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Fooling the brain by mirroring the hand: Brain correlates of the perceptual capture of limb ownership

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Abstract.
Background: Mirror therapy (MT) is an increasingly employed method aimed at reducing phantom pain and other negative sensations following loss of a limb or damage to sensorimotor systems. However, the brain processes associated with the perception of limb ownership, a key correlate of MT, are unknown.
Objective: To examine whether transient perceptions of limb ownership together with associated neural activity can be elucidated using a purpose-developed mirror reflection task combined with electrophysiological (EEG) measures and cutting-edge analyses.
Methods: Brain activity was measured online using EEG in 20 healthy controls while they produced opening-closing movements of one hand in control conditions or while viewing the mirror reflection of the movements. The key experimental condition required participants to make a foot pedal response whenever a change in perception of ownership (of a mirror-reflected limb) occurred (Mirror condition). Control conditions and a strict epoching regime were employed using standard subtractive logic to isolate the perception of limb ownership (which was further verified by self-reports).
Results: Data from 15 participants were suitable for complete analysis; the remaining reported no experience of ownership. Significant spectral power increases were found in central-parietal regions in association with perceptions of ownership, with the most prominent effect specific to the alpha frequency band (8–13 Hz) measured at the right parietal area. Source localization analyses further identified brain networks associated with the mirror reflection condition in the alpha frequency (parietal lobe) and the beta frequency (middle temporal areas). These were distinct from localized networks associated with the foot pedal response.
Conclusion: Transient perceptions of ownership can be captured experimentally, and are associated with localized sites of neural activation. This is an initial step toward eventual development of therapeutic targets for interventions including brain computer interfaces (BCIs) aimed at ameliorating the negative effects associated with impaired or missing limbs.

Keywords: Neurorehabilitation, amputation, phantom limb, mirror, perception of ownership, bimanual

1. Introduction

Forms of mirror therapy (MT) are becoming increasingly common in medical and non-medical settings due to their simplicity of access (Chan et al., 2007; Flor, 2008; Ramachandran & Altschuler, 2009); however, quite a lot remains unknown about the efficacy of MT and the mechanisms underlying its reported effects. In a typical application, a patient experiencing pain or other unwanted sensations of one limb or a phantom limb moves his or her intact limb while viewing a mirror reflection of that movement. In control participants the result is an illusion that both hands are moving (Franz & Packman, 2004). It is unknown whether and how this illusion might be capitalized upon to result in a change in the

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experience of unwanted sensations, for example, forms of pain in those with phantom limb experiences. However, evidence is accumulating that a significant factor underlying MT is perceptual.

One account of the effects of MT is that the visual illusion of a moving intact limb compensates for a mismatch between motor intention and sensory visual and proprioceptive feedback of an impaired or missing limb (Harris, 1999; McCabe, Haigh, Halligan, & Blake, 2005; Ramachandran & Altschuler, 2009). A related possibility is that the brain is actually 'fooled' during the mirror illusion, which opens a therapeutic window during which perceptions can be manipulated and hopefully altered (Franz & Packman, 2004). Both views depend to some extent on people having a suspension of belief, at least momentarily—i.e. 'I know that isn't my actual other hand (in the mirror), but I can momentarily suspend that disbelief'; they also seem to depend on a perception of ownership (that the mirror-reflected limb is physically present at its visually-apparent location). Attention might also provide heightened awareness as a result of the visual realism of the virtual limb (Brodie, Whyte, & Waller, 2003; Franz & Packman, 2004), perhaps even through forms of covert awareness (Franz, 2004). Any effect also might be sensitive to whether a perceived limb appears as an actual limb, as compared to an artificial/prosthetic one (Holmes, Snijders & Spence, 2006).

The perception that a virtual limb (seen in the mirror) *is* a person's *other* limb (ownership), is typically reported verbally and retroactively; that is, only after the experience which often lasts many seconds or even minutes. In fact, self-reported ownership has become a key indicator of success in mirror manipulations aimed to reduce negative sensations and perceptions (Chan, et al., 2007; Franz & Packman, 2004; Lotze et al., 1999; MacIver, Lloyd, Kelly, Roberts, & Nurmikko, 2008; McCabe, 2011; Ramachandran, Rogersramachandran, & Cobb, 1995). However, the perceptual capture of ownership has eluded investigations to date. There presently is no demonstration of a precise temporal correlation of perceptions of ownership and the associated brain changes; this forms the primary aim of the present study.

Studies on brain processes using functional magnetic resonance imaging (fMRI) have demonstrated neural activity in the superior temporal and superior occipital gyri (Hamzei et al., 2012) in association with MT in healthy subjects and using self-report measures. Also using fMRI, MacIver et al. (2008) found a significant reduction in intensity and unpleasantness of pain scores in association with reduced cortical reorganization in the (contralateral) primary motor (M1) upper limb region, the ipsilateral M1 and primary sensory (S1) upper limb regions, and the anterior cingulate cortex (ACC) bilaterally. While those studies are extremely important in pointing to where in the brain to look for task-related neural activity, fMRI is limited in temporal resolution, thereby posing problems in attempting to elucidate precise temporal correlations between behavioural changes or perceptions and their associated neural effects.

