# Bodies in the Brain

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Thesis submitted for the award of Doctor of Philosophy
September 2006

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# Abstract

Fundamental to our ability to successfully interact with the world is the representation of our body in the brain. Through uni-modal visual processes we are able to perceive others but it is only through combining visual, somatosensory and motor information that we are able to form a complete representation of our own body. The aim of this thesis was to investigate the 'extrastriate body area' (EBA), an area selective for images of the human body, and to assess whether and how it may be fitted into a body-touch crossmodal network. Here we report that the EBA is a region that has underlying populations of neurons selective for not only images of different types of body parts but also for images of one's own body parts. Further, it is reported that somatosensory brain regions respond to visual body part images and the EBA to tactile stimulation. Thus, it is argued that, together with the right inferior parietal lobe, a region identified as selective to one's own body and tactile stimulation, the EBA and initial somatosensory processing areas form the basis of a body-touch network as part of the body's representation in the brain.

# Acknowledgements

Firstly, I would like to begin by thanking those people who have been directly involved with this work throughout the last four years, especially for their help, support, advice and encouragement. Especially I would like to thank my principal supervisor Paul Sowden who has guided me throughout this whole process and has always enthusiastically supported me since I began this PhD. I would also like to extend my gratitude to all those who have assisted me in completing this work. To Terry Thacker, David Rose, Emre Özgen, Nick Jenkins, Helen Payne, Simon Mathews and to all those I have missed but have bothered over the last four years.

I would like to extend a special thank you to all those involved in helping me through my fMRI learning experience. Especially I would like to thank Ari Lingswaren for all his help in using the scanner and also to all those who have helped in to understand fMRI design and especially analysis. To Marius Peleen (finally I will stop asking you questions!), Chun-Chia Kung, Paul Downing, Armin Heinecke, Hester Brenman and I expect many, many more, thank you for all your assistance (and patience!).

This work has been supported by a bursary in the first year from the University of Surrey Psychology Department and in the last three years by a grant from the Economic Social Research Council.

Lastly, I would like to thank all my friends and especially my parents who have supported me throughout my studies and lastly to Mary, my wife for all your patience and understanding thank you.

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The body is a unit, though it is made up of many parts; and though all its parts are many, they form one body. So it is with Christ.

**1 Corinthians 12:12**

# Chapter One: Introduction

## 1.1. Overview

**The purpose of this thesis is to explore the representation of the human body in the brain focussing on the selectivity of the extrastriate body area (EBA) and its role within a putative crossmodal network of body and touch. Using fMRI as the main investigative method the experiments detail the initial localisation of the EBA and exploration of this area with regard to perception of one's own body using an adaptation based analysis method termed fMR-Adaptation. Further, this thesis seeks to address the findings of these experiments by exploring how they can be placed within a network with somatosensory and other cortical 'association' regions.**

## 1.2. Neural basis of human object recognition

Despite the highly complex nature of the visual environment, humans are able to successfully distinguish between and identify objects within a fraction of a second even under sub-optimal viewing conditions. Kanwisher, McDermott and Chun (1997) propose that a wide variety of evidence from cognitive psychology (for example Yin, 1969), computational vision (for example Turk and Pentland, 1991), neuropsychology (Damasio, Tranel and Damasio, 1990) and neurophysiology (Desimone, 1991) suggests that object and face recognition involve different mechanisms and distinct cortical areas.

These mechanisms underlying human object recognition have gained a great deal of attention not least because efforts to simulate such processes with computers have resulted in little success (Grill-Spector and Malach, 2004) and it has been proposed that there are a number of distinct cortical regions that are specialised for processing a particular type/category of visual stimuli (see Kanwisher, 2000).

Through the use of functional magnetic resonance imaging (fMRI) a number of such cortical areas have been localised that respond significantly more to one specific category of visual stimuli than another. The largest of these areas is the Lateral Occipital Complex (LOC; figure 1.1) on the lateral bank of the fusiform gyrus, which responds significantly more to images of objects than non-object textures (Malach, Reppas, Benson, Kwong, Jiang, Kenedy, Ledden, Brady, Rosen and Tootell, 1995).

