



# The role of cognitive control and top-down processes in object affordances

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Accepted: 22 February 2021  
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## Abstract

A widely held though debatable claim is that the picture of an object like a frying pan automatically elicits features of a left/right-handed grasp action even in perceptual tasks that make no demands on the observer to consider the graspable properties of the depicted object. Here, we sought to further elucidate this claim by relying on a methodology that allowed us to distinguish between the influence of motor versus spatial codes on the selection of a left/right-handed response while electroencephalographic data were recorded. In our experiment, participants classified images of frying pans as upright or inverted using a left/right key press or by making a left/right-handed reach-and-grasp action towards a centrally located response element while we recorded electroencephalographic (EEG) data. In line with previous evidence (Bub, Masson, & van Noordenne, *Journal of Experimental Psychology: Human Perception and Performance*, 47(1), 53–80, 2021), these two modes of responding generated distinct correspondence effects on performance induced by the same set of images. In terms of our EEG data, we found that neither motor (the lateralized readiness potential) nor visual (N100 and P100) potentials were sensitive to handle-response hand correspondence. However, an exploratory theta analysis revealed that changes in frontal theta power mirrored the different correspondence effects evoked by the image on key press responses versus reach and grasp actions. Importantly, our results provide a link between these disparate effects and the engagement of cognitive control, highlighting a possible role of top-down control processes in separating motor features from the task-irrelevant features of an object, and thus in claims regarding object affordances more generally.

**Keywords** Cognitive control · EEG · Object affordance · Theta power · Time-frequency · Event-related potential · VEP · Attention

The notion of an object's affordance, originally developed by Gibson (1979), refers to the actions offered (i.e., afforded) by an object in relation to the physical capabilities of an observer. For example, the hand used to reach and grasp a mug is influenced by the orientation of the handle on the left or right. Supporting the idea of an object affordance, right-handers are much less likely to use their dominant hand to grasp a mug when the handle is oriented to the left (Bryden & Huszczynski, 2011). From a Gibsonian standpoint, we could say that the physical

characteristics of the object, including the spatial location of the handle, afford a left-handed or right-handed grasp action.

Gibson's conceptualization of the potential for action afforded by an object has been greatly modified in recent years. It is now frequently argued that even a picture can automatically trigger affordances driven by the graspable properties of the depicted object (see Proctor & Miles, 2014, for a recent review). Evidence taken as support for this claim is that the handle of the object on the left or right, though task-irrelevant, generates correspondence effects on the selection of left/right-handed key press to a visual or conceptual attribute of the depicted object. Responses are faster and more accurate when the location of the handle is aligned (i.e., corresponding) rather than misaligned (i.e., noncorresponding) with the side of the key press. The influence of the handle on performance occurs, it is claimed, because key-press responses to the depicted object are influenced by its graspable properties.

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Despite widespread endorsement of this idea, much of the evidence remains unconvincing. While some work has led to the inference that components of a grasp action are triggered by the task-irrelevant features of an object regardless of the intentions of an observer (Tucker & Ellis, 1998), other work has shown either noncorrespondence (Tipper et al., 2006; Yu et al., 2014) or even reverse correspondence effects (Bub, Masson, & van Noordenne, 2021; Cho & Proctor, 2011) when participants make key presses to classify objects. Numerous correspondence effects induced by images of graspable objects appear to be due to spatial codes affecting the selection of any left/right-sided key-press response, even responses made with the feet (Phillips & Ward, 2002) or with the index/middle finger of a single hand (Cho & Proctor, 2010). There is little evidence that the handle of the object has an automatic effect on the selection of a left or right hand.

A number of studies have incorporated electroencephalographic (EEG) data to further elucidate the nature of the codes generated by task-irrelevant properties of graspable objects. These have unfortunately also yielded disappointing and sometimes conflicting results. A study by Goslin et al. (2012) attempted to directly address the question of whether images of graspable objects automatically trigger motor affordances by examining both the lateralized readiness potential (LRP) and two visual evoked components (P100 and N100) in a task that required participants to make key presses to classify handled objects as either household items or tools. Goslin et al. (2012) found an effect of congruency (i.e., when the location of the response hand matched the position of the handle) for both the LRP, and an interaction between response hand and handle location in early visual components (P100 and N100). They concluded that these findings showed an obligatory connection between visual and motor pathways in the perception of graspable objects. However, a further electrophysiological investigation by Lien et al. (2013) provided no support for this claim, as Lien and colleagues were unable to replicate the effect of the handle on the P100 and N100 reported by Goslin et al. for the same centrally presented images of graspable objects. Lien et al. also argued that the LRP can become active quite early after stimulus onset, complicating attempts to directly link this ERP component to response activation or selection.

We should note, however, that these divergent results include analyses of the behavioural effects of the graspable objects on response time that hardly permit any clear inferences about the nature of any changes observed in the EEG signal. Goslin et al. (2012) required subjects to classify objects as tools or kitchen utensils by means of a left/right-handed key press. The correspondence effect of the handle on response time was only reliable for tools and was completely absent for utensils. Although both the P100 and N100 were modulated by the correspondence between response hand and handle orientation, these effects were likewise only apparent for

tools, and were very small. Lien et al. (2013) failed to show any reliable effects whatsoever on key-press responses for either category. If anything, in contradiction to the behavioural effects observed by Goslin et al., kitchen utensils showed a weak trend towards a correspondence effect, whereas no effect was observed for tools.

Here, we wish to further pursue the relationship between the codes induced by the image of a graspable object and their putative effects on EEG data. Our view is that different control processes may help explain the disparities in whether or not correspondence effects are present. In fact, correspondence effects clearly depend on the coding of response options in working memory (Ansorge & Wühr, 2004), and it may be that top-down influences (modulated by task design or demands; Bub & Masson, 2010; Bub et al., 2018) are more relevant to the emergence of correspondence (or reverse correspondence) effects on the selection of a key-press response. Moreover, Bub, Masson, and van Noordenne (2021) found that when subjects make key presses to classify objects and the base of an object protrudes laterally (whole object centred; Cho & Proctor, 2011), participants are faster and more accurate when the location of the handle is opposite to the key-press location. In fact, these findings find support in an argument advanced by Cho and Proctor (2011), that the stimuli themselves have two spatial codes in opposite directions—subjects have to expend more resources classifying the object when the handle is on the same side as the response hand. That is, it is the base of the object that protrudes to the left or right of the midline of said object that produces correspondence effects. However, when subjects instead make a cued-reach action to classify the object, an effect of handle is present, as performance is faster and more accurate when the response hand is on the same side as the object's handle. In the reach action case, Bub, Masson, and van Noordenne (2021) argued that it is instead motor codes involved in the planning of a reach action that generate the correspondence effects. To summarize briefly, key presses induced reverse correspondence effects while reach actions induced correspondence effects despite the exact same images being used. These two findings in conjunction are important because they suggest that different cognitive processes are required across these two response modes—which Bub and colleagues suggested was due to the introduction of different control processes between the two response modes.

To complement conventional response time analyses, delta plots showing the change in response time effects across quantiles (Pratte et al., 2010) can be used to infer whether correspondence effects develop in different patterns across response modes. That is, delta plots can provide the ability to distinguish between different time courses of correspondence effects. If motor codes generated by a reach action lead to differences in how objects are perceived (i.e., by emphasizing the handle of the object rather than the base) when

compared with cases where subjects make key presses, then it seems possible that the time course of correspondence effects in the key-press response mode and reach-grasp response mode could differ due to attentional differences between the two response modes. We will return to a discussion of the time courses of correspondence effects and what they may mean for different response modes later in the paper.

Thus, previous work by Bub, Masson, and van Noordenne (2021) has argued for a role of different control processes in driving correspondence effects. Building upon these claims, we believe that it is possible that frontal theta power could be sensitive to these response mode differences, due to a series of compelling experiments arguing that frontal theta power reflects cognitive control (Cavanagh et al., 2012; Cavanagh & Frank, 2014; Cohen & Donner, 2013). Specifically, frontal theta bursts occur during response conflict as an indication that further cognitive resources should be recruited (Cohen & Cavanagh, 2011), as conflict has been suggested to cause cognitive control processes to be initiated (Botvinick et al., 2001). This finding by Cohen and Cavanagh (2011) is pertinent to the present experiment: oscillatory brain activity is sensitive to large-scale networks (e.g., providing a solution to the binding problem) and allows for the quantification of neural responses that are not perfectly time locked to an event.