Electroencephalography (EEG), a non-invasive technique of measuring brain activity from the scalp with high temporal resolution, makes possible a temporally precise method of elucidating brain changes at or around the time a subjective perception or experience of ownership occurs. Event related desynchronization (ERD) in the beta frequency is proposed to be associated with motor preparation, execution and imagery (Pfurtscheller & Aranibar, 1979), whereas event related synchronization (ERS) is proposed to correspond to an inactive state or inhibition of the responsible neuronal populations (Neuper, Wörtz, & Pfurtscheller, 2006). Indeed, some research has suggested that the alpha frequency might serve a similar function as the beta frequency (Leske et al., 2014). It also has been proposed that beta rhythms are related to kinesthetic illusions (Keinrath, Wriessnegger, Muller-Putz, & Pfurtscheller, 2006), and there is a likely role of alpha rhythms in illusory sensation (Muller et al., 2013; Stroganova et al., 2009; van Erp, Philippi, de Winkel, & Werkhoven, 2014).

Given that the most frequently used experimental approach in association with MT involves querying participants to obtain their subjective perceptions after a (often prolonged) trial of mirror intervention, it has not been possible to time-tag the actual perceptual event of ownership. The present study aimed to circumvent this problem and begin to bridge the gap between perception and brain processes by testing whether perceptions of ownership can be captured experimentally. It was hypothesized that effects in the alpha and beta frequencies are identifiable in brain areas likely to be involved in the perception of ownership. Accordingly, the target regions of this study were primarily frontal-central and parietal which would be correlated with changes in reported perceptions. The hope was to provide a crucial step to target therapeutic windows for potential interventions that might be developed in future studies with the aim of ameliorating the experience of pain in patients with sensorimotor damage of the limbs.

2. Methods

2.1. Participants

Twenty undergraduate students of the University of Otago, ranging in age from 18 to 21 years (mean age 20.0) participated; only 15 were included in the data analyses because 5 did not report effects of the mirror manipulation on any trial. Of the included sample, 14 were right handed and 1 was left handed. All had normal or corrected to normal vision, were naive to the task and purpose of the study, and gave their written informed consent before participating. Procedures were approved by the University of Otago Ethics Committee.

2.2. Materials

2.2.1. Mirror setup

The mirror box consists of a small rectangular wooden box with a mirror (30 cm by 30 cm) placed vertically in the middle so that it is perpendicular to the sagittal plane extending from the midline of a participant's body (Fig. 1). Participants inserted one hand on each side of the mirror which reflects one hand while the other hand is placed behind the mirror out of view (Franz & Packman, 2004).

A 20 cm × 15 cm foot pedal was used to register participants' responses to mirror sensations which they later described verbally when cued at the end of the trial. A signal is sent from the pedal apparatus to the EEG computer as an event marker in the EEG data file to indicate the time of perceived perceptual change, using an Arduino chipset.

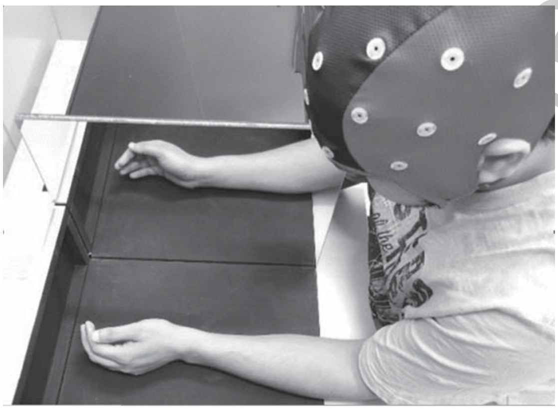

Fig. 1. Picture of the mirror box setup reflecting the left hand, with a participant wearing the EEG cap. Underneath the table is the foot pedal (not shown) on which a brief foot response is used to indicate changes in perception of the 'virtual limb' (that which is seen in the mirror).

2.2.2. EEG

Given that our related studies revealed no sign of EMG activity in the hidden hand of any participant (Debnath & Franz, 2016), we used EEG alone (without EMG) in the present study to avoid the risk of inadvertently drawing attention to the hidden/resting hand which might complicate interpretations. Continuous EEG data were recorded using a 32-channel ANT machine (ANT B.V., Enschede, The Netherlands), Advanced Neuro Technology amplifier, and ASA (version 4.7) software on a Dell Intel computer.