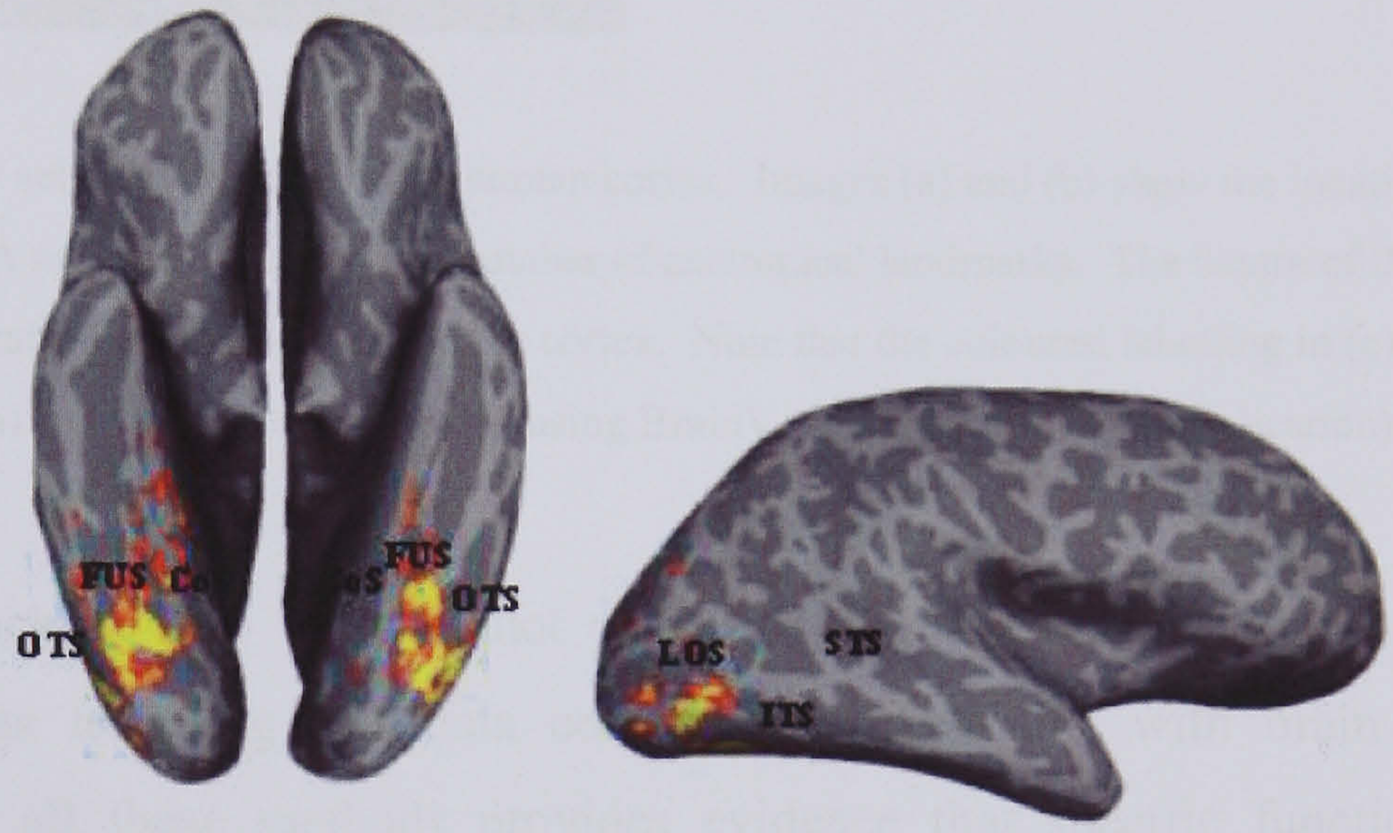



**Figure 1.1.** The lateral occipitotemporal cortex. Images show the location of the lateral occipital complex (LOC) on the lateral (left) and medial (right) surface of an inflated cortex. Images are taken from Grill-Spector *et al.* (2001). The LOC region has been extensively reported to be maximally sensitive to object images.

Kanwisher, McDermott and Chun (1997) identified a region of the fusiform gyrus that was specifically responsive to images of human faces (Fusiform Face Area; FFA) and an area responsive to scenes termed the Parahippocampal Place Area (PPA; Epstein et al., 1999). More recently Downing, Jiang, Shuman, and Kanwisher (2001) localised the Extrastriate Body Area (EBA) which appears to preferentially respond to images of the human body (PPA, FFA and EBA shown in figure 1.2.).

