for no reason or purpose and devoid of any consequences. But, if by lifting her left hand she sends someone to the gallows and by lifting her right she sets him free, there are moral implications to her decision (Maoz & Yaffe, 2013).

We previously investigated monkeys deciding between smaller, immediate rewards and larger, delayed ones. We found single-unit activity in the dorsolateral prefrontal cortex and striatum that predicted the choice of the animals before they were even shown the visual cues that represented the decision alternatives. This early activity was more predictive the more the values of the decision alternatives for the monkeys were similar. We therefore interpreted this as bias activity, which then integrated together with the activity related to the values the animals attributed to the decision alternatives to form the final decision. When the values of the decision alternatives were divergent, the bias made little difference in the decision outcome; when the values were similar, the bias had a greater role in the decision (Maoz et al., 2013). Accordingly, we hypothesized that the bias would have a greater effect on the decision outcome in deliberate decisions than in arbitrary ones.

In other previous work we showed that deliberate decisions can also be predicted before they occur, even online and in real time. The previous real-time system that we built was able to predict which hand a patient would raise when she or he waited for a go-signal that followed a 5 s countdown to move. Hence, the system made a prediction only once, 0.5s before go-signal onset (Maoz, Ye, Ross, Mamelak, & Koch, 2012).

Here, with the help of the Bial Foundation, we have been constructing a much more sophisticated system that would continuously predict, online and in real time, which hand the patient would raise if she raised it at that moment. In previous progress reports, we had documented features of LFP activity that we had found to be predictive of the hand a subject would raise before action onset. Unfortunately, since the last progress report, in February 2014, we have had no new patients on which to test our features and continue the construction of the real-time system.

We had initially focused on intracranial recordings because, being closer to the neural activity source, they are cleaner and more robust than other neural recording techniques, In that they offer both high spatial and temporal resolutions. However, intracranially implanted patients are rare and far in between. Thus, while 10 electroencephalography (EEG) subjects could be recorded in a week, recording from 10 patients is likely to take 1-2 years. What is more, while EEG electrode placement tends to cover much of the cortex and is up to the researchers, implantation targets in patients are naturally based only on clinical considerations. So a specific subregion of the brain that yielded promising data in one patient might be targeted again only a few patients later. As real-time analysis is more prone to noise than analysis averaged over many trials and subjects, issues with availability of good recording sites can considerably extend the time required to construct and run a real-time system.

We have therefore shifted our focus from intracranial recordings to EEG. This is also the reason that our new Bial project, “Are free will and moral responsibility real or illusory? On the causal role of consciousness in decision-making, a combined EEG and intracranial study” for 2015 gives EEG recordings a more prominent role than this project. Preparing for EEG analysis, we gathered preliminary data from subjects playing our matching-pennies game (described in previous progress reports). In this game, subjects raised their left or right had at the go signal in the attempt to raise the same hand as their opponent (player 1) or a different hand than their opponent (player 2). They are financially incentivized to succeed, receiving $0.10 from their opponent in each round they win, both players starting the task with $5. In addition to these deliberate decisions, subjects also played an arbitrary version of the game, in which their winnings were uncorrelated to the hand they and their opponent raised.

We constructed a preliminary decoding system based on decrease of power in the μ band (6-14 Hz) before movement onset, hereafter termed μ suppression (Pfurtscheller & Aranibar, 1977; Salvaris & Haggard, 2014). In particular, looking at neural differences between trials that would culminate in left/right-hand raises, we found earlier and stronger differences for arbitrary decisions in comparison to deliberate ones. So we focused on the interval between 900 and 700 ms before movement onset. Using 5-fold cross-validation (training on randomly selected 80% of the trials and testing on the remaining 20%, 5 times), our preliminary system was able to predict with 55.7% average accuracy (95% confidence interval: 54.0% to 57.3%) for arbitrary decisions, but with only 49.2% average accuracy (95% confidence interval: 48.1% to 50.3%; Figure 1) for deliberate decisions, a significant difference (paired t-test p=0.0002). So, even this preliminary decoding system suggests that, already 700-900 ms before movement onset, there is some information about which hand a person would raise during arbitrary decisions (decoding accuracy significantly above chance), but not during deliberate decisions (accuracy at chance).

While our decoding system based on μ-band power shows promise, relying on a combination of features instead of a single one is more likely to result in higher accuracy (Lemm, Blankertz, Dickhaus, & Müller, 2011), especially given the noisier and less-robust nature of EEG recordings in comparison to intracranial recordings. We have therefore begun investigating other potential features. These include phase coupling (Canolty et al., 2010; Cohen, Elger, & Fell, 2009), cross-band phase/amplitude coupling (Canolty et al., 2006; Cohen et al., 2009), and cross-region coupling (Cocchi, Zalesky, Fornito, & Mattingley, 2013). We will continue investigating these features as part of our 2015 Bial project.