EEG electrodes were mounted on an Ag/AgCI sintered ANT WaveGuard cap with electrodes placed according to the international 10–20 montage system (Klem, Lüders, Jasper, & Elger, 1999). The data were sampled at 1024 Hz. The ground electrode was located on the scalp at a fixed position of the cap. The mathematical average of both mastoid electrodes was used as a reference. Electrode impedances were kept below 5KΩ. Data were re-sampled offline at 512 Hz and digitally filtered (FIR) with band-pass from 0.1 Hz-40 Hz. Independent component analysis (ICA) was conducted on filtered EEG data, which decomposed the EEG data in a set of sources with maximally independent time courses (Jung et al., 2000). Ocular artifacts (eye movements) were corrected using a completely automatic algorithm (ADJUST) (Mognon, Jovicich, Bruzzone, & Buiatti, 2011); this method identifies artifactual independent components by combining stereotyped artifact-specific spatial and temporal features to capture blinks, eye movements, and generic discontinuities on a feature selection dataset. Remaining artifacts were rejected using the criterion of absolute voltage value 100 μV. Spectral EEG activity was assessed by short-time Fourier transform in EEGLAB (Delorme & Makeig, 2004), creating event related spectral perturbations (ERSP); this provides a two-dimensional (latency by frequency) representation of mean change in spectral power (in dB) relative to baseline. The spectral power was converted to log power (10*log10 of the signal), and averaged across all trials for each time bin: pre-pedal press stage (–4.0 s to –3.0 s, –3.0 to –2.0 s with respect to time 0.0, the pedal press) which is aimed to capture the start of the perceptual experience, and post-pedal press stage

(0.0 to 1.0 s, 1.0 to 2.0 s, following the pedal press), which is thought to be after the perceptual experience (conservatively measured). We leave out the time just prior to the pedal press time-stamp (–1.0 s to 0.0) which reflects when the motor processes associated with that response actually occur (as elucidated during pilot tests). Thus, all measures are in reference to the foot pedal press at time 0.

As a methodological consideration in understanding the EEG analyses, it is important to note that both the PRE (before the foot pedal press) and POST (after the foot pedal press) intervals consisted of the same repetitive open-closing movements of the (active) left hand for our key Mirror manipulation. Thus, by subtracting PRE from POST phases the logic is: what is left over does *not* reflect brain activity related to movements of the active hand (given that those movements are equated in the two phases, an effect confirmed with further analysis). The Randpress condition involved identical characteristics during PRE and POST, except that a foot response occurred to separate those phases. Thus, subtracting POST-PRE theoretically isolates any brain activity related to the foot pedal response. The double subtraction (A-B: see Table 1) then isolates what we refer to as *perceptual capture* of any changes between PRE and POST associated with perceptions of the hidden hand (the hand located in the virtual position of the mirror reflection) after removing effects of the foot pedal press. For EEG analysis, as an extra precaution to avoid activity potentially related to processes associated with the foot pedal response, our earliest PRE interval was –4.0 s (or 4 seconds prior to the foot pedal response) which is before activation of the foot pedal response would be expected to occur (calculated on the basis of pilot studies); the aim being to capture the time the perception begins to occur.

The EEG channels of interest were predetermined from previous research as being representative of activity overlying, respectively the frontal (F3, Fz, F4), central (C3, Cz, C4), and parietal (P3, Pz, P4) lobes (Fu & Franz, 2014). Event related spectral perturbations (ERSP) at each channel were analyzed using 4×5 repeated-measures ANOVAs with time interval (–4.0 s to –3.0 s, –3.0 to –2.0 s, 0 to 1.0 s, 1 to 2.0 s) and frequency bin (delta: 1–4 Hz, theta: 5–7 Hz, alpha: 8–13 Hz, beta: 14–30 Hz, gamma: 31–40 Hz) as within subjects factors. These were followed up with *t*-tests where appropriate.

Sources of EEG spectral activity were further investigated using eLORETA (Exact Low Resolution Electromagnetic Tomography) (Pascual-Marqui et al., 2011). The eLORETA method is a discrete, three-dimensionally distributed, linear, weighted minimum norm inverse solution that assembles scalp EEG into a three-dimensional matrix of cortical generators consisting of 6239 5 mm^3 voxels in a MNI152 template (Mazziotta et al., 2001). The output of

Table 1

Descriptions of the key experimental conditions on which simple and double subtractions were applied to isolate (capture) the perception of ownership

	PRE(press)	*POST(press)*	*POST minus PRE*
Mirror condition	-left hand moving	-left hand moving	**Change in perception+possible effects related to the foot pedal response: (A)**
	-normal perception -mirror view	-changed perception -mirror view	
RandPress condition	-no hand movement	-no hand movement	**Isolating just the effects of the foot pedal response common to PRE and POST: (B)**
	-normal perception -mirror covered*	-normal perception -mirror covered*	
Mirror- RandPress			**Perception of a change (in limb ownership) as later verified by self-report (double subtraction: A – B)** **Theoretically, this removes effects related to the foot pedal response, isolating effects of interest.**

Note. **Bold** denotes attributes that are theoretically isolated using experimental subtractions. PRE refers to the task performed prior to a foot-pedal response. POST refers to the task performed in intervals following a foot-pedal response. PRE and POST use the same movement task, which is a required hand movement of the left hand (see text); PRE and POST intervals are theoretically identical (therefore, POST minus PRE theoretically removes effects associated with the movement). The double subtraction aims to isolate brain activity associated with the perceptions induced by means of the mirror. *The RandPress condition was conducted with the mirror box covered and in a separate experiment with the mirror visible (with no hand movement). We noted that the latter experiment might induce visual distractions (and data were noisier); thus, the covered mirror was used in the present experiment. Note further that the control task, Covered mirror condition (reported in Methods), yielded no meaningful effects nor any reported perceptual changes or foot pedal responses, thus yielding no result after the POST minus PRE subtraction. That condition was therefore eliminated from further analysis.

an eLORETA localisation contains a voxel image for each requested frequency band. Localisation by eLORETA is theoretically exact (even in the presence of structured biological noise), albeit with low spatial resolution (Pascual-Marqui, et al., 2011; Pascualmarqui, Michel, & Lehmann, 1994). Source localisation was performed using the LORETA software package (version 20141117, freely available from the KEY Institute's website).