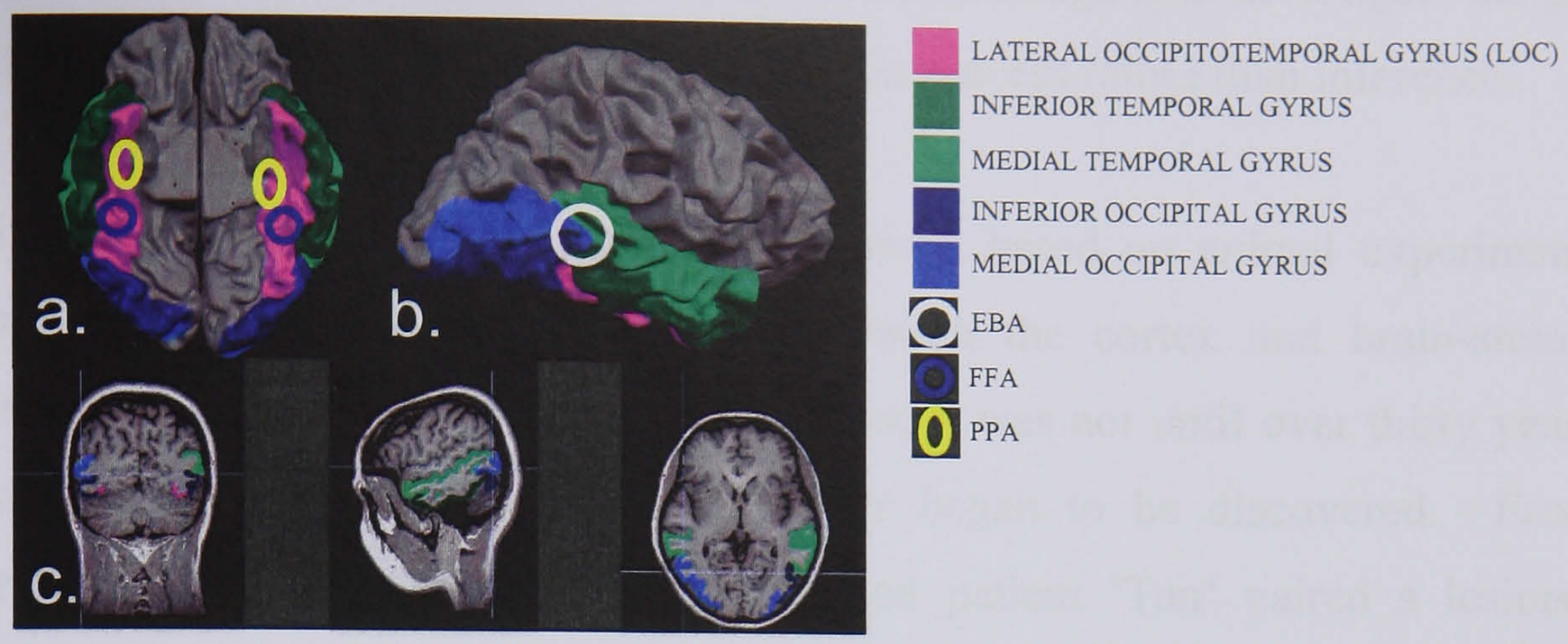



**Figure 1.2.** Object selective regions of the human cortex. Images (a) and (b) show the location of the LOC, PPA, FFA and EBA in relation a number of anatomical landmarks. The centre of the cross in (c) marks the location of the EBA within the cortex. Note that the coloured labelling in (c) is relative to that in (a) and (b). (Image produced using BrainVoyager's BrainTutor application)

Evidence for such regions is based not only on fMRI research but also on other methods such as lesioning and data collected from patients with brain injury. Research using all these methods provides evidence that specific functions are primarily processed by dedicated cortical regions. This is known as Localisation of Function.

### 1.2.1. The Origins of Localisation of function

The origin of localisation of function is founded in Gall's (1810-1819) 'The Anatomy and Physiology of the Nervous System in General, and of the Brain in Particular'. This outlined his theory of phrenology, that the brain is the organ of the mind, and that mind has a set of different mental faculties, each particular faculty being represented by a different part or region of the brain's underlying functions evident from the structure and shape of the cranium. Despite its lack of empirical evidence and the theory's foundations on flawed inference it led anatomists and physiologists to investigate the concept of mental processes as being linked to specific cortical regions directly.

Direct investigation of the cortex using techniques such as selective surgical ablation, direct electrical stimulation and post-mortem clinical studies of patients with

neurological deficits allowed anatomists and physiologists to investigate the possible separate functions of the brain using scientific process rather than inference.

Circa 1825, Flourens (1825) drew conclusions based on animal experiments that large divisions in the brain, such as between the cortex and brain-stem, were responsible for different functions. However, it was not until over thirty years later that the individual functions of the cortex began to be discovered. Famously, Broca's (1861) post-mortem examination on patient 'Tan' paired a lesioned left inferior frontal region with inability to talk ('Tan's aphasia'), concluding that this cortical region (Broca's Area) controlled motor production of speech. Broca's work was closely followed by Wernicke's (1864) research into the localisation of speech production, evidence of fine-scale localisation of function in the cortex found by Fritsch and Hitzig (1870) , and Krause's (1908) cortical stimulation work on anesthetised patients, which contributed substantially to the mapping of the motor cortex.

By the early twentieth century the concept of cortical organisation by function had become established and improvements in methods led to further developments in the functional organisation of the brain such as Penfield and Jasper's (1954) mapping of the sensory and motor cortices. However, recent developments in non-invasive techniques such as Position Emission Topography (PET) and fMRI have promoted an acceleration in research on functional brain organisation such as the mapping of the retinotopy of the visual system (Sereno, Dale, Reppas, Kwong, Belliveau, Brady, Rosen and Tootell, 1995).