While it is difficult to tie frontal theta power directly or solely to cognitive control processes, converging evidence from single-cell recordings in primates shows that frontal theta power is involved in binding the anterior cingulate cortex to other brain regions involved in control processes (Womelsdorf et al., 2010). More importantly however, there is evidence that frontal theta power varies with response-time in Simon-type tasks, increasing for incongruent trials relative to congruent trials much like response time (Nigbur et al., 2011; Töllner et al., 2017; van Driel et al., 2012; van Driel et al., 2015). Researchers have suggested that this frontal theta power increase reflects the behavioural adjustment needed to adapt to the increased conflict that is present on incongruent trials relative to congruent trials (Nigbur et al., 2011). The suggested role for frontal theta power in cognitive control, and the claim by Bub and colleagues that control processes play a role in explaining correspondence effects, provides justification for investigating whether or not frontal theta oscillations vary across object-based correspondence effects.

The questions we wish to pursue are whether EEG components might be usefully applied to further elucidate the distinct codes induced by whole object centred images of objects across two different response modes (key press, reach-grasp), and whether frontal theta power might be sensitive to these different control processes across the two response modes. In the present work, upright/inverted judgments were made in response to the same set of images, carried out by means of (i) a left/right-handed key-press response, or (ii) a left/right-handed reach-and-grasp action on an external response

element. The former mode of responding induces reverse correspondence effects because of spatial codes triggered by the base of the object protruding on the left or right (Proctor et al., 2017). The latter mode induces positive effects of the handle on the planning of a goal posture involving the right or left hand (Bub et al., 2018; Bub & Masson, 2010). Our goal was to analyze ERPs (P100, N100, LRP) and EEG (frontal theta power) given robust and divergent correspondence effects of the depicted object on response selection.

EEG is an ideal candidate for investigating these effects because of work showing that EEG is sensitive to both motor preparation differences (the LRP; Eimer, 1998) and attentional effects tied to stimulus location and complexity (the P100 and N100 components; Luck et al., 1990). Arguments advanced previously by Bub, Masson, and van Noordenne (2021) suggest that competing spatial codes in the key-press response mode cause the reverse correspondence effects while motor codes in the reach-grasp response mode cause the correspondence effects—meaning there are distinct spatial and motor effects in the two response modes. Thus, because EEG is sensitive to both attention and motor preparation, EEG could provide one avenue for confirming or disconfirming these claims about the role of spatial and motor codes in these correspondence effects. In addition, given the proposed link between frontal theta power and cognitive control (Cavanagh & Frank, 2014), and the claim that control processes differ across the two response modes (Bub, Masson, & van Noordenne, 2021), the analysis of frontal theta power could also allow for the extension of work using EEG to examine cognitive control in the Simon task to work examining object correspondence effects.

Behaviourally, as in previous investigations of this task (Bub, Masson, & van Noordenne, 2021), we expected that we would observe an interaction between response mode and correspondence effect. That is, we expected that in the key-press response mode participants would be slower to respond on corresponding trials than noncorresponding trials, while in the reach-grasp response mode participants would be slower to respond on noncorresponding trials than corresponding trials. For the P100 and N100, we expected that if attentional shifts to the relevant part of the object can be detected using EEG then we would observe an effect of correspondence in the key-press response mode, but no effect of correspondence in the reach-grasp response mode on the P100 and N100, due to the competing spatial codes present in the key-press response mode. Moreover, we would also expect an effect of response mode on the P100 and N100 due to the differences in how attention is directed between the two response modes. For the LRP, we expected the reverse of the visual potentials—an effect of correspondence in the reach-grasp response mode, but no effect of correspondence in the key-press response mode—due to the claim that action intentions generate motor codes related to planning in the reach-

grasp response mode, but not in the key-press response mode. Finally, we conducted an exploratory analysis of frontal theta power, which yielded a prediction of an interaction between correspondence and response mode—similar to what we expected from our response-time data given previous work highlighting that frontal theta power is sensitive to behavioural effects in Simon tasks (e.g., Nigbur et al., 2011). Specifically, we predicted that frontal theta power would show a reverse correspondence effect in the key-press response mode and a correspondence effect in the reach-grasp response mode.

## Method

### Subjects

Thirty-three subjects, enrolled in psychology courses at the University of Victoria, participated for extra credit in their course. Two subjects were excluded due to error rates above 15%, and a third subject was excluded due to data quality problems in the EEG (independent components analysis could not be completed). The remaining 30 subjects (eight males and 22 females) had an average age of 22 years (range: 18–39 years), and 28 were right-handed. While we did not perform an a priori power analysis for this experiment, the target sample size for this experiment was based on prior investigations with similar procedures and design (Bub et al., 2018; Bub, Masson, MacRae, & Marshall, 2021). These previous investigations were informed by a power analysis in which the authors would be able to detect a small effect for a

repeated-measures comparison assuming a correlation of .90 to .95 between conditions. All subjects provided written, informed consent before beginning the experiment. Ethics approval was obtained from the University of Victoria Human Research Ethics Board.

### Materials

All testing occurred in a soundproof room, with subjects seated 55 cm in front of a 59-cm monitor ( $1,680 \times 1,050$  pixels resolution). Stimulus presentation and data acquisition were controlled using MATLAB (Version 8.2, The MathWorks, Natick, MA, USA) through the Psychophysics Toolbox extension (Brainard, 1997; Pelli, 1997), on a Linux-based operating system (Ubuntu Version 16.04). The stimuli consisted of four grayscale images of a frying pan (see Fig. 1). Each image was centred on a gray rectangle so that the left-most and right-most edges of the pan were equidistant from the nearest vertical border of the rectangle. The visual angle of the rectangle was  $10^\circ 29' 0.53''$  (width) and  $16^\circ 23' 0.92''$  (length) when viewed from a distance of 55 cm.

### Procedure

Before beginning the task, subjects were instructed to minimize extraneous head and body movements, and then received written instructions presented on the computer monitor. Subjects were told that during the task they would be presented with images of a frying pan and that the task was to classify the orientation of the frying pan as either upright or inverted. Following this, subjects were given instructions for either the



**Fig. 1** Frying pan stimuli used in the experiment. Note that the pan is centered against the gray rectangle



key-press or reach-grasp response mode. After completing all trials in one response mode, subjects completed a second set of trials in the other response mode. Order of presentation of these two response modes was counterbalanced across subjects.

In the key-press response mode, subjects were instructed to respond on the keyboard that was in front of them using their left index finger for the “A” key and their right index finger for the “L” key. Subjects completed two separate blocks of 112 trials with each block defined by the assignment of key to response category (left key = upright, right key = inverted, or vice versa). The order of these two blocks was counterbalanced across subjects. In the reach-grasp response mode, subjects depressed the “A” and “L” keys using their left and right index fingers, respectively. They responded by lifting one hand and grasping a response element that consisted of a horizontally oriented aluminum cylinder placed in front of them and firmly mounted on a stationary base. Assignment of hands to the two response categories was arranged as in the key-press response mode with 112 trials in each block.

For each of the four blocks of 112 trials, the first 12 trials were considered practice trials, leaving 100 critical trials with each frying pan image being presented equally often across those trials. After completing each set of practice trials, a self-paced rest break was given, in which subjects were prompted to ask the experimenter if they had any questions. A rest break was also provided after completing each set of 50 critical trials.

Each trial began with a fixation cross presented at the center of the monitor for 250–350 ms, which was then replaced with a blank screen for 250–350 ms. Following this, one of the four frying pan stimuli was shown at the centre of the monitor for 650–750 ms, after which it was replaced with a blank screen until the participant responded. In the reach-grasp response mode, extensive pilot testing revealed an overabundance of eye movements and motor artifacts when subjects returned their hand to the keyboard, which negatively impacted data quality. Because of this, in the reach-grasp response mode, after making their response, subjects were instructed to keep their hand on the response element until they heard a beep (about 2 s post response), after which they could return their hand to the keyboard.

## Data recording

EEG data were recorded from 64 electrodes mounted in a fitted cap with a standard 10–20 layout (ActiCAP, Brain Products GmbH, Munich, Germany) and using Brain Vision Recorder software (Version 1.10, Brain Products GmbH, Munich, Germany). All electrodes were referenced to a common ground, and during recording, electrode impedances were kept below 20 k $\Omega$ . EEG data were sampled at 500 Hz,

amplified (ActiCHamp, Revision 2, Brain Products GmbH, Munich, Germany), and filtered through a low-pass anti-aliasing filter of 245 Hz.