Functional independent components analysis (fICA) was conducted on the eLORETA localisation images following the method of Aoki and colleagues (Aoki et al., 2015); technical details can be found in Pascual-Marqui, et al. (2011). Briefly, a mean localisation image is first calculated for each frequency band for each participant on data from each condition. Next the data from each participant and condition are concatenated, and fICA is performed in order to find maximally spatially independent spectral components. Each resulting component indicates regions and frequencies that tend to be active together with a voxel image for each specified frequency (Aoki, et al., 2015).

Questionnaire. Adapted from (Botvinick & Cohen, 1998; Holmes, Snijders, & Spence, 2006) an illusion questionnaire using a 7-point scale for each item ranging from strongly agree (7) to strongly disagree (1) with questions pertaining to strength of the induced perceptions (as a method of verifying overall impressions of those perceptions) was employed. Example questions include: "I felt as if the hand in the mirror were my hand"; "It seemed as if I might have more than one left or right hand"; "The hand in the mirror began to resemble my own (real) hand, in terms of shape, skin tone, freckles or some other visual feature". All participants were asked to complete this questionnaire after all experimental trials were collected. The abbreviated handedness questionnaire of Oldfield (1971) was also administered.

2.3. Design and procedures

Participants performed three conditions: Random press (a control for foot pedal responses: RandPress), Covered mirror, and Mirror (our critical experimental condition). The Covered mirror condition was included only as an extra precautionary measure aimed to assist us in identifying whether factors such as attentional effects, possible subjective biases or expectations, or other confounding effects might be influencing any potential findings of interest. The theoretical visual, motor, and perceptual processes in pre-response (PRE) and post- response (POST) stages are illustrated in Table 1 for each experimental condition. The subtraction logic is listed in the last column, with the implicated (changed) process highlighted.

During Mirror and Covered mirror conditions, participants were instructed to move the left hand by opening and closing it at an approximate pace of 2 Hz (practiced thoroughly beforehand) without touching the table (with the four fingers touching the thumb and then opening); the resting/inactive hand was covered and shielded from view. This task has been used in our previous work which is related to the present study (Debnath & Franz, 2016). Participants each practiced this paced task for a few minutes prior to any experimental testing, and all found it easy to perform without requiring substantial attention demands (and there was no pace signal during the actual experimental trials). Importantly, this movement was constant for PRE- and POST- phases of the trials rendering its properties to be removed with the subtraction method. In the random foot pedal condition each participant was instructed: 'On the following trials, please rest your hands on the table, and sometime during the trial which will last approximately a half minute, please press the foot petal once using the foot that is most comfortable'. The participant then placed his/her foot on the foot pedal (all chose the right foot), and practiced this task for a few trials following which the RandPress condition was collected. After all random foot pedal trials were complete, participants were further instructed: "On the following trials, please press the foot pedal when noticing any changes in sensation or perception including ownership of the reflected limb or any other sensation changes, and do this while continuing to perform the opening-closing hand movements of [this] hand" (where the experimenter pointed to the participant's left hand: see Fig. 1 caption for additional details). At this time, 'ownership' was defined as 'the limb in the mirror feels like your actual limb', and participants were queried further to be sure they understood what was being asked of them. The Covered mirror condition differed from the Mirror condition (which were randomized for order) in that the mirror was covered with black cloth in the former. Participants were instructed in both of those conditions to focus their eyes on precisely the mirror-image location of where the hand would appear (although we avoided using those terms and just pointed to the location). Thus, without use of the mirror, participants were focusing attention on a location where no image of the hand was present;

with use of the mirror, participants focused attention on the same location but this time occupied by the mirror image of the moving hand.

As described above, sessions always began with the RandPress condition so that participants would not have any prior knowledge of the upcoming manipulations. The order of Mirror and Covered mirror conditions was counterbalanced across participants. Each consisted of 12 consecutive trials lasting 32 seconds per trial. A short break was given between trials to query participants about their sensations and perceptions on that trial (all comments were carefully logged and audio-recorded at the time by an experimenter). A trial was deemed invalid when the participant had any trouble with the pedal, and the trial was then repeated (this occurred on approximately 2% of trials across all participants combined).

3. Results

3.1. Behavioural and qualitative

For each of the 15 included participants, there were equal numbers of valid RandPress control trials, and findings were analyzed within-subject and then averaged across all of them. We first examined the Covered mirror condition and confirmed that there were no observable effects of interest. Specifically, there were no pedal presses by any participants. Two experimenters' independent assessments confirmed that there was no observable movement in the hidden hand of any participant. After thorough analysis of the Covered mirror condition without evidence of any type of effect to report, we omit that condition from further discussion.

Our post-experimental questionnaire revealed that 75% of participants reported they convincingly experienced changes in perception as a result of the mirror. The remaining 25% reported either not knowing (8%) or disagreeing that the mirror played any role on their perceptions (17%).