### 1.2.2. Lateral Occipital Complex and Fusiform Face Area

Both objects and faces are highly complex stimuli recognised and distinguished with relative ease. For this reason it has been suggested in the literature that both objects and faces have functional regions dedicated to their respective processing. PET studies in the early 1990's began to reveal that there were a number of ventral and temporal brain regions responsive to images of objects and faces (for example Haxby, Grady, Horwitz, Ungerleider, Mishkin, Carson, Herscovitch, Schapiro, and

Rapoport,1991). However, the exact location and nature of these areas was not identified until the increase of fMRI use in cognitive neuroscience in the latter part of the decade as discussed next.

### *1.2.2.1. The Lateral Occipital Complex (LOC)*

An extensive region of the lateral fusiform gyrus has been consistently shown to be preferentially activated by images of objects (familiar and unfamiliar) compared to non-object textures (Malach *et al.*, 1995; Grill-Spector, Kushnir, Edmond, Itzchak and Malach, 1998; Grill-Spector, Kushnir, Hendler, Edelman, Itzchak and Malach, 1998). This region labelled the lateral occipital complex (LOC) has also been shown to be sensitive to the illumination and viewpoint but not the position and size of objects (Grill-Spector, Kushnir, Edelman, Avidan, Itzchak and Malach, 1999; size invariance also found by Malach et al., 1995; inferior temporal selectivity to object invariance has been demonstrated by Vuilleumier, Henson, Driver and Dolan, 2002)) and can be further subdivided into both caudal dorsal and the posterior-fusiform regions (Grill-Spector *et al.*, 1999).

The proposed object processing function of the LOC is also supported by a number of event-related potential (ERP) studies (for example see Allison, Ginter, McCarthy, G., Nobre, Puce, Luby and Spencer, 1994), which found higher responses for objects than non-objects (scrambled controls) in left and right fusiform and inferior temporal gyri. Furthermore, a number of lesion studies from brain-damaged patients have indicated that damage to the fusiform and occipito-temporal region result in a number of object recognition deficits (e.g. Damasio, 1990) and comparative results have been found in transcranial magnetic stimulation (TMS) studies involving these cortical regions (Stewart, Meyer, Frith, & Rothwell, 2001).

Grill-Spector, Kourtzi and Kanwisher (2001) comment that the strong activation of the LOC to visual images of objects (via simple cognitive-subtraction paradigms as discussed later in chapter two) is not itself evidence that it is the region of the brain that is responsible for object recognition. However, the evidence discussed from

lesioning, TMS and ERP studies adds substantial weight to the important role of the LOC in object recognition.

### *1.2.2.2. The Fusiform Face Area (FFA)*

Early single unit recordings in macaque superior temporal sulcus (STS) cortex demonstrated neuronal selectivity for faces (for example Gross, Roche-Miranda and Bender, 1972) and more recently this has been supported by single unit recordings in the fusiform gyrus of humans (see Allison *et al.,* 1994). Further evidence for a face selective region of human cortex has come from patients with brain damage to the posterior right hemisphere that has resulted in face recognition deficits termed prosopagnosia. These patients are unable to recognise previously familiar faces (see Bodamer, 1947; De Renzi, 1997) yet are able to largely recognise/name objects. There is also a double-dissociation with reported cases (such as patient CK; Moscovitch, Winocur and Behrmann, 1997) where object identification is impaired yet face recognition is intact.

This evidence has been supported by more recent neuroimaging studies that have allowed more precise localisation of the now established FFA. The function and the role of the FFA was initially investigated by Kanwisher, McDermott and Chun (1997). Using fMRI they sought to identify a face selective area in human cortex (i.e. the FFA) and investigate its level of response to a number of other types of stimuli that may be causing the activation of the area (e.g. low level feature extraction and recognition of any animate objects). They concluded that the response of the FFA was indeed specialised for faces and could not be explained by other confounds or types of stimuli (for a counter view see Tarr and Gauthier, 2000).

Further imaging studies have successfully localised the FFA and implicated it, among other things, in the recognition of one's own face (Sugiura *et al,* 2000), differential processing of different races (Phelps, 2001) sensitivity to human faces but not animals (Kanwisher, Stanley and Harris, 1999), sensitivity to inversion of faces (Haxby, Ungerleider, Clark, Schouten, Hoffman, and Martin, 1999) and the importance of facial feature configurations (Yovel and Kanwisher, 2004).

## 1.3. The Extrastriate Body Area (EBA)

It is clear that the neurophysiological, neuropsychological and neuroimaging literature has offered a great deal of support for both the existence and role of specialised functional regions for object recognition. As has been discussed, both the LOC and FFA have been widely researched especially with the increasing prevalence of fMRI. In addition, a recent study has localised a functional region near the FFA and LOC that is sensitive to images of the human body and termed the extrastriate body area (EBA).

### 1.3.1. Localisation of the Extrastriate Body Area (EBA)

Originally localised by Downing, Jiang, Shuman & Kanwisher (2001) the extrastriate body area (EBA) was found to be preferentially activated by images of the human body (but not faces) over a variety of non-body stimuli. Observers were shown body-part and object-part images and when the object-part data were subtracted a distinct occipito-temporal functional region was identified in both the right and left hemispheres (this can be seen in figure 2.3 in the following chapter).