## Data processing

EEG data were processed using the standard methods of our laboratory (<http://www.krigolsonlab.com/data-analysis.html>). Initially, all excessively noisy and faulty channels for a particular subject were removed from analysis, although all removed channels were later interpolated. Following this, the EEG data were down sampled to 250 Hz and re-referenced to the average of the two mastoid electrodes (TP9, TP10). Then, data were filtered using a dual-pass Butterworth filter with a passband of 0.1–30 Hz and a notch filter at 60 Hz. Segments were then created from –1,000 ms to 2,000-ms centred on each event of interest—namely, onset of the stimulus image and response detection (key press or key liftoff). Following this, a restricted Infomax independent components analysis (ICA) was conducted to identify ocular artifacts (Luck, 2014), and the corresponding ICA components were plotted using head maps and components deemed to correspond to eye blinks were removed manually. Data were then reconstructed using the remaining ICA components, and any previously removed channels were interpolated using the method of spherical splines.

To examine the ERP responses, the data were segmented using a 1-s epoch (–200 ms to 800 ms) around stimulus onset and a 1.5-s epoch (–200 to 1,300 ms) around response onset. All segments were baseline corrected using a 200-ms window preceding stimuli or response onset. Finally, all segments underwent an artifact rejection algorithm that removed segments that had gradients greater than 10  $\mu$ V/ms and/or a 150  $\mu$ V absolute within-segment difference. For the stimulus-locked data, the artifact rejection algorithm led to an average rejection of 7.96% (95% CI [6.25%, 9.67%]) of the total ERP data for each subject. For the response-locked data, the artifact rejection algorithm led to an average rejection of 12.23% (95% CI [9.63%, 14.83%]) of the total ERP data for each subject.

Frontal theta power was extracted using custom scripts (<https://github.com/Neuro-Tools>), adapted from previous work (Cohen, 2014). We conducted a time-frequency wavelet analysis where data processing was the same as for the ERPs, with the only difference being that data were segmented using a larger epoch—from –500 ms to 1,500 ms—around the same events of interest as the ERPs. The wavelet analyses were conducted on the segmented data by multiplying fast Fourier transformed EEG data with complex Morlet wavelets (Gaussian-windowed complex sine wave with a Morlet parameter of 6 and a frequency range of 1 Hz to 30 Hz in 30 linear steps). The artifact rejection algorithm led to an average rejection of 12.16% (95% CI [9.70%, 14.62%]) of the total wavelet data for each subject.

Following artifact rejection, subject average ERP waveforms and theta wavelets were computed for each of the following combinations of events and conditions: (1) key-press image onset, corresponding; (2) key-press image onset, noncorresponding; (3) key-press response, corresponding; (4) key-press response, noncorresponding; (5) reach-grasp image onset, corresponding; (6) reach-grasp image onset, noncorresponding; (7) reach-grasp response, corresponding; and (8) reach-grasp response, noncorresponding. For the ERPs, difference waves were then created by subtracting noncorresponding trials from corresponding trials, and when comparing response modes, the reach-grasp waveform was subtracted from the key-press waveform. Grand average response mode and difference waveforms for ERPs were computed from the individual data, although only the stimulus-locked ERP events are reported here. We provide an analysis of the response-locked data in the supplemental materials (see Fig. S2 and S3). For the wavelets, grand average response mode specific time-frequency wavelets and difference plots were computed from the individual averaged data around the same events as the ERP data but only for the stimulus locked events.

## Behavioral data analysis

Response time in the present experiment was defined as the time from the onset of stimulus presentation to either a key press (key-press response mode) or key lift off (reach-grasp response mode). For response time, responses less than 100 ms and greater than 1,700 ms were excluded from analysis. The lower cutoff was chosen as response times shorter than 100 ms likely signify anticipation responses. The upper cutoff was defined so that 0.5% of trials were excluded (Ulrich & Miller, 1994). Error trials were defined as trials where the incorrect response was made. For response time, only correct trials were included in the analyses. All statistical tests were conducted in R (Version 3.5.3; R Core Team, 2019).

To investigate the behavioral effect of correspondence across response modes, response time and error rates were analyzed using a  $2 \times 2$  (response mode  $\times$  correspondence) repeated-measures analysis of variance (ANOVA). Pairwise comparisons (using the Holm correction) were computed to interpret the interaction between response mode and correspondence by verifying the presence of correspondence and reverse correspondence effects. Error bars on the figure represent 95% within-subject Bayesian highest-density intervals (Nathoo et al., 2018).

To examine how the correspondence effect changed across the response-time distribution, we also examined the effect across quantiles using delta plots (Pratte et al., 2010). For these analyses, we computed five response-time quantiles for each combination of response mode and correspondence. To calculate the quantiles, a subject's response times within a

response mode were rank ordered and divided into five consecutive bins. The first bin contained the shortest 20% of the response times, the next bin contained the next 20% shortest times, and so on. The mean response time for each bin was then computed. Next, a correspondence effect for each quantile, within each combination of response mode was generated by subtracting the mean of the noncorresponding trials from the mean of the corresponding trials in the appropriate bin. This process established a set of five response time correspondence effects for each subject, representing five sections of the full response-time distribution. The correspondence effect for each bin was then averaged across subjects to generate a mean correspondence effect for each response time quantile. To analyze the change in the correspondence effect across quantiles, we conducted linear trend analyses on the slopes of the delta plots using a linear polynomial contrast. The error bars shown in the delta plots are 95% within-subject Bayesian highest-density intervals (Nathoo et al., 2018).

## Electrophysiological data analysis

### Visual potentials

We examined two visual potentials, the P100 and N100. We quantified the visual potentials across O1, O2 and Oz on a participant-by-participant basis by calculating the mean voltage  $\pm 12$  ms of the maximal difference on the grand average waveform separately for the P100 (112 ms) and N100 (136 ms). We chose these electrodes based on prior research (Lien et al., 2013) and per the results of a calculation of the scalp maximum of the response mode difference wave (electrode O2) between 100 and 148 ms. We conducted one-sample  $t$  tests on the grand average of the difference wave between noncorresponding and corresponding trials to probe correspondence differences. When comparing across response modes, we collapsed across the noncorresponding and corresponding trials and then computed one-sample  $t$  tests on the difference wave of the key-press minus the reach-grasp response mode.

### Lateralized readiness potential

To compute the lateralized readiness potential (LRP), we used the averaging method (Eimer, 1998), whereby we calculated the grand average difference wave separately for both corresponding and noncorresponding trials using the following equation:

$$LRP = \frac{[left\ hand(C4-C3)-right\ hand(C3-C4)]}{2}. \quad (1)$$

We used this method to quantify the LRP to replicate the analyses from Goslin et al. (2012) and Lien et al. (2013). We

used the time frame from the previous investigations (Goslin et al., 2012; Lien et al., 2013) as per the suggestion from Kappenman and Luck (2016) to avoid false positives. This method led to quantification of two LRP components, the early LRP (100 to 200 ms) and the late LRP (200 to 500 ms). We quantified these two potentials by finding the mean voltage of  $\pm 24$  ms of the maximal difference of the grand average difference wave for both the early (132 ms) and late (268 ms) LRP. We conducted one-sample  $t$  tests on the difference wave between the noncorresponding and corresponding trials.

### Frontal theta power

We measured frontal theta power between 4 to 7 Hz (Sauseng et al., 2006) using a 300-ms window at electrode Cz. We chose electrode Cz based on previous work (Cavanagh & Frank, 2014) and the calculation of the scalp maximum from the response mode grand average difference wave (Cz). Frontal theta power was measured in micro-volts squared ( $\mu V^2$ ), as fast-Fourier transformed data were not logarithmic transformed. In the key-press response mode, the 300-ms window was between 300 and 600 ms, whereas in the reach-grasp response mode, the window was between 500 and 800 ms. We then computed a  $2 \times 2$  (response mode by correspondence) repeated-measures ANOVA, followed by pairwise comparisons using the Holm correction to investigate correspondence effects within response modes.