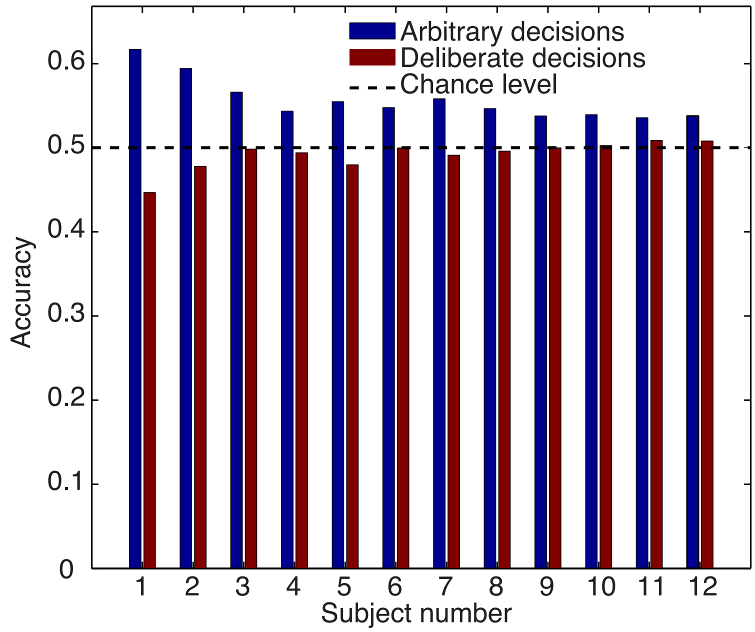

Figure 1: Subject-by-subject decoding accuracy for deliberate and arbitrary decisions 700-900 ms before action on set in matching-pennies task

Another facet of our research relates to the growing "crisis of confidence" in the reliability and replicability of findings in neuroscience and psychology (Pashler & Wagenmakers, 2012). In the wake of this reproducibility issue, some have turned to techniques for decoding neural data on the single-trial level, which are generally considered safe havens of reliability and replicability. There, as in our real-time system (Maoz et al., 2012), a statistical model is constructed using only part of the empirical data, and this model is then used to predict another, independent part of the data. If successful, this is thought to bode well for the data's replicability. However, we show various biases that persist even for this more-rigorous analysis method, and explain how to overcome them. We are further developing a tool that would calculate the maximum likely decoding accuracy for data given its signal and noise profiles, against which scientists could compare their results (Maoz & Salvaris, in preparation).

Last, neuroscience is not carried out in a vacuum, of course. And research directions and experimental data interpretations are critically influenced by relevant concepts on which the researchers rely, consciously and unconsciously. This is especially true when investigating high-level concepts, like the role of consciousness in volition. We have therefore investigated how neuroscientists on the one hand typically explicitly endorse materialistic views of the world, while at the same time their writing suggests implicit dualistic tendencies. This has important consequences for their scientific work. But it also has societal repercussions outside the lab. One example is the "my brain made me do it" defense, which claims mitigated criminal responsibility due to anomalies in a defendant's brain, and is increasingly used in court (Mudrik & Maoz, 2014). This paper has been recently published, acknowledging the support of the Bial Foundation.

In sum, with the generous support of the Bial Foundation, we have over the past few two years conducted research with 5 consenting, intracranially implanted epilepsy patients, and with numerous subjects recorded using EEG. Our research has helped demonstrate that deliberate decisions can be decoded online and in real time before action onset (Maoz et al., 2012). We also challenged the conclusion that many drew from the Libet and followup experiments – i.e., that consciousness played no causal role in decision-making: We showed that neural activity that predicts future decisions is not necessarily part of the decision process, and may be related to ongoing bias activity, especially for arbitrary decisions (Maoz et al., 2013). We also showed that the early predictability of arbitrary decisions does not generalize well to more-interesting deliberate decisions (Mudrik, Maoz, Yaffe, Adolphs, & Koch, In preparation). Further, we demonstrated that the method used in the Libet experiment to measure the onset of the decision in humans was fundamentally inaccurate and biased, and thus flawed (Maoz et al., 2015). In other veins of our research, we have been contributing to overcoming the crisis of confidence in psychology and neuroscience by investigating and correcting potential errors in decoding of neural data (Maoz, Salvaris, Rutishauser, & Adolphs, In preperation). We looked into where neuroscience can and cannot contribute to the notion of moral and criminal responsibility (Maoz & Yaffe, 2013). And we investigated important conceptual issues that drive research directions and data interpretation in the neuroscience of decision-making, free will and consciousness and in the relation between neuroscience and society (Mudrik & Maoz, 2014).

We therefore sincerely thank the Bial Foundation for having supported this important research. And we are honored that the foundation has decided to continue and fund our new project for 2015, "Are free will and moral responsibility real or illusory? On the causal role of consciousness in decision-making, a combined EEG and intracranial study." We are looking forward to this continued partnership with the foundation in the year to come.

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