Furthermore, analysis showed that in all observers there was a clear set of EBA voxels that were uniquely activated by the EBA localiser and which did not overlap with the LOC, FFA, PPA or the visual motion area V5. The responsiveness of the EBA was consistently significantly greater to bodies than objects whether they were whole or partial and photographs or line drawings.

The study by Downing *et al* (2001) has since propagated a number of studies to investigate the functional nature of the EBA itself. Such studies are necessary for two main reasons. Firstly, consistent replication of the localisation of the EBA is important to show that it was not just a consequence of the specific localisation method used. Secondly, as with the LOC and FFA discussed above localisation itself is not sufficient to prove the role of an area in object recognition and the functional nature of that area must be investigated to fully understand its role and function within the human visual system.

As the main focus of this thesis is on the functional role of the EBA the following sections will discus in detail the studies that have investigated the functional properties of the EBA. However, firstly studies preceding Downing *et al's* (2001) will be discussed to establish whether there is any basis in the neuropsychological and neurophysiological literature for the existence of a 'body area'.

### 1.3.2. Basis for the existence of a body selective cortical brain region

#### *1.3.2.1. Are human bodies special?*

As has been established, and substantiated further in the literature, faces are a special class of visual stimuli that are supported by a dedicated processing region (FFA). However, the recent localisation of the EBA by Downing *et al.* (2001) suggests that bodies, like faces, have a dedicated cortical area. In a recent paper Slaughter, Stone and Reed (2004) discuss how bodies, like faces, may be subject to special processing and highlight a number of important features and functions that support the idea that they may be processed similarly to faces.

The organisation of the human body like the face is both symmetrical, configured the same for all humans and unchanging (e.g. the head, torso, limb arrangement). It is often argued that faces are recognised from the configuration of their parts and disruption of this configuration, for example, through inverting the face has been shown to impair facial recognition (see Carey and Diamond, 1994). A comparable effect has also been demonstrated by Reed, Stone, Bozova and Tanaka (2003) who reported that body part identification was significantly faster for upright than inverted body images that were configurably plausible, a finding similar to that in faces but not reported in other classes of stimuli such as houses.

Furthermore, as highlighted by Slaughter *et al.* (2004) bodies are conveyers of social information and provide spatial and emotional information about others. Slaughter, Heron and Sim (2002) suggested that the information extracted from bodies is different from that of faces and, for example, that it is easier to extract information from static faces than from bodies whereas a great deal of information can be

extracted from moving bodies. However, conversely Lander and Chuang (2004) argue that motion improves facial recognition although there is also evidence from point light display studies that support the notion that bodies convey a great deal of information when they are moving compared to when they are static (Clarke, Bradshaw, Field, Hampson and Rose, 2005).

Reed, McGoldrick, Shackelford and Fidopiastis (2004) suggested that one reason for specialised human body representations is for survival purposes, and more specifically using these specialised representations to help humans prepare their bodies for action, a mechanism not necessary for other types of objects. Reed *et al.* (2004) investigated the specialised representation of the human body using a variety of card sort tasks and multidimensional scaling analysis. The results revealed that object organisation did not follow a simple animate (human and bear) vs. inanimate (bike) organisation but instead the human body was arranged on its ability to perform actions. Reed *et al.* propose that this finding adds another piece of the puzzle as to why human bodies may be represented differently in the human cognitive system, which they add to evolutionary (Wilson, 2002), behavioural (Reed *et al*, 2003) and neuropsychological explanations (Bauxbaum and Coslett, 2001). This differentiation of human body images from other object classes further suggest that they may be represented in the cortex by a specialised functional region.

Further supporting the specialised nature of the human body, Downing, Bray, Rogers and Childs (2004) reported that unexpected/task irrelevant human body stimuli were detected in an 'inattentional blindness' task when attention was on a separate task. This suggests that the human body may be prioritised for attentional selection (a finding that has also been found with faces; Lavie, Ro and Russell, 2003) and as Downing *et al.* (2004) highlight, attentional priority is assigned to classes of stimuli (e.g. faces and bodies) that are represented in selective cortical areas (such as the FFA and EBA).

*1.3.2.2. Evidence from neurophysiology*

In a comprehensive single cell study of macaque inferior temporal (IT) cortex Desimone, Albright, Gross and Bruce (1984) reported a small number of cells highly sensitive to images of hands (in addition to a number of cells responsive to faces). These hand cells responded only to hand stimuli that were configurably sound (i.e. not scrambled) and not to any of the other simple (e.g. bars and gratings) or complex (e.g. faces and objects) stimuli presented. Furthermore, the cells were responsive to orientation changes in monkey and human hands and white silhouette cut outs of the hands (although not as much as the colour 3D hand models). From this it was evident that the cells were responsive to the shape of the hand and enhanced by more detailed information such as colour. The recording site in this study correlates with the localisation of the EBA using fMRI in macaque anterior STS (Pinsk, DeSimone, Moore, Gross and Kastener, 2005). However, the results do not suggest a direct homologue but rather a more continuous representation of monkey body in macaque anterior STS.