To complement our 4 to 7 Hz frontal theta analysis, we also applied pixel-based (also known as voxel-based) permutation testing to both response modes at electrode Cz (Cohen, 2014; see also <https://github.com/Neuro-Tools>). We chose a pixel-based permutation test because it removes the subjectivity of choosing a specific set of frequencies to represent frontal theta—work from the literature has used 4 to 7 Hz (Nigbur et al., 2011) and 4 to 8 Hz (Cavanagh et al., 2012; Nigbur et al., 2012)—or a specific time window. Thus, for both response modes, a separate frequency range and time range could be found by the pixel-based permutation testing. For pixel-based permutation testing, at each time point and frequency, a participant's average for corresponding and noncorresponding trials was computed. After this, the corresponding and noncorresponding labels were randomly permuted at each time and frequency across all the participant averages, and repeated-measures  $t$  tests were computed at each point for each permutation. From this random distribution, the most negative and most positive (i.e., most extreme) observations were chosen. After this, this process—extracting the minimum and maximal of the random permutations across time and frequency—was repeated 1,000 times. This led to the creation of a distribution of the most extreme random  $t$  scores (i.e., our null hypothesis) across both time and frequency. Then we conducted repeated-measures  $t$  tests at all time points

and frequencies for our own data, and any  $t$  values that were in the tails (i.e., 95th percentile or less than 2.5% or greater than 97.5%) were kept. Given that permutation testing does not allow for summary statistics, we then used the time frame and frequency window determined by the permutation test for the key-press and reach-grasp response modes to extract the output for each participant. We then computed means, 95% within-subject Bayesian highest density intervals, Cohen's  $d$ , and  $t$  values on the difference between reach-grasp and key-press trials for the participants.

To further investigate the link between frontal theta oscillations and behaviour, we correlated the average difference between noncorresponding and corresponding trials across participants for both response time and the frontal theta power extracted from the permutation test. This analysis was conducted on both the key-press response mode and the reach-grasp response mode. Note that all error bars on the EEG figures and error measures for the components and oscillatory activity represent 95% within-subject Bayesian highest density intervals (Nathoo et al., 2018).

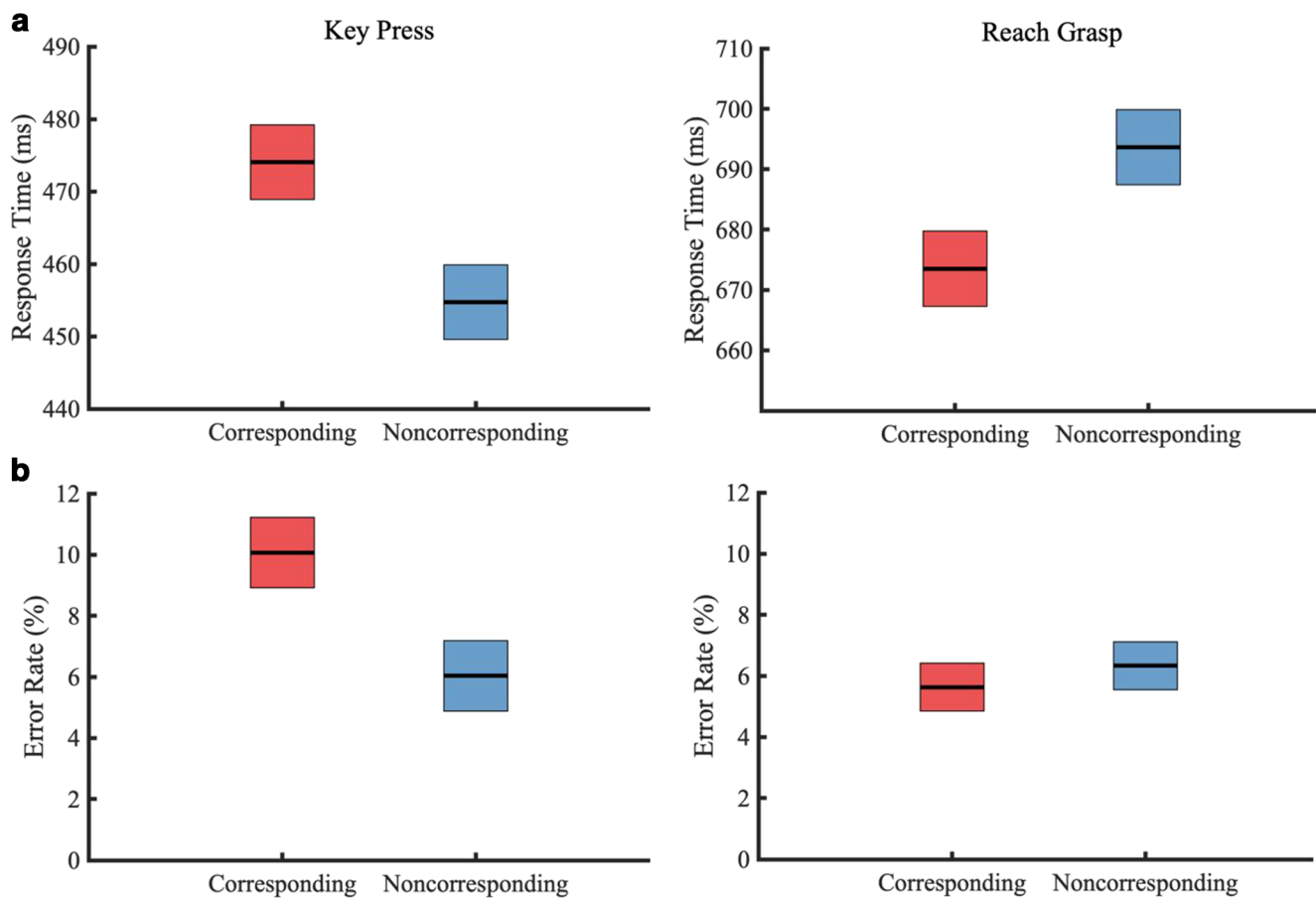
### Source localization

We conducted source localization using Brain Electrical Source Analysis software (BESA 6.0; MEGIS Software, Munich, Germany) on the frontal theta power segments across both response modes (key-press, reach-grasp). Specifically, we applied the BESA procedure to the frontal theta power (4 to 7 Hz) difference (noncorresponding minus corresponding) for each response mode. The window of analyses were the same windows as specified in the conventional (nonpermutation) wavelet analysis: 300 to 600 ms for the key-press response mode, and 500 to 800 ms for the reach-grasp response mode. As per previous work using source analysis on frontal theta power (Nigbur et al., 2011), we used a four-shell ellipsoid model of the scalp (Berg & Scherg, 1994) and had the BESA software provide a single dipole without additional constraints (Van Veen & Carter, 2002). We tested the stability of each dipole by repeating the dipole fitting with randomly seeded start points and by including multiple dipoles to determine whether the dipoles moved locations.

## Results

### Behavioral results

Mean correct response time and mean percent error are shown in Fig. 2. A  $2 \times 2$  (response mode  $\times$  correspondence) repeated-measures ANOVA revealed an effect of response mode,  $F(1, 29) = 71.28$ ,  $p < .001$ ,  $\eta_p^2 = .71$ ,  $MSE = 20,223$ , as subjects



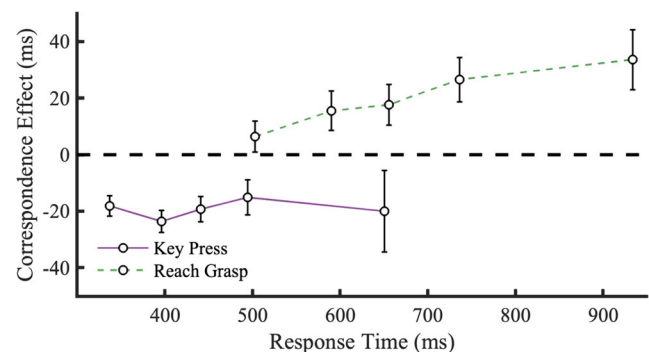
**Fig. 2** Mean response time (a) and mean percentage error (b) as a function of response mode and correspondence. Error bars represent 95% Bayesian highest density intervals

were quicker to respond in the key-press response mode ( $\bar{X} = 464$  ms) than in the reach-grasp response mode ( $\bar{X} = 683$  ms). There was also an interaction between response mode and correspondence,  $F(1, 29) = 28.47$ ,  $p < .001$ ,  $\eta_p^2 = .50$ ,  $MSE = 410$ , but no main effect of correspondence,  $F(1, 29) = 0.01$ ,  $p = .93$ ,  $\eta_p^2 = .00$ ,  $MSE = 569$ . Planned comparisons conducted on the interaction revealed that subjects were slower to respond on corresponding trials ( $\bar{X} = 474$  ms) compared with noncorresponding trials ( $\bar{X} = 455$  ms; correspondence effect =  $-19$  ms) in the key-press response mode,  $p < .005$ . In the reach-grasp response mode, the opposite was true, as subjects were quicker to respond on the corresponding rather than noncorresponding trials ( $\bar{X} = 674$  ms corresponding,  $\bar{X} = 694$  ms noncorresponding, correspondence effect =  $20$  ms;  $p < .005$ ).