To further examine effects due to our critical Mirror condition, we first separated mirror trials for which at least one foot press occurred, from those without any foot presses (the latter of which indicated to us a lack of reported perceptual change by the participant). In total, there were 151 trials (each 32.0 seconds in duration, to total 4832.0 seconds of data for brain activity analyses) in which one foot pedal press occurred on each, accounting for 84% of the total Mirror trials. Those are referred to herein as 'valid' trials. In response to our post-trial question, 'What did you feel that made you press the foot pedal?' all participants subjectively reported some form of the following: "the hidden hand felt like it was moving", "my right hand moved like the other hand", or "I felt like my real hand moved" (pointing to or lifting the hidden hand). We further queried participants to confirm it was the hidden hand they were referring to. Participants' remarks (in addition to further post-experimental questionnaires) confirmed that our general method was valid for the intended purposes and that participants had some experience of 'ownership' as defined above. When further asked approximately how long the perceptual or sensation effect lasted, those participants who supplied an answer reported estimations between 2 and 6 seconds (and we did not get any responses indicating that the effect occurred for a longer time; thus, it was transient). In some participants this change occurred more than once during a trial (and we assessed this by repeated foot pedal presses but did not include those in the reported analyses because those trials cannot be equated in number with the single foot pedal press of the RandPress control trials). Three participants replied that they did not know how long they felt the perception.

3.2. EEG findings

We averaged the EEG data for each participant to enable more specific statistical treatment after including the left hander who did not show any obvious differences from the right handers. The average spectral power of all trials in the RandPress control condition was then subtracted from the average spectral power of all valid trials in the Mirror condition for each time bin and frequency bin.

The main effects of frequency were shown to be significant only at the Fz site [$F(4,56) = 3.01$, $p = 0.026$]. Further pairwise comparisons after Bonferroni corrections indicated that spectral power at the theta (4–7 Hz) frequency band was significantly lower than the spectral power at the beta (14–30 Hz) frequency band ($p = 0.033$). Thus, the main effects of frequency were not particularly informative (nor did we have specific hypotheses for frequency bands other than alpha and beta).

Of interest in terms of our hypotheses, a main effect of time interval was found at the C4 site [$F(3,42) = 3.45$, $p = 0.025$] and all parietal channels: P3[$F(3,42) = 5.22$, $p = 0.004$], Pz[$F(3,42) = 3.48$, $p = 0.024$], and P4[$F(3,42) = 3.91$, $p = 0.015$]. Further pairwise comparisons (after Bonferroni corrections) using the early pre-response (PRE) interval (–4.0 s to –3.0 s) compared to early post-response (POST) interval (0 to 1.0 s) indicated a highly significant spectral power increase at the right parietal site (P4, $p = 0.005$). This significant effect is also shown at the left parietal site (P3, $p = 0.027$), and the vertex parietal site (Pz, $p = 0.049$). Pairwise comparisons using a slightly later PRE interval (–3.0 s to –2.0 s) compared with early POST (0 to 1.0 s) indicated a significant spectral power increase at the left (P3, $p = 0.044$) and right (P4, $p = 0.016$) parietal sites. Comparisons using late POST (1.0 s to 2.0 s) did not show any significant effects ($p > 0.05$), suggesting that the majority of perceptual effects did not persist for longer than about 4.0 s.

A significant interaction of time interval X frequency was found only at the right parietal site (P4), [$F(12,168) = 2.48$, $p = 0.035$] with simple effects isolating the alpha frequency band [$F(3,42) = 5.47$, $p = 0.003$]. Further pairwise comparisons (after Bonferroni corrections) at the P4 site indicated a highly significant power change when comparing