*1.3.2.3. Evidence from neuropsychology*

There are a number of studies in the neuropsychological literature that have diagnosed a neurological deficit known as autotopagnosia. Pick (1922) defined autotopagnosia as patients who were unable to localise body parts on themselves or others when cued verbally or asked to model the performance of another individual. Furthermore a number of studies (Gainotti, Caltagirone, Careechi, and Ibba, 1976; Sauguet, Benton and Hecaen, 1971; Suzuki, Yamadori and Fujii, 1997) have reported a deficit in both naming and describing the functions of body parts. However, in a recent paper Guariglia, Piccardi, Puglisi Allegra and Traballesi (2002) remark that autotopagnosia is often accompanied by other cognitive deficits (in many cases this is aphasia) making it difficult to ascertain the true or pure deficits caused by autotopagnosia.

Guariglia *et al* (2002) investigated the case of EC who despite appearing to have all cognitive functions and being able to carry out every day activities (such as dressing

which is often affected in cases of autotopagnosia confounded with aphasia) was unable to localise body parts on verbal and non-verbal commands. This is the first case of 'pure' autotopagnosia where none of these other deficits are present.

Furthermore, autotopagnositic patient JPB as investigated by Ogden (1985) was completely unable to localise body parts but was able to indicate animal and object parts (also reported in patient GL; Buxbaum and Coslett, 2001). In relation to the EBA this is potentially important as the EBA is significantly more selective to human body parts than animal or object parts (as demonstrated by Downing *et al*, 2001).

The evidence from the neuropsychological literature suggests that as with objects and faces, recognition of human body parts is affected by localised brain injury. However, at present no studies have explicitly investigated the location of the EBA in relation to lesions causing autotopagnosia. Despite this, the existence of autotopagnosia provides an interesting correlate for the representation of the human body and the cortex. Interestingly, Schwoebel and Coslett (2005) cite a number of studies associated with left hemisphere regions and body description/naming deficits and speculate a possible link between such deficits and the EBA.

### 1.3.3. Current evidence for the role of the EBA

Following Downing *et al's* (2001) paper describing the localisation of the EBA a number of studies, mainly using fMRI, have further investigated the possible roles and functions of the EBA. These can be divided into a number of general areas: visual processing in the EBA; the EBA and action perception; the EBA and the performance of motor actions.

#### *1.3.3.1. Visual selectivity of the EBA*

The majority of the studies investigating object selectivity in human occipital temporal cortex (especially in the case of the EBA) have utilised fMRI. However, Urgesi, Berlucci and Aglioti (2004) used repetitive transcranial magnetic stimulation

(rTMS) to investigate the selectivity of the EBA. Observers were presented first with a target image followed by scrambled image mask and then a choice of two images one of which matched the target. This task was carried out for body, face and object stimuli and it was reported that interference caused by the rTMS resulted in a significant increase in reaction times to the body part but not facial or object part stimuli.

The results of this study suggest that not only is neural activity in the EBA correlated with the visual perception of human body images but that it is also causally involved in the process. With fMRI we can generally show that a brain region is associated with a certain task. However, rTMS allows us to infer that a cortical region is used in a task as is the case here with the EBA and body part stimuli.

Localisation of the EBA has also been achieved using a novel experimental paradigm that recorded brain activity using fMRI while observers viewed a short extract from a 'James Bond' film. Bartels and Zeki (2004) combined psychometric and fMRI data to extract patterns of activation and were able to reliably distinguish the EBA in comparison to Downing *et al's*. (2001) original localisation.

Although, it has been established (as discussed in section *1.3.2.2.*) that single cell studies on macaque cortex have shown response to human bodies in the STS (Wachsmuth, Oram and Perrett, 1994) little about the large scale representation of objects in macaque cortex is known. Whilst Logothetis, Guggenberger, Peled and Pauls (1999) used fMRI to identify a face selective region of anterior STS no body selective region had been identified until recently when Pinsk *et al.* (2005) used fMRI to investigate the cortical representation of faces and bodies in macaque cortex. They successfully replicated previous findings showing a face recognition area. However, in addition they were able to localise a body selective region in anterior STS. The functional organisations of these areas are similar to that of human FFA and EBA although it is worth noting that human object selective regions are more posterior (i.e. not in the STS but around the occipito-temporal cortex).

In a recent study Peelen and Downing (2005) reported comparable levels of activation in the fusiform gyrus to both faces and bodies. This could potentially challenge the concept of distinct cortical regions for faces and bodies i.e. FFA and EBA. However, further investigation revealed two distinct peaks of activation within the fusiform gyrus responding to faces and bodies respectively. The mid-fusiform region responding to body images was termed the fusiform body area (FBA) and its role is not yet entirely clear. However, it further points towards the complex and structured organisation of human object recognition and more specifically the representation of the human body in the cortex.