For percentage error, a repeated-measures ANOVA indicated that there was no main effect of either response mode,  $F(1, 29) = 1.45$ ,  $p = .24$ ,  $\eta_p^2 = .05$ ,  $MSE = 88.5$ , or of correspondence,  $F(1, 29) = 4.08$ ,  $p = .05$ ,  $\eta_p^2 = .12$ ,  $MSE = 20.41$ . However, there was an interaction between correspondence and response mode,  $F(1, 29) = 19.73$ ,  $p < .001$ ,  $\eta_p^2 = .40$ ,

$MSE = 8.5$ . Follow-up planned comparisons showed that there was only a reverse correspondence effect in the key-press response mode,  $p < .01$ , whereby there were more errors on corresponding trials than noncorresponding trials.

An analysis of the delta plots (see Fig. 3) revealed results in concordance with previous work (Bub, Masson, MacRae, & Marshall, 2021). In the key-press response mode, the slope of the correspondence effect appears more shallow than the slope



**Fig. 3** Mean correspondence effect (noncorresponding minus corresponding) on response time for the two response modes as a function of response time quantile. Error bars represent 95% Bayesian highest density intervals



in the reach-grasp response mode, which was consistent with an observed interaction between the linear trend across quantiles and response mode,  $t(116) = 10.65$ ,  $p < .001$ .

## Electrophysiological results

### Visual ERPs

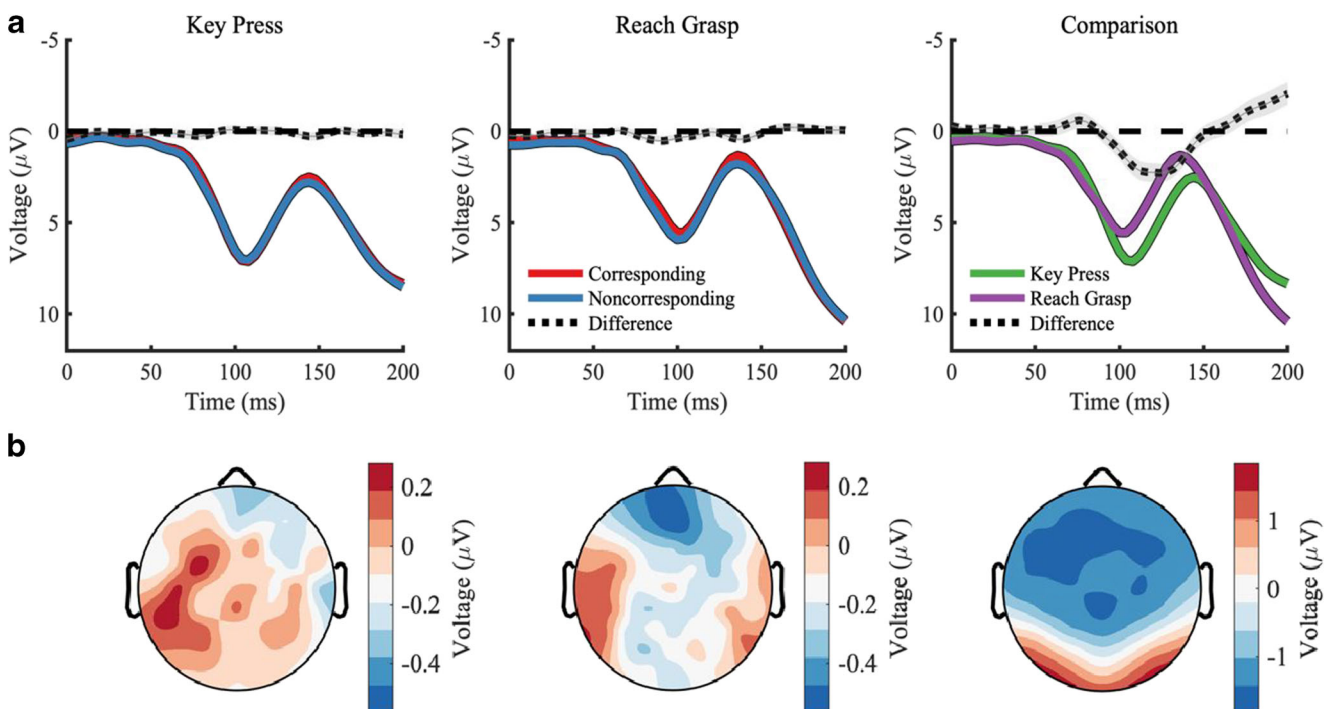
We examined the P100 and N100 components separately for each response mode and for corresponding and noncorresponding trials (see Fig. 4). For both of these components we averaged across electrodes Oz, O1, and O2. For the P100, there was no effect of correspondence in either the key-press response mode,  $\bar{X} = 0.07 \mu\text{V}$ ; 95% HDI:  $-0.16, 0.30$ ;  $t(29) = 0.32$ ,  $p = .75$ ,  $d = 0.06$ , or the reach-grasp response mode,  $\bar{X} = -0.19 \mu\text{V}$ ; 95% HDI:  $-0.42, 0.04$ ;  $t(29) = 0.83$ ,  $p = .42$ ,  $d = -0.15$ . When collapsing across correspondence condition and comparing the two response modes, there was an effect of response mode,  $\bar{X} = 1.77 \mu\text{V}$ ; 95% HDI:  $1.30, 2.24$ ;  $t(29) = 3.75$ ,  $p < .001$ ,  $d = 0.69$ . The same pattern of results was observed for the N100 component. That is, there was no effect of correspondence in either the key-press response mode,  $\bar{X} = -0.10 \mu\text{V}$ ; 95% HDI:  $-0.28, 0.28$ ;  $t(29) = 0.53$ ,  $p = .60$ ,  $d = -0.10$ , or the reach-grasp response mode,  $\bar{X} = -0.28 \mu\text{V}$ ; 95% HDI:  $-0.51, 0.05$ ;  $t(29) = 1.26$ ,  $p = .22$ ,  $d = -0.23$ , but there was an effect of response mode,  $\bar{X} = 1.41 \mu\text{V}$ ; 95% HDI:  $1.00, 1.82$ ;  $t(29) = 3.41$ ,  $p < .005$ ,  $d = 0.62$ .

### Lateralized readiness potential

As per previous work (Goslin et al., 2012; Lien et al., 2013), we examined the lateralized readiness potential on corresponding and noncorresponding trials (see Fig. 5). In the key-press response mode, there were differences between noncorresponding and corresponding trials at both the early time frame, 100 to 200 ms;  $\bar{X} = 0.66 \mu\text{V}$ ; 95% HDI:  $0.46, 0.88$ ;  $t(29) = 3.35$ ,  $p < .01$ ,  $d = 0.61$ , and late time frame, 200 to 500 ms;  $\bar{X} = -0.66 \mu\text{V}$ ; 95% HDI:  $-0.90, -0.42$ ;  $t(29) = 2.71$ ,  $p < .05$ ,  $d = -0.50$ . In contrast, in the reach-grasp response mode, there was a difference in the 100 to 200 ms timeframe,  $\bar{X} = 0.48 \mu\text{V}$ ; 95% HDI:  $0.27, 0.69$ ;  $t(29) = 2.29$ ,  $p < .05$ ,  $d = 0.42$ , but not the 200 to 500 ms timeframe,  $\bar{X} = -0.18 \mu\text{V}$ ; 95% HDI:  $-0.43, 0.07$ ;  $t(29) = 0.75$ ,  $p = .46$ ,  $d = -0.14$ . Importantly, the direction of the early LRP effect was positive—noncorresponding was more positive than corresponding—in both of the two response modes.