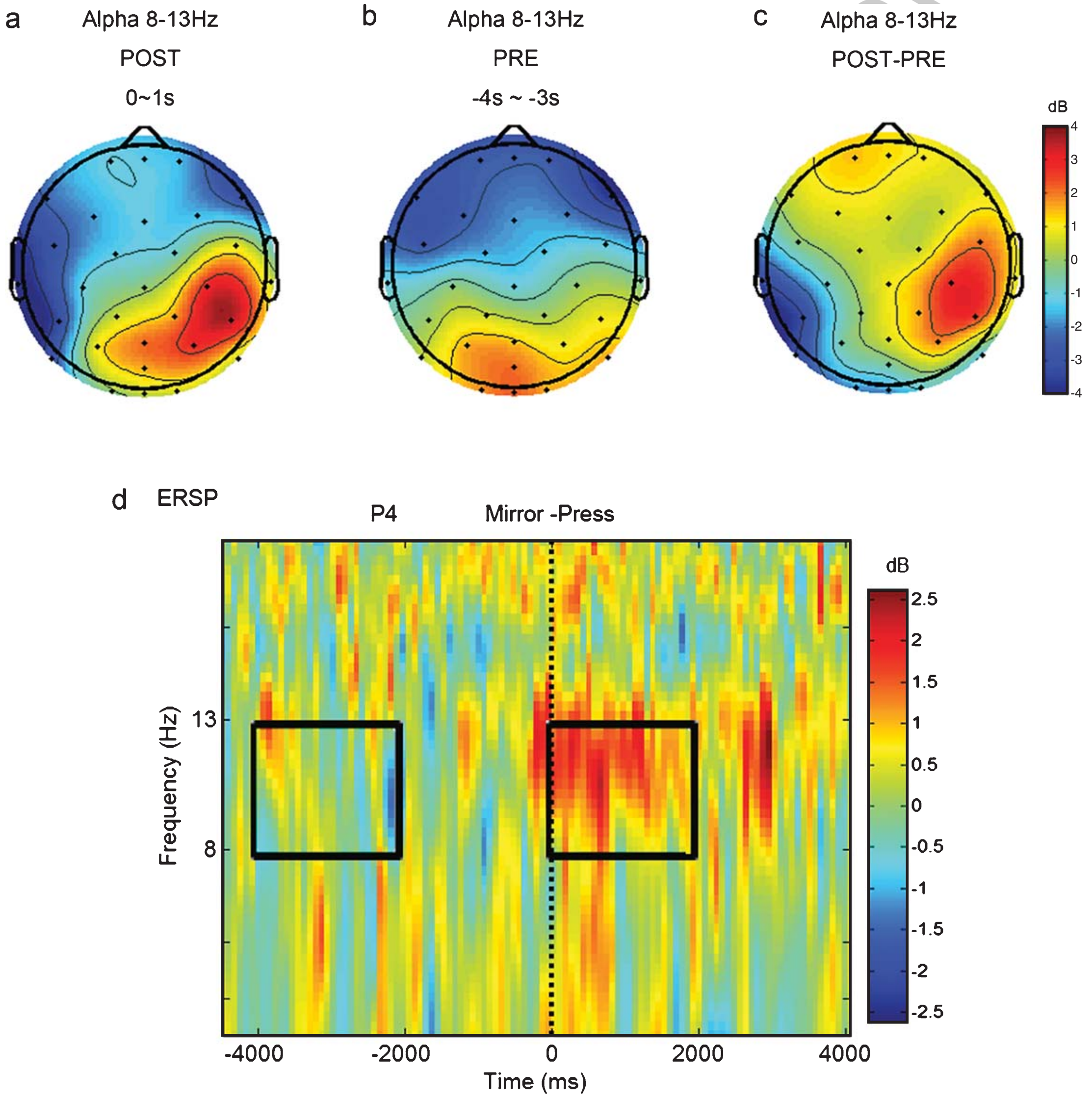

Fig. 2. Alpha frequency effects after subtracting the Random Press condition from the Mirror condition, with whole brain alpha activity shown for the (a) POST interval (0 to 1.0 s), (b) PRE interval (–4.0 s to –3.0 s), and (c) subtraction of POST minus PRE, with color scale shown on the right. (d) Difference between Mirror and Random Press conditions for Event Related Spectral Perturbations (ERSP) at the P4 channel (right parietal site), with alpha frequency (8–13 Hz) marked in boxes for PRE and POST time intervals.

early PRE (–4.0 s to –3.0 s) versus early POST (0 s to 1.0 s) ($p = 0.001$) and when comparing late PRE (–3.0 s to –2.0 s) versus early POST (0 s to 1.0 s) ($p = 0.002$). The prominent effects at parietal regions, particularly on the right side of the brain (P4) (Fig. 2), suggest that parietal areas play a particularly important role in the perceptual change associated with limb ownership (and see below for further effects on localization which are consistent with this interpretation).

In sum, the spectral power at central-parietal regions significantly increased after the foot pedal press in all frequency bins. However, the most significant spectral power change is shown in the alpha frequency band at the right parietal lobe which is contralateral to the moving hand.

3.2.1. Functional ICA analysis in eLORETA

Differences in spectral power found by electrode-wise comparisons were further investigated using fICA of eLORETA in the attempt to localize the primary sources. We included both alpha and beta frequencies in this analysis as dictated by our hypotheses. Average alpha and beta spectral generator images for each participant were first derived separately for the artifact-free PRE (–4.0 to –3.0 s) and POST (0 to 1.0 s) epochs of both the Mirror and Random press trials. These source localizations were concatenated, and fICA was used to find maximally spatially independent components. The components were Z-transformed, with a value of 3.0 or greater indicating significant activation (Aoki et al., 2015), and ordered by the percentage of variance that they accounted for. Five components were extracted, enough to explain 90% of the variance in the images. The loading of each component in each spectral generator image was compared using Statistical Non-Parametric Modelling (SnPM) with a within-subjects t-test as the statistic of interest. The PRE vs POST difference in component loadings during Mirror trials was compared to the same difference during Random press trials.

The omnibus null hypothesis for the SnPM test was rejected at a low threshold, indicating significant differences in the activity of all components ($p < 0.000001$). Based on spatial distribution, frequency range, and t-test results, we first identified independent components (IC): IC1, IC4 and IC5 as artifacts of eye movements, temporal electromyogram and occipital baseline shifts, respectively. We further identified IC3 as the Random press condition related brain networks in right parietal areas for both alpha and beta frequencies (Fig. 3). Finally, the key Mirror manipulation related brain networks are shown in IC2, which is found at the right parietal areas in the alpha frequency band and at the left middle temporal areas in the beta frequency band (Fig. 4).