*1.3.3.2. The EBA and the perception of action*

Until recently it has been unclear as to the role of the EBA in the perception of actions performed by the human body. As has been established, the EBA is highly selective for images of the human body although these data have dealt largely with static rather than dynamic body/body part stimuli. Addressing this in a recent publication Downing, Peleen, Wiggett and Tew (in press) investigated this question using fMRI and two critical conditions: coherent and incoherent motion. In the coherent condition observers viewed a set of images in the correct order of an actor performing an action and conversely in the incoherent conditions these images were shown in a random order (to create a meaningless sequence). The results of the study showed that the EBA was not selective for differences between successive images of relatively similar postures. Therefore, in this coherent stimuli condition there was a greater degree of adaptation than in the incoherent condition where relatively different postures were shown. Despite the apparent lack of involvement of the EBA in action perception the results do suggest that the EBA represents the static (rather than dynamic) structure in the perception of human action as part of a functional network that perceives human action (see Giese and Poggio, 2003).

A further study conducted by Peleen, Wiggett, and Downing (2006) supported these findings. Investigating the response to point-light stimuli that convey biological motion, they reported that the EBA (and FBA; as discussed in 1.3.3.1.) is largely insensitive to changing point-light patterns but is responsive to the presence of the

body form itself. Further it was reported that the pSTS (a finding supported by Grossman and Blake, 2002) integrates biologically salient information as part of the network previously described.

*1.3.3.3. The EBA and the performance of action*

Current research into the functional properties of the EBA has primarily concentrated on the response of the EBA to visual stimuli. However, in a recent paper Astafiev, Stanley, Shulman and Corbetta (2004) reported that the EBA was modulated by goal-directed movements of the observer's body parts and motor imagery, a finding that implicates the EBA in the integration of motor actions. Comparably, a more general link between the visual and tactile modalities has been shown previously by Macaluso, Frith and Driver (2000) demonstrating that visual areas can be influenced by other modalities. Further, from their findings Astafiev *et al.* (2004) suggest that the EBA, like the superior temporal sulcus (STS) may be part of a system for perception and action.

However, these findings have been disputed by Peleen and Downing (2005) who replicated Astafiev *et al's* (2004) study. Whilst action modulation was found in the EBA, a whole brain analysis on the movement conditions showed the peak of the region responding to visually guided motor acts to be relatively distinct (subsequently named the action related region or ARR) with a 14-19% spatial overlap with the EBA. This overlap does not necessarily implicate the same neurons in motor and body perception and Peleen and Downing comment that if this were the case a positive voxel-by-voxel correlation would be expected. Testing for this they examined the correlation between the action activity and EBA activity in this intersection and reported no significant difference from zero in this region. This suggests that the region shared by the EBA and the ARR contains overlapping but functionally distinct groups of neurons (as an alternative technique fMR-Adaptation could be used here to draw inferences regarding the selectivity of groups of underlying neurons in a functional region). The existence of this separate ARR has been disputed by Astafiev *et al.* in a reply where they question the methods and formulae used to calculate the size of the ROI's used in Peleen and Downing's

Chan, Peelen and Downing (2004) examined the response of the EBA to egocentric images and views of the self and others. This was intended to tease apart whether the EBA was sensitive to the views of the self (egocentric; photographs of each participant in a variety of predetermined poses were used for the egocentric images) and/or others (allocentric) and to see whether (in the advent of low responses) the EBA was too early on in the processing of body information to respond to such stimuli. They reported that the response of the right (but not left) hemisphere EBA was greater to allocentric than to egocentric views. However, they did not find a clear distinction between the self and familiar others in either the right or left hemisphere. They proposed that their findings may imply an early role for the EBA in social vision and that connections to the representation of the human body and the self are dealt with by the STS.

Saxe, Jamal and Powell (2006) have also investigated the response of the EBA to egocentric and allocentric images. However, in this study isolated body part images (rather than poses as used in Chan *et al.*, 2004) were used shown from different perspectives rather than actual images of the observers. The response in the right EBA was reported to be higher in the allocentric condition, a result consistent with Chan *et al's.* (2004) initial findings. Furthermore, Saxe *et al.* (2006) reported a suppressed BOLD response in the post central gyrus (primary somatosensory cortex) when observers viewed allocentric images (but did not report any enhancement with egocentric images). These findings appear very much supplementary as activation appeared to be correlated with the region representing the sensory organisation of the foot, although this may have been a result of more effective stimulus manipulation with the foot images.