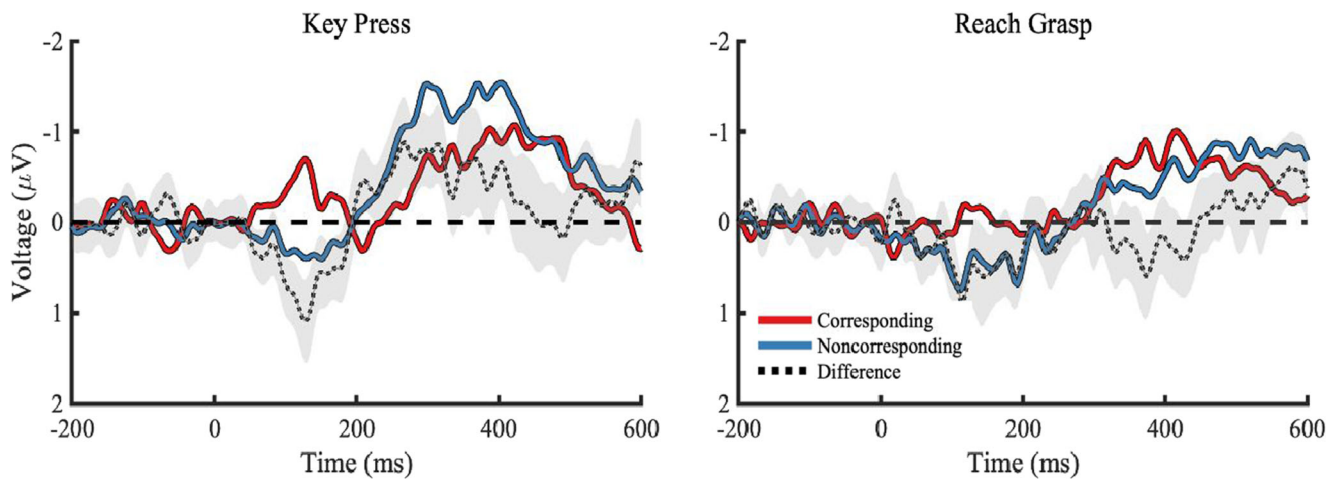
### Frontal theta power

We also examined frontal theta power (see Fig. 6), where we obtained results that paralleled our behavioural analysis of response time. A  $2 \times 2$  (response mode  $\times$  correspondence) repeated-measures ANOVA applied to this measure found a main effect of response mode,  $F(1, 29) = 23.80$ ,  $p < .001$ ,  $\eta_p^2 = .45$ ,  $MSE = 1.95$ , and an interaction between correspondence



**Fig. 4** **a** Grand average ERPs for visual potentials as a function of response mode and handle correspondence. The comparison case shows ERPs for each response mode averaged across correspondence.

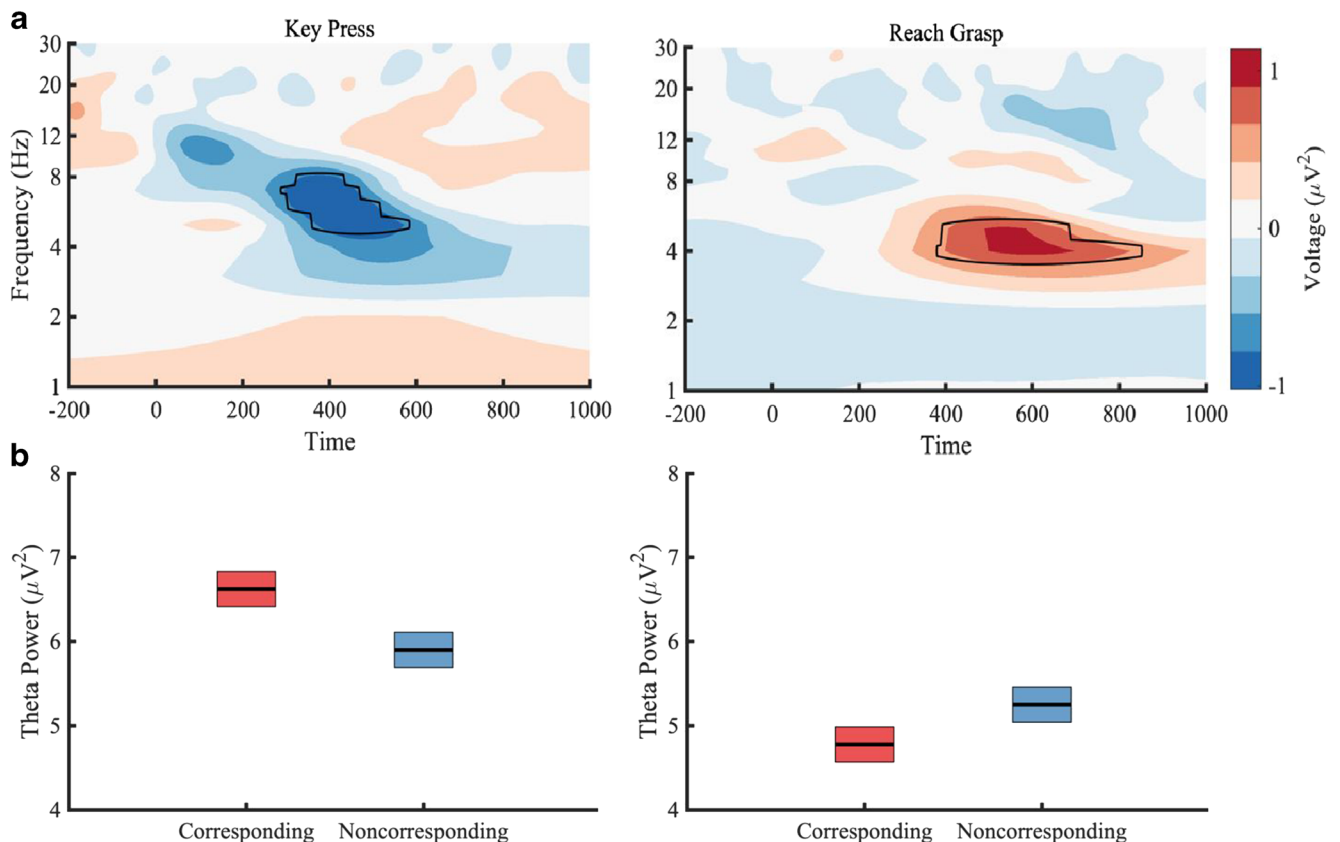
Measurements are from the occipital electrodes (Oz, O1, O2). **b** Scalp topographies of the difference waves (75 to 175 ms). Error bars represent 95% Bayesian highest density intervals



**Fig. 5** Lateralized readiness potentials time-locked to image presentation for the two response modes. Error bars are 95% Bayesian highest density intervals

and response mode,  $F(1, 29) = 15.44$ ,  $p < .001$ ,  $\eta_p^2 = .35$ ,  $MSE = 0.70$ . There was no main effect of correspondence,  $F(1, 29) = 1.27$ ,  $p = .27$ ,  $\eta_p^2 = .04$ ,  $MSE = 0.36$ . Follow-up pairwise comparisons revealed that there was a correspondence effect in the key-press response mode, with the corresponding trials ( $\bar{X} = 6.62$

$\mu V^2$ ) showing higher theta than the noncorresponding trials ( $\bar{X} = 5.89$   $\mu V^2$ ;  $p < .005$ ), and a correspondence effect in the opposite direction in the reach-grasp response mode, with corresponding trials ( $\bar{X} = 4.78$   $\mu V^2$ ) showing lower theta than noncorresponding trials ( $\bar{X} = 5.25$   $\mu V^2$ ;  $p < .05$ ).



**Fig. 6** **a** Time-frequency wavelet difference waves (noncorresponding minus corresponding) for each response mode measured at electrode Cz. The black lines indicate differences that survived the pixel-based

permutation test. Note that the y-axis scale is logarithmic, **b** Frontal theta power averages as a function of response mode and handle correspondence. Error bars are 95% Bayesian highest density intervals

Furthermore, we applied pixel-based permutation testing to the time-frequency wavelets in the corresponding and noncorresponding trials for both the key-press and reach-grasp response modes. For the key-press response mode, as per the conventional analysis, noncorresponding trials had lower theta power than corresponding trials,  $\bar{X} = -0.94 \mu V^2$ , 95% HDI:  $-1.15, -0.73$ ;  $t(29) = 4.42$ ,  $p < .001$ ,  $d = 0.80$ . Most importantly, there was a cluster of differences in frontal theta activity that survived permutation testing between 5 to 8 Hz and 288 to 588 ms. Conversely, for the reach-grasp response mode, noncorresponding trials had higher theta than corresponding trials,  $\bar{X} = 0.86 \mu V^2$ , 95% HDI:  $0.66, 1.06$ ;  $t(29) = 4.06$ ,  $p < .001$ ,  $d = 0.74$ . As well, permutation testing revealed a cluster of differences in frontal theta activity between 4 to 5 Hz, and 380 and 854 ms.

To examine the relationship between response time and frontal theta power, we correlated both response time differences (noncorresponding minus corresponding trials) and frontal theta power differences (noncorresponding minus corresponding) across both response modes (see Fig. 7). The correlations between response time and frontal theta power revealed a moderate, positive correlation for the key-press response mode ( $r = .33$ ) and a large, positive correlation for the reach-grasp response mode ( $r = .62$ ).