4. Discussion

We aimed to experimentally capture the perception of ownership of a moving hand, as induced by the well-known mirror reflection illusion. An initial

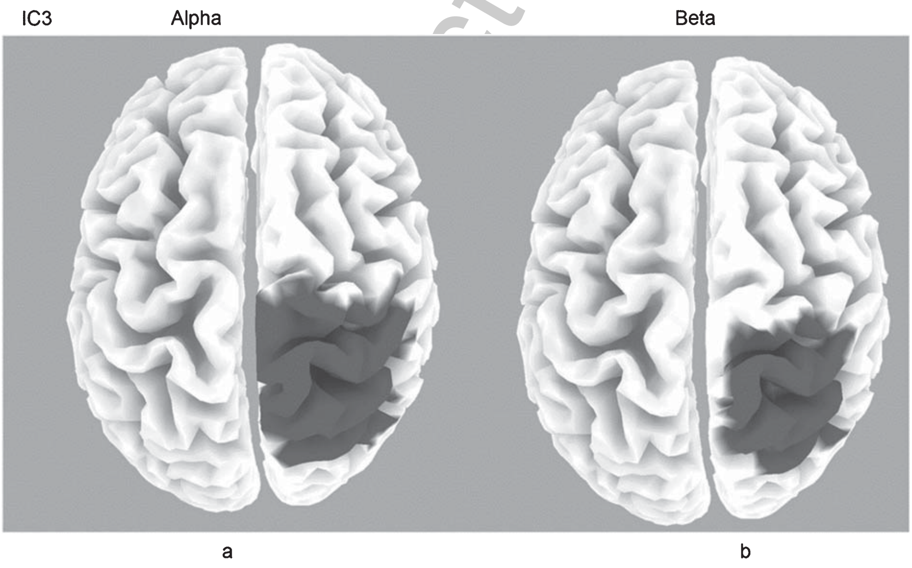

Fig. 3. LORETA-ICA component 3 (IC3) comprises the right parietal regions (with maximum difference at the Postcentral Gyrus: BA7) in both (a) alpha and (b) beta frequency ranges. Correlated activity increases in these areas were associated with the random press condition.

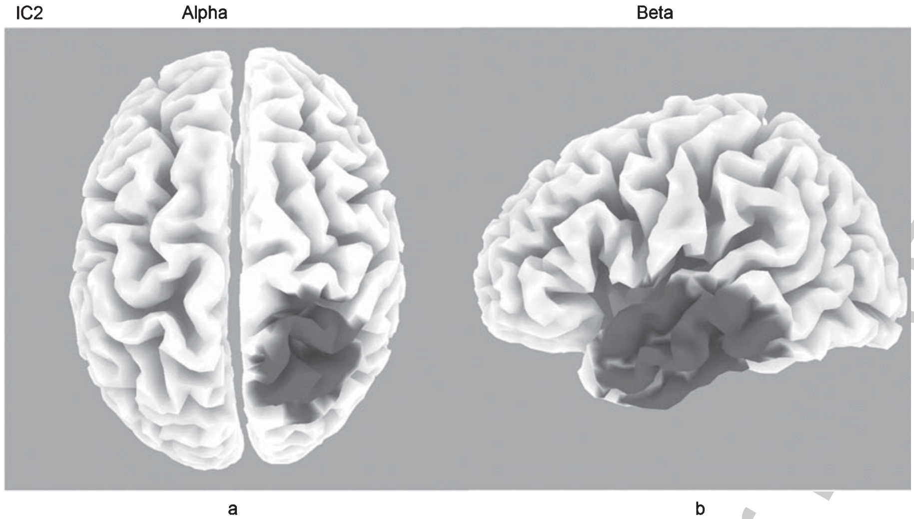

Fig. 4. eLORETA-ICA component 2 (IC2) comprises (a) right parietal activation (maximum difference at BA7) at the alpha frequency range and (b) left middle temporal activation at the beta frequency range (maximum difference at Middle Temporal Gyrus: BA21). Correlated activity increases in these areas were associated with the Mirror condition.

finding is that 25% of our participants experienced no perceptible change with the MT manipulation. Thus, a perceptual effect is not induced in all participants which suggests that the mirror intervention might not be effective in those who do not experience such perceptions. Reasons for individual differences are open to speculation. The remainder of the reported effects pertains to participants who did experience a clear perceptual change with the mirror manipulation.

Our key findings revealed stronger event-related synchronization (ERS) after the pedal press (POST) compared with before (PRE) in the right parietal region at the alpha frequency range, that which was also localized in our ICA analysis: Fig. 4). The fact that this lateralized effect was not common to central-motor/frontal areas suggests that it was not entirely due to actual movement. To further qualify this, we note that a separate (independent) component of activity localized to the right parietal lobe in both the alpha and beta frequencies is related to the foot pedal press (IC3; Fig. 3). This is also outside of primary motor areas, and appears to be related more to sensorimotor processing in parietal sites; notably, the required left hand movements and also the foot pedal response are quite well-learned tasks, which is consistent with this interpretation. Thus, in keeping with a rather conservative approach and conclusions, it seems clear that our experimental subtractions (Table 1), coupled with effects of localization, provide support for the hypothesis that the perception of the correlates of ownership can be captured temporally using this new procedure; such processing implicates a centro-parietal network with sources localized to BA7 in the right parietal lobe (in the alpha frequency range) and BA21 in the left temporal lobe (in the beta frequency range).