However, findings from these studies may not draw a complete picture and it may be that using an alternative method of analysis such as fMR-Adaptation (fMR-A; for example see Grill-Spector and Malach, 2001) will provide a more sensitive test of the own/other body distinction. The use of adaptation and the application of fMR-A is extensively discussed in chapters three and four and is used to investigate the EBA's response to own/other body images. The advantage of using this technique is that it allows inferences to be made regarding the selectivity of groups of underlying

neurons in a functional region that may otherwise go undetected in a standard fMRI analysis.

## 1.4. Multimodal processing of vision and touch

The integration of information from multiple senses is fundamental to effective interaction with our world. One single event involves a multitude of brain regions communicating with one another in order to create even the simplest response. For example, when an object touches you it is necessary (on a basic level) for at least the somatosensory, visual and motor areas to interact in order to produce an appropriate response, a network that Astafiev *et al.* (2004) pointed towards in their coupling of the performance of motor actions and the EBA. However, experiments detailed in the literature (see Saxe *et al.*, 2006) have not yet provided a direct investigation into the possible link of the EBA and somatosensory brain mechanisms. Despite this there is a great deal of established literature that has provided evidence for solid links between the mechanisms of vision and touch.

### 1.4.1. The influence of vision on touch

There have been a wide range of studies that have demonstrated how vision can affect somatosensation. One such study was conducted by Tipper, Lloyd, Shorland, Dancer, Howard and McGlone (1998) and provided evidence that vision of a body part (hand), independent of proprioceptive orienting (where the eyes and head are orientated towards the site of somatosensation), can significantly affect somatosensation (see also Taylor-Clarke, Kennet and Haggard, 2002) thereby illustrating cross-modulation of touch by vision. This was even evident when the hand was viewed, via a video-camera and monitor, from the perspective of a third party and hence the viewpoint was not one that could be gained from orienting of the eyes and the head to the hand.

In a subsequent study Tipper, Phillips, Dancer, Lloyd, Howard and McGlone (2001) again provided evidence of vision facilitating detection of tactile targets for both familiar, frequently viewed, areas (e.g. the hands) and unfamiliar, infrequently

viewed, areas (e.g. the back of the neck). The effect with unfamiliar areas was significantly lower than with familiar areas which may suggest that internal personal body representations may act top-down to aid the somatosensory system, with more familiar representations providing the greatest assistance. However, currently few brain imaging studies have specifically investigated the response in the EBA to familiar and unfamiliar body images as in Tipper *et al.'s* study or whether the EBA would be responsible for dealing with such differentiation (the effect of self-other body stimuli has been investigated by Chan, Peleen and Downing, 2004, as was discussed earlier in 1.3.3.4.).

The influence of vision on somatosensation has been perhaps most clearly demonstrated in an elegant study conducted by Kennett, Taylor-Clarke and Haggard (2001). Previous studies such as Tipper *et al.* (1998) had shown how sight of a body part could reduce target detection times, although such findings may have been a result of spatial attention or something other than the viewing of a stimulated body region. Kennett *et al.* (2001) investigated the effects of viewing a body site prior to tactile stimulation (two-point discrimination task). Observers viewed the location of stimulation (the arm) until 50ms prior to the presentation of a tactile stimulus. It was reported that sensitivity was improved when the stimulation site was primed directly and more so when it was magnified but no such effect was found when viewing an object in the same spatial location showing that viewing the body part itself prior to stimulation aided somatosensation. Furthermore, in a follow-up study Taylor-Clarke, Kennett and Haggard (2002) recorded event-related potentials (ERPs) from somatosensory cortex while observers received stimulation as in the previous Kennet *et al.* (2001) study. The results showed task relevant modulation of somatosensory cortical responses by visual information (i.e. when the body site was viewed directly). These findings have been further supported by results from a recent magnetoencepalography (MEG) study conducted by Schaefer, Flor, Heinze and Rotte (2006). In this study modulation of primary somatosensory cortex activity was found only when observers attributed seeing their own hand touched in a video with a touch on their real hand.

These findings highlight the specific modulation of somatosensory cortex by viewing human body images. These results also suggest that the findings are not the effect of any type of spatial orienting but rather the images themselves. Although no such studies have yet implicated the EBA as a possible visually selective region involved in such a cross modal network with somatosensory cortex, its selectivity for body part images make it a candidate.

### 1.4.2. Pre-existing cross-modal networks between vision and touch

Evidence for the EBA on its own does not illustrate the mechanisms of cross-modulation. Further, even if the EBA is involved, the interaction between two major systems such as vision and touch, will involve multiple other brain regions. For example, Macaluso, Frith and Driver (2000) in an fMRI study, have shown that areas classically labelled as unimodal visual areas, such as the lingual gyrus, respond to visual stimulation significantly more strongly when paired with concurrent tactile stimulation on the same side as the visual stimulation (e.g. right visual stimulation and right tactile stimulation). From this it was proposed that an 'effective connectivity network' existed that indicated reciprocal connections between the occipital cortex, posterior parietal cortex and inferior parietal lobe, and that it was this network that was responsible for the crossmodal