Unconscious determinants of free decisions in the human brain

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There has been a long controversy whether subjectively “free” decisions are determined by brain activity ahead of time. Here we show that the outcome of a decision is encoded in brain activity of prefrontal and parietal cortex even up to ten seconds before it enters awareness. This delay presumably reflects the operation of a network of high-level control areas that begin to prepare an upcoming decision long before it enters awareness.

The impression that we are able to freely choose between different possible courses of action is fundamental to our mental life. However, it has been suggested that this subjective experience of freedom is no more than an illusion, and that our actions are initiated by unconscious mental processes long before we become aware of our intention to act[1-3]. In a previous experiment[1], electrical brain activity was recorded while subjects were asked to press a button as soon as they felt the “urge” to do so. Interestingly, their conscious decision to press the button was preceded by a few hundred milliseconds by a negative brain potential, the so-called “readiness potential” (RP) that originates from a brain region involved in motor preparation, the supplementary motor area (SMA). Because brain activity in the SMA consistently preceded the conscious decision it has been argued that the brain had already unconsciously made a “decision” to move even before the subject became aware of it.

However, these intriguing experiments have left a number of important controversial questions open[4-6]: (1) The readiness potential is generated by the SMA, and hence only provides information about late stages of motor planning. Thus, it is unclear whether the SMA is indeed the cortical site where the decision for a movement originates[7] or whether high-level planning stages might be involved in unconsciously preparing the decision[8], as shown in studies on conscious action planning[9-12]. (2) The time delay between the onset of the readiness potential and the decision is only a few hundred milliseconds[1]. It has been repeatedly argued that at such short delays potential inaccuracies in the behavioural measurement of the decision time could lead one to misjudge the relative timing of brain activity and intention[3-6]. (3) An important question is whether any leading brain activity indeed *selectively* predicts the specific outcome of a choice ahead of time. In order to rule out that any leading activity merely reflects unspecific preparatory activation[13], it is important to study free decisions between more than one behavioural option[11,14].

Here we investigated directly which regions of the brain pre-determine conscious intentions and how early they start shaping a motor decision. Subjects who gave informed written consent performed a freely paced motor decision task while their brain activity was measured using functional magnetic resonance imaging (fMRI; see **Fig. 1** and **Supplementary Methods**). They were asked to relax while fixating on the center of the screen where a stream of letters was presented. At some point, when they felt the urge to do so, they should freely decide upon one of two buttons, operated by the left and right index fingers, and press it immediately. In parallel they should remember the letter presented when their motor decision was consciously made. After subjects pressed their freely chosen response button a “response mapping” screen with four choices appeared. By selecting the corresponding letter with a second button press subjects indicated when they had made their motor decision. After a delay the letter stream started again and a new trial began. The freely paced button presses occurred on average 21.6 s after trial onset, thus leaving sufficient time to estimate any potential buildup of a “cortical decision” without contamination by previous trials. Both left and right response buttons were pressed equally often and most of the intentions (88.6 %) were reported to be consciously formed within 1,000 ms prior to the movement (see **Supplementary Material** for details).

Next we directly assessed how much predictive information each brain region contained about the specific outcome of a motor decision at *various time points* before and after it reached awareness. For each time point we measured how much information could be decoded from local patterns of fMRI signals in various brain regions using statistical pattern recognition techniques[15]. These pattern-based decoders were trained to predict the specific outcome of a subject’s motor decision by recognizing characteristic local brain patterns associated with each choice. This highly sensitive approach had several advantages over previous studies. First, it allowed us to investigate any potential *long-term* determinants of human intentions that preceded the conscious intention much beyond the few hundred milliseconds observed over the SMA[1,14]. Second, it allowed us to investigate for each brain region separately how much information it had about the outcome of a motor decision. Finally, it allowed us to identify whether any leading brain activity indeed selectively predicted the outcome of the subject's choice, rather than reflecting potentially unspecific preparatory processes.

In order to validate our method we first investigated from which brain regions this decision could be decoded *after* it had been made and the subject was executing the motor response. As expected, two brain regions encoded the outcome of the subject's motor decision during the execution phase: primary motor cortex and SMA (**Fig. 2**, top). Next, we addressed the key question of this study, whether any brain region encoded the subject's motor decision ahead of time. Indeed, we found that two brain regions encoded with high accuracy *prior* to the conscious decision whether the subject was about to choose the left or right response, even though the decision had not yet been made (**Fig. 2**, bottom; threshold p=0.05 fwe-corrected for multiple spatial and temporal comparisons). The first region was in frontopolar cortex, BA10. The predictive information in the fMRI signals from this brain region was already present 7 seconds prior to the subject's motor decision. Taking into account the sluggishness of BOLD responses the predictive *neural* information will have preceded the conscious motor decision by up to 10 seconds. There was a second predictive region located in parietal cortex stretching from the precuneus into posterior cingulate cortex. Importantly, there was no overall signal increase in the frontopolar and precuneus/posterior cingulate during the preparation period (**Supplementary Fig. 3**). Rather, the predictive information was encoded in the local spatial pattern of fMRI responses, which is presumably why it has not been noticed before. When the statistical threshold was relaxed several other regions of frontal cortex exhibited predictive information, albeit less pronounced (**Supplementary Table 1**). Importantly, we also ensured that there was no carry-over of information between trials, so that the high decoding performance preceding the motor decision by up to 10 seconds cannot reflect decoding related to the previous trial (**Supplementary Material**). Finally, we also assessed to which degree the *timing* of the decision could be predicted ahead of time. We found that decoding of the time decision was possible as early as 5 seconds preceding the motor decision, but mainly from pre-SMA and SMA, whereas in the frontopolar and parietal cortex this was only possible just before the motor decision

(**Supplementary Fig. 3**). Thus, in very early stages there appears to be a double dissociation between brain regions shaping the specific *outcome* of the motor decision and brain regions determining the *timing* of a motor decision. At later stages right before the conscious decision both of these regions begin to encode timing and handedness information. Finally in order to further investigate the involvement of frontopolar cortex and precuneus in selecting intentions we investigated voluntary decisions where subjects have to decide between left and right responses at an externally determined point in time. In this case the time when a decision is selected is under experiment control. This revealed that frontopolar cortex was already predictive during the selection of the response whereas the predictive information in precuneus began after the selection during the delay. This is in agreement with a trend in the main experiment that showed that the information in lateral frontopolar cortex peaked already at the earliest time point. One interpretation of this finding is that frontopolar cortex was the first cortical stage at which the actual decision was made, whereas precuneus was involved in storage of the decision until it reached awareness. Importantly, in this control experiment the intention was selected consciously, suggesting that similar networks might be involved in conscious and unconscious preparation of decisions (see **Supplementary Material** and **Supplementary Fig. 9** for full details).

Taken together, two specific regions in the frontal and parietal cortex of the human brain had considerable information that predicted the outcome of a motor decision the subject had not yet even consciously made. This suggests that when the subject's decision reached awareness it had been influenced by unconscious brain activity up to even 10 seconds before, thus also providing a potential cortical origin for unconscious changes in skin conductance preceding risky decisions[8]. Our results go significantly beyond previous studies[1-15] by showing that the earliest predictive information is encoded in specific regions of frontopolar and parietal cortex, not in SMA. This preparatory time period in high-level control regions is considerably longer than reported previously for motor-related brain regions[1,14], and is considerably longer than the predictive time exhibited by the SMA in the current study (**Supplementary Fig. 3**). Also, in contrast to most previous studies[1,13], it reveals that this prior activity is not an unspecific preparation of a response. Instead, it specifically encodes how a subject is going to decide. Thus, the SMA is presumably not the ultimate cortical decision stage where the conscious intention is initiated as has been previously suggested[7]. Importantly, the lead times are too long to be explained by any timing inaccuracies in reporting the onset of awareness, a major criticism of previous studies[4-6]. The temporal ordering of information suggests a tentative causal model of information flow, where the earliest unconscious precursors of the motor decision originated in frontopolar cortex, from where they influenced the build-up of decision-related information in the precuneus and later in SMA where it remained unconscious for up to a few seconds. This substantially extends previous work that has shown that BA10 is involved in storage of *conscious* action plans[9-11] and shifts in strategy following negative feedback[12]. Thus, a network of high-level control areas begins to shape an upcoming decision long before it enters awareness.

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AUTHOR CONTRIBUTIONS

J.D.H, C.S.S, M.B. and H.J.H. conceived the experiment. C.S.S. and J.D.H. carried out the experiment. C.S.S. analyzed the data. J.D.H. and C.S.S. co-wrote the paper.