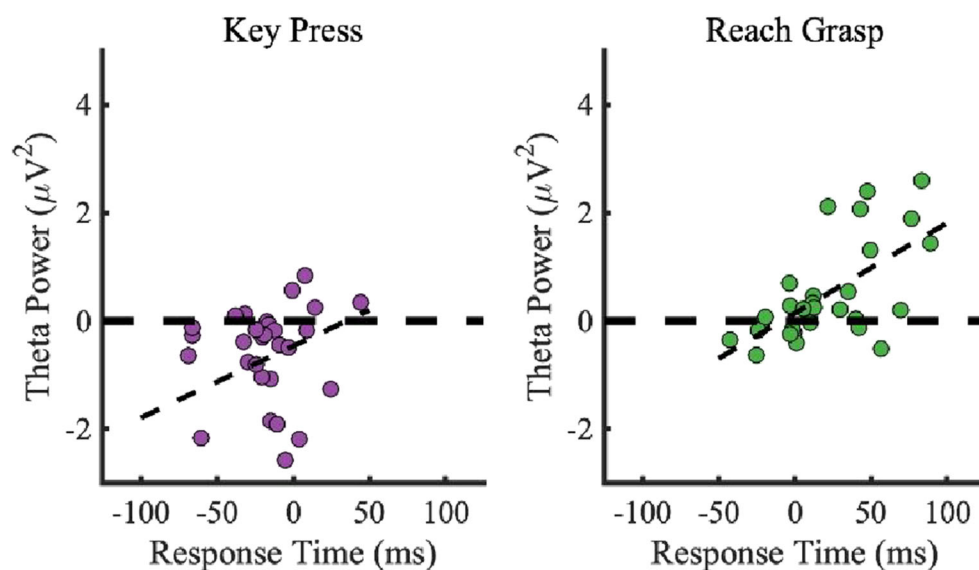
### Source analysis

We conducted source localization to determine if there were source differences between the key-press and reach-grasp response modes when examining the correspondence effects (see Fig. 8). The dipole source of the key-press response mode was located medially towards the primary motor cortex ( $X =$

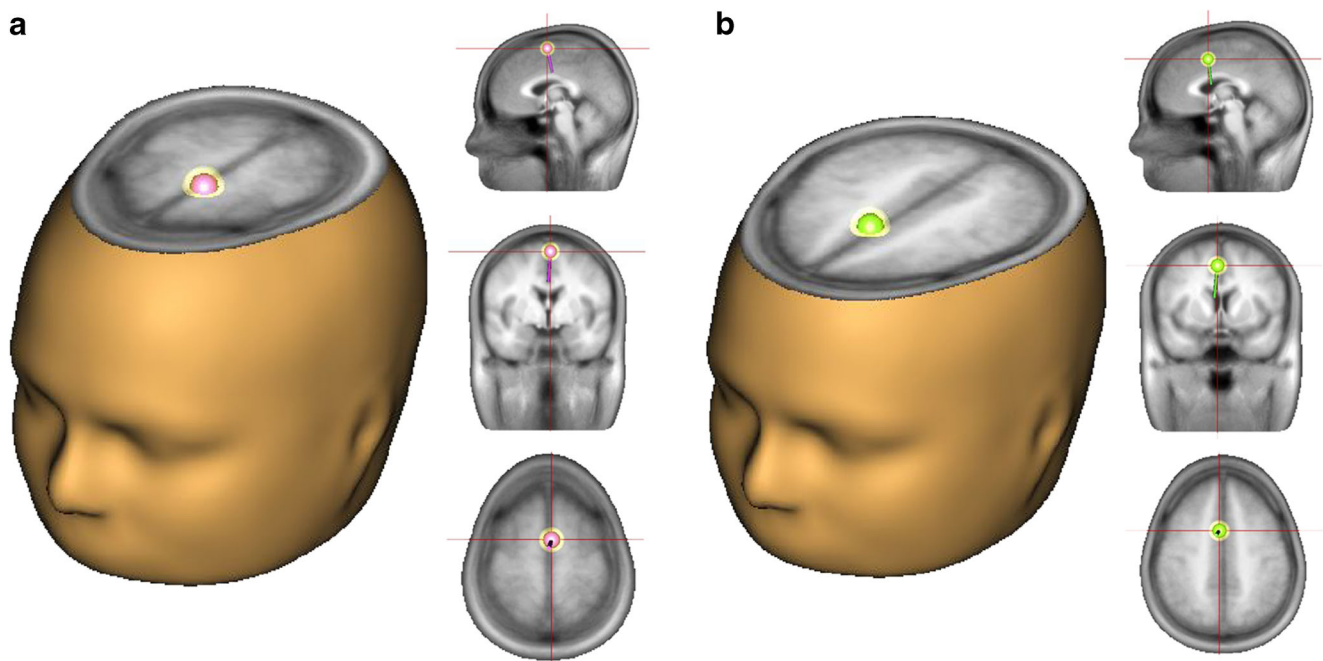
$-2.2$ ,  $Y = 16.7$ ,  $Z = 92.9$ , residual variance = 3.35%). In contrast, the dipole source of the reach-grasp response mode was located more anteriorly and ventrally to the key-press dipole, towards the medial prefrontal cortex ( $X = 3.7$ ,  $Y = 22.8$ ,  $Z = 77.3$ , residual variance = 7.12%).

### Discussion

In the present work, we examined visual ERP's, the lateralized readiness potential, and frontal theta power when participants were asked to classify handled objects across both key-press and reach-grasp response modes. As anticipated, behaviourally we observed a reverse correspondence effect in response time when participants made key-press responses and a correspondence effect when participants made grasping movements to presented objects, supporting previous claims that correspondence effects depend more on the spatial information of the image itself and the motor intention of the observer but are not the result of an inherent property of the handled object (Bub, Masson, & van Noordenne, 2021). As well, we observed a different pattern in the quantiles of the effect of correspondence between the key-press and reach-grasp response modes. We found that while the correspondence effect grows across the reach-grasp response mode quantiles, the reverse correspondence effect remains the same across the key-press response mode quantiles. These quantile findings are identical to previous quantile findings showing that whole object centred images generate invariant effects across the quantile when subjects make key presses to classify the object (Bub, Masson, MacRae, & Marshall, 2021). In contrast, when subjects make reach actions, the correspondence effect across the quantiles can either increase as we found in the present work (Bub,



**Fig. 7** Correlation between frontal theta power and response time for the correspondence effect (noncorresponding minus corresponding) across key-press and reach-grasp response modes



**Fig. 8** Source localization for the (a) key-press response mode and (b) reach-grasp response mode

Masson, MacRae, & Marshall, 2021) or can remain the same (Bub et al., 2018).

We argue that these quantile differences are due to attentional differences between the key-press and reach-grasp response mode (see Zhang et al., 1999). While Proctor and Miles (2014) argued that correspondence effects related to motor representations will occur rapidly—suggesting our findings do not indicate that the correspondence effect is automatic when subjects make reach actions—we believe that because in the present paradigm attention is directed towards the base of the object for the upright/inverted decision, the effect of the handle takes time to grow across the quantile. In other task conditions, such as those used by Bub et al. (2018), the effect of the handle remains consistent across both fast and slow responses due to the choice of the object (a beer mug). Moreover, we observed larger motor potentials for the reach-grasp as compared with the key-press response mode (see Figs. S2 and S3 in the supplemental materials), showing there was greater motor activation in the reach-grasp response mode due to the motor codes.

In terms of the ERP data, we found no evidence that the visual potentials were sensitive to either correspondence or reverse correspondence effects, although we did find a difference between the key-press and reach-grasp response modes. Overall, these visual potential findings disconfirm the idea put forward by Goslin et al. (2012) that visual potentials are sensitive to correspondence effects. The results from our LRP analysis also do not support the claim that correspondence effects manifest in the LRP. In the LRP, noncorresponding trials showed a distinct positive waveform, while

corresponding trials showed a distinct negative waveform (replicating Goslin et al., 2012, and Lien et al., 2013). However, given our behavioural findings we would expect the LRPs to be reversed when comparing the two response modes—which is not the case. Thus, we suggest that it is not the preparation of the incorrect action on noncorresponding trials that leads to this difference in LRPs in our paradigm, but merely a visual attribute of the stimuli due to the asymmetrical nature of the images (echoing Vainio et al., 2014). In fact, this suggestion by Vainio et al. (2014) is supported in our own data as we found an interaction between handle side and electrode at both posterior and frontal electrodes. This interaction suggests that our LRP effects are driven by volume conduction at more posterior sites (see “Visual Potential ANOVAs” in the supplemental materials). As per above, we also observed larger motor potentials for the reach-grasp response mode (see Figs. S2 and S3), showing greater motor activation in the reach-grasp response mode, which was not reflected in the LRP.