Precisely how different portions of the right parietal lobe might work together (or perhaps in opposition) for actual movement versus perception of ownership, remains to be disentangled. Similarly, it is not yet known how different bands of activity might work together. Notably, in addition to our subtractions through experimental methods and our confirmatory ICA analyses, we also found consistent evidence with our primary findings from the perceptual reports of the participants and their answers to questionnaires (which were adapted from other studies investigating the neural basis of limb/hand ownership: see Introduction). Our findings of localization in the beta range implicate a source in the temporal lobe close to those found in a recent fMRI study (superior temporal lobe) also using a mirror manipulation (Hamzei, et al., 2012). A precise role of the temporal cortex in the perception of ownership remains to be elucidated.

Our findings also seem consistent with previous studies suggesting that alpha band oscillation is correlated with illusory perceptions in both visual and auditory modalities (Lenggenhager, Halje, & Blanke, 2011; Muller, et al., 2013; Shevelev, Kamenkovich, & Sharaev, 1996). For example, Lenggenhager et al. (2011) using virtual reality technology and a visuotactile conflict showed body-specific alpha band power modulations in bilateral sensorimotor cortices; notably however, our effects isolate alpha in primarily the right side of the brain. Indeed, a similar relationship between illusion of limb movement and beta rhythm has been shown in central brain areas (Keinrath, et al., 2006).

It is important to point out that the present findings (obtained only in controls) do not lead to any direct claims in relation to phantom limb pain or related effects. Demonstrations of cortical remapping following amputation in non-human animals and in humans (Birbaumer et al., 1997; Flor et al., 1995; Lotze, et al., 2001; MacIver, et al., 2008; Merzenich et al., 1984), do however lead to the intriguing possibility that through manipulations such as the mirror box, perceptions can change and further influence brain plasticity. Indeed, functional imaging studies have demonstrated findings consistent with the claim that sensorimotor rhythms are generated in brain regions shown to be involved in phantom limb pain (Lotze, Flor, Grodd, Larbig, & Birbaumer, 2001). The amount of perceived phantom limb pain has also been linked with the ability of a person with chronic pain to psychologically adjust to the physical environment (Jensen et al., 2002; Jensen, Turner, Romano, & Karoly, 1991), which suggests that the extent to which effects of pain are modifiable differs across people. Although critical studies remain to be conducted in order to examine any direct links, the possibility that malleable perceptual effects might be used as therapeutic avenues toward pain reduction, is ripe for investigation.

This study aimed to isolate perceptions of ownership and associated brain activity as an initial step in the direction outlined above. The present findings could be further confirmed by replication, and in particular, by testing participants with strong reported perceptions of ownership against those who report none. In the present study, 25% of participants reported having no subjective perceptions of ownership in our Mirror condition (and therefore never pressed the foot pedal in that condition); but that sample was too small to analyse. If this proportion of 'non-responders' is representative, then it should be possible to recruit a control group of sufficient size to be used in direct comparisons against those who do respond.

A possible attempt at an intervention might be to teach (or encourage) a person with phantom limb pain to learn to prolong a positive perception (such as ownership, if that brings on a positive feeling/sensation) with that perception replacing a negative one such as pain. Another possible avenue for development involves implementing machine-learning algorithms in the attempt to classify neural activity associated with the perception of ownership as distinct from the perception of what might be considered its opposite (perception of dis-ownership or detachment of a limb). If successful, the development of a brain-computer-interface (BCI) might follow as a potential intervention for pain (or other negative perceptions). These and other cognitive behavioral interventions rely on utilizing perception as a therapeutic window for brain change.

Possible limitations of the present study are just as those with any brain imaging study in that we cannot be absolutely certain that the effects on brain activity are in fact associated with the perceptual event of interest. However, as pointed out above, at least some of our findings converge nicely with previous studies. We also find it highly unlikely that we would obtain meaningful and statistically-significant findings using our conservative methods; specifically, those involve isolation of specific temporal epochs and application of subtractive logic on manipulated control conditions (in this case a double subtraction). We set ourselves up to fail in that we did not at all expect to find strong support for our hypothesis. Finding such support seems somewhat compelling. We further acknowledge that the utility of subtractive logic, which originates from the seminal work of Donders (1868: described in Sternberg, 1969) cannot be overstated.

In sum, the present study provides evidence that specific changes occur in relevant neural rhythms with people's transient perceptions of limb ownership in response to a mirror box manipulation, providing a critical start point (and method) toward further development of this approach. Our findings highlight involvement at the alpha frequency with a primary localized source in the right parietal lobe. Although far less pronounced, we also find beta effects with a primary source located in the left temporal gyrus. Thus, it seems feasible to 'capture' the perception of ownership in terms of its underlying neural correlates. This is a first step which provides support for the idea that perceptions are malleable and can be manipulated experimentally, and that associated neural activity can be identified.

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