FIGURE CAPTIONS

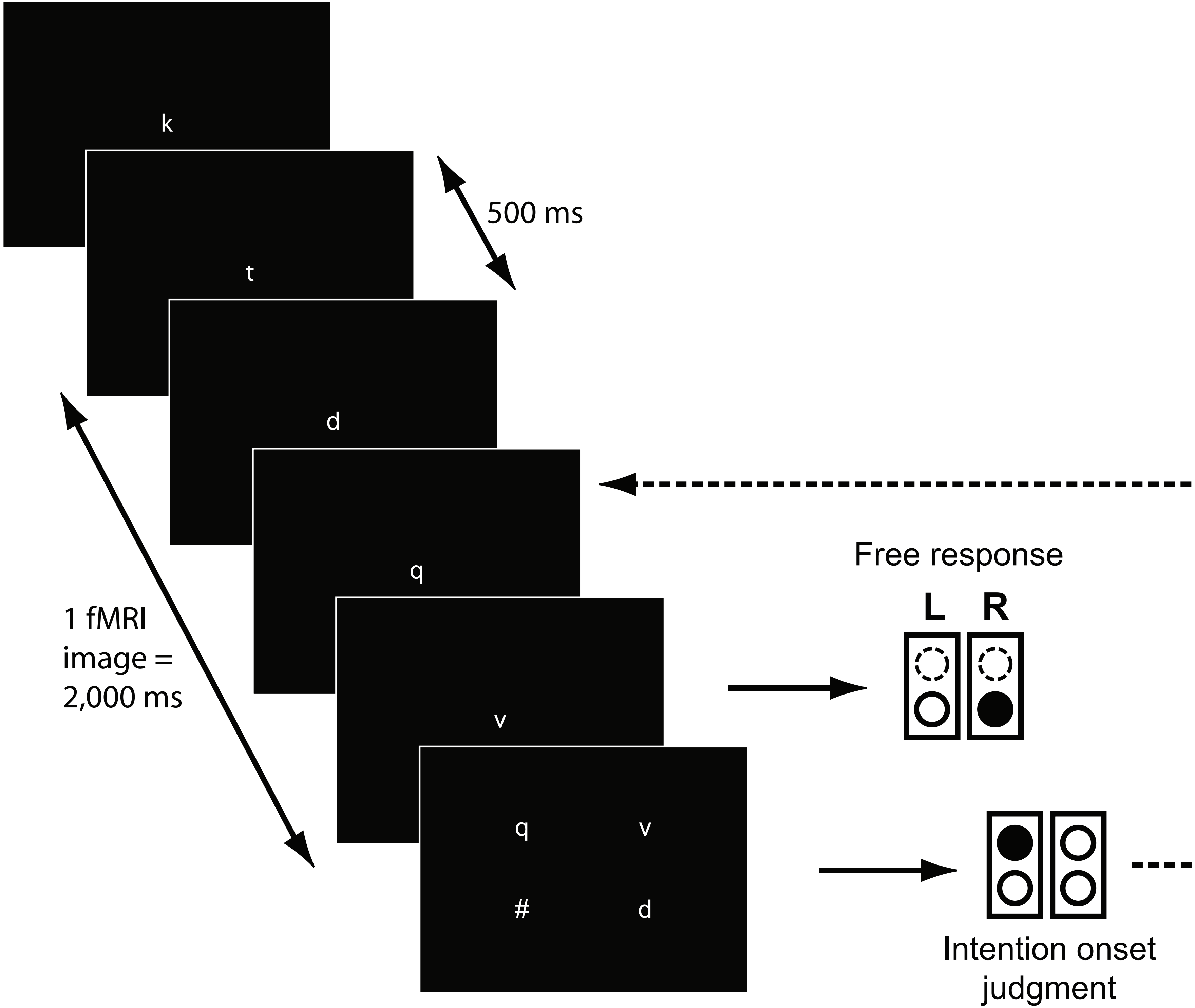
Figure 1: Measuring the onset time of conscious motor intentions. Subjects viewed a letter stream that updated every 500 ms (shown here only for a few frames). At some point they spontaneously made the decision for either their left or right index finger and then pressed the corresponding button ("free response"). Subsequently, they were presented with a response mapping screen that instructed subjects which second button to press to report the time when they consciously made the motor decision (see **Supplementary Material** for details).

Figure 2: Decoding the outcome of decisions before and after they reached awareness. Colour-coded brain areas show regions where the specific outcome of a motor decision could be *decoded* before (bottom, green) and after (top, red) it had been made. The graphs depict separately for each timepoint the accuracy with which the subject's "free choice" to press the left or right button could be decoded from the spatial pattern of brain activity in that region (solid line, left axis; filled symbols: significant at $p<0.05$; open symbols: not significant; error bars = s.e.m.; chance level is 50 %). As might be expected, decoding accuracy is higher in cortical areas involved in the motor execution of the response, than in areas shaping the upcoming decision before it reaches awareness (note difference in scale). The vertical red line shows the *earliest* time when the subjects became aware of their choices. The dashed (right) vertical line in each graph shows the onset of the *next* trial. The inset in the bottom left shows the representative spatial pattern of preference of the most discriminative searchlight position in frontopolar cortex for one subject.

SUPPLEMENTARY INFORMATION GUIDE

Combined File with Supplementary Figures, Tables, Discussion and Methods.

Contents: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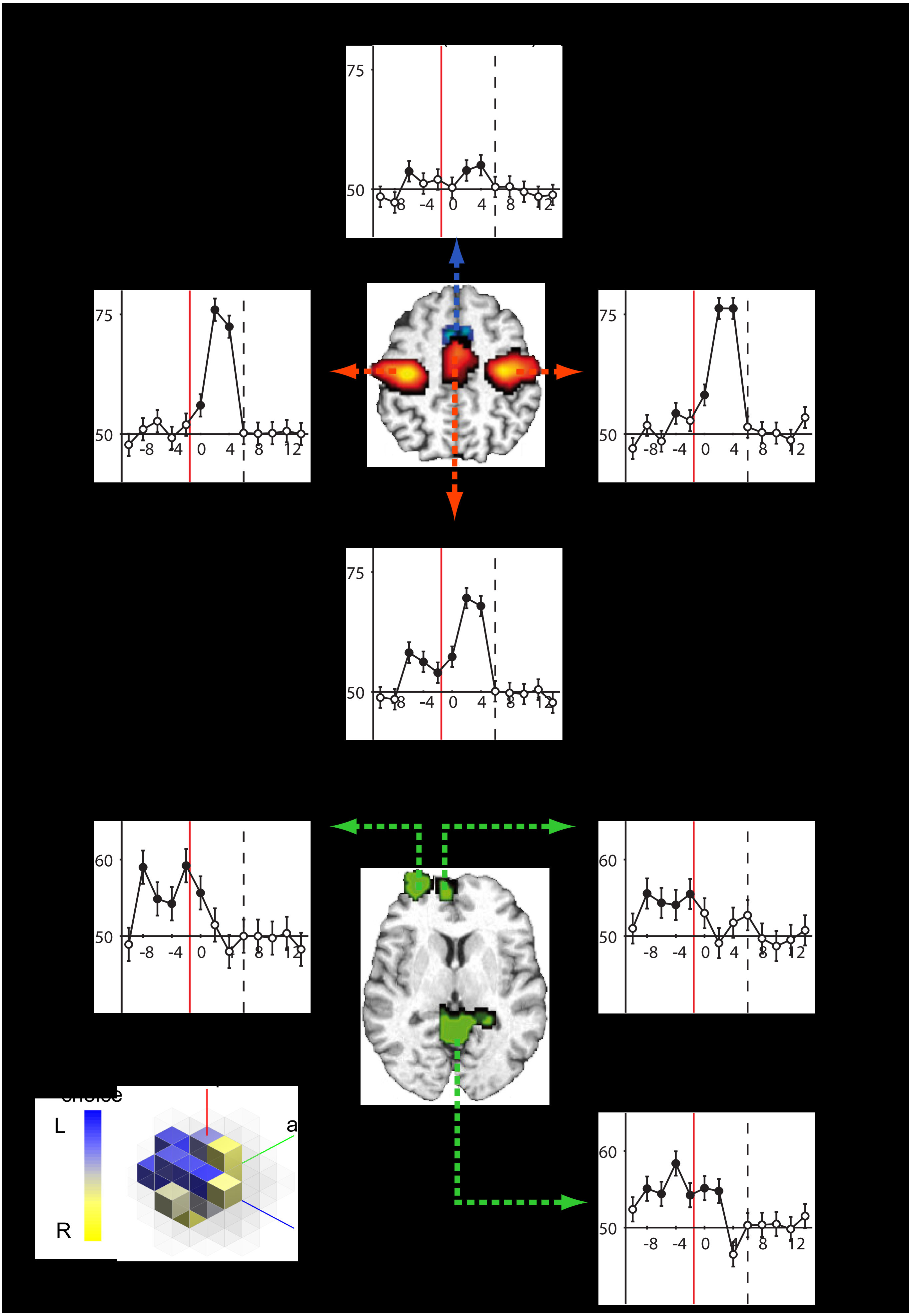

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