The main finding of the present work was derived from an exploratory analysis and revealed that frontal theta power was increased on corresponding trials compared to noncorresponding trials in the key-press response mode and increased on noncorresponding trials compared with corresponding trials in the reach-grasp response mode (identical to the behavioural effect). Moreover, we found that across both response modes, the response time effects were positively correlated with frontal theta power. Our belief here is that this frontal theta difference relates to differences in the cognitive control levels required in the two response modes, given the fact that frontal theta is a measure of



cognitive control (Cavanagh & Frank, 2014) which response conflict elicits (Cohen & Cavanagh, 2011).

These frontal theta findings support our conjecture that the differing levels of conflict between corresponding and noncorresponding trials within the two response modes would be reflected by changes in frontal theta activity. On the key-press corresponding trials, where there is conflict between the response hand and the opposing spatial codes generated by both the base and the handle of the object, more cognitive resources need to be recruited in order to complete the correct response—the base of the object is more important for the upright/inverted decision due to its importance in making the upright and inverted judgement (e.g., Cho & Proctor, 2011). We believe that the conflict on corresponding trials is reflected as higher theta power when compared with noncorresponding trials because on the noncorresponding trials the base of the object and the response hand are on the same side. This same explanation would hold for frontal theta findings from the reach-grasp response mode, as on noncorresponding trials where the response hand and the frying pan handle are opposed, more cognitive resources need to be recruited compared with corresponding trials (akin to the “Simon effect”; Cho & Proctor, 2010).

In addition to the Response Mode  $\times$  Correspondence interaction in frontal theta, we also observed an effect of response mode, with key-press trials eliciting higher frontal theta power than reach-grasp trials. While we cannot say that this response mode difference is specifically due to cognitive control differences (see the Limitations section below), we do believe that the key-press and reach-grasp response mode theta difference is related to control processes that differ between the two response modes. We argue that this is the case because of the competing spatial codes generated in the key-press response mode by the handle of the object and by the base of the object (task-irrelevant dimensions) as the participant responds to the object orientation (the task-relevant dimension). In this case, the spatial codes generated by the task-irrelevant dimension compete with the selection of the left and right key press—meaning there is more response conflict when compared with the reach-grasp response mode where the motor code drives the effect entirely (e.g., Bub & Masson, 2010). Relatedly, previous work has shown larger object-based Simon effects occur for within-hand responses than for between-hand responses (Cho & Proctor, 2011), which Cho and Proctor suggested may have occurred because each stimulus contained two components in opposite locations, which in turn added further conflict in addition to that already present for within-hand key presses (e.g., Buckolz et al., 1996). Moreover, the difference between the key-press and reach-grasp response mode in the visual potentials further suggest that how the objects were visually processed differed between the two response modes (e.g., He et al., 2008), supporting our conjecture that spatial codes impacted the key-press response mode, but not the reach-grasp response mode.

The results of the pixel-based permutation test on these frontal theta findings highlight the possibility of different neural

substrates between the key-press and reach-grasp response modes. In fact, our frontal theta power differences parallel work by Nigbur et al. (2011), who examined frontal theta power across a variety of tasks: an Eriksen flanker task, a Simon task, and a no-go task. Across these three tasks the theta profiles (timing and frequency range) differed for each task—a finding we also observed between the key-press and reach-grasp response modes. Other work also corroborates these frontal theta profile differences as frontal theta power has different profiles dependent on the task (Cavanagh et al., 2012). Our claim of distinct neural processes demonstrated by frontal theta power profile differences is also supported by work showing dissociations of two separate and functionally distinct frontal theta patterns in Simon tasks (Töllner et al., 2017).

Our permutation results alone are merely suggestive of distinct mechanisms underlying the two tasks. However, the results from our source analysis provide evidence that task demands impact theta sources in our paradigm, which we posit may reflect distinct cognitive processes governing the key-press and reach-grasp response modes. Specifically, the key-press response mode was localized to theta activity from the primary motor cortex, while the reach-grasp response mode was localized to theta activity from the medial prefrontal cortex. We argue that this source difference is due to the motor intention and planning that is integral in the reach-grasp response mode, but that is not present in the key-press response mode. We argue this is the case because frontal regions such as the anterior cingulate cortex are more active in the Simon task than in the Stroop task, while more posterior regions are active in the Stroop task than the Simon task—which was speculated to be due to greater planning and response selection in the Simon task (Liu et al., 2004).

That is not to say that our two response modes are equivalent to the Stroop or Simon task, specifically, but merely to point out that while conflict resolution is believed to play a role in the institution of control for both the Stroop and Simon task, evidence suggests that control processes enhance stimulus processing in the Stroop task, but cause response inhibition in the Simon task (Egner, 2008). Thus, if our hypothesis about differing roles of conflict in the key-press and reach-grasp response modes are true, then our findings find support in the claim by Egner (2008) of multiple, different kinds of conflict that do not rely on one specific mechanism across tasks. Given the differing locations of our theta sources, our results are then in line with claims that while theta power acts as a communication signal for control processes between a variety of brain regions (Cavanagh & Frank, 2014), the brain regions involved in theta activity are heavily dependent on task demands (Nigbur et al., 2011). Moreover, we believe that our differing theta profiles and theta sources further support claims made by Bub, Masson, and van Noordenne (2021) that the correspondence effects generated by cued reach actions are evidence of a distinct neural process when compared to

the reverse correspondence effects generated by key presses. Future work is needed to disambiguate the specific brain regions active in our two response modes, but the source analysis we conducted may provide an indication of what to expect.

## Limitations

An issue present in the current work is the fact that our response method differed between the key-press and reach-grasp response modes. That is, participants had to press the correct key on the keyboard for the key-press response mode while they had to lift the correct key on the keyboard for the reach-grasp response mode. Although we had to choose these different responses in order to ensure EEG markers could be effectively sent to mark the responses, the fact that the two responses differ means that these response types (key press vs. liftoff) are fully confounded with the response mode (key press vs. reach-grasp). Future work could consider changing the key-press response mode to a key-liftoff instead. Doing so would mean that the two responses are identical, except for the cued reach action.

A second limitation related to differences between response modes is that in the reach-grasp response mode participants had to wait 2 seconds with their hand on the graspable object. During piloting, we found that the reach-grasp response mode had a large number of motion and eye artifacts that were caused by the participants lowering their eyes and returning their hand to the correct key on the keyboard. Thus, we added the 2-s wait time to reduce eye movement and motion artifacts. However, this means that the overall presentation rate of trials differed between response modes. While we believe that the presence of the behavioral effects that have been observed previously in this type of paradigm (e.g., Bub et al., 2018; Bub, Masson, & van Noordenne, 2021) suggest this change to protocol had little effect on behaviour, this difference in protocol between response modes acts as a confounding variable for our results.

## Conclusions

Overall, our work highlights the role of cognitive control in explaining object correspondence effects. Behaviourally, participants showed correspondence effects in the reach-grasp response mode and reverse correspondence effects in the key-press response mode. However, these behavioural differences did not manifest in motor response activation (the LRP) nor in visual attention (the P100 and N100). Instead, an exploratory analysis revealed theta oscillations as a possible mechanism sensitive to object and response hand correspondence, providing a neural basis of these correspondence effects. If frontal theta does in part reflect cognitive control (as argued by Cavanagh & Frank, 2014) and top-down control

processes play a role in explaining object correspondence effects (a claim advanced by Bub, Masson, & van Noordenne, 2021), we believe that our frontal theta power findings indicate the presence of these top-down control processes. We hypothesize that these top-down processes play some role in whether correspondence effects are produced during the presentation of a handled object. Taking this claim further, we suggest that this role of top-down processes in explaining these effects thus necessitates that object affordances (as reflected by correspondence effects) are not universally elicited by pictures of objects. We believe that further investigations into the role of frontal theta power and cognitive control in object affordances could contribute to the literature more generally.

**Supplementary Information** The online version contains supplementary material available at <https://doi.org/10.3758/s13414-021-02296-z>.

**Funding** All authors would like to acknowledge support from the Natural Sciences and Engineering Research Council of Canada: Thomas Ferguson & Olave Krigolson (RGPIN 2016-0943), Daniel Bub (RGPIN 2018-03753), & Michael Masson (RGPIN 2015-04773).

## Declaration

**Conflict of interest** The authors have no conflict of interests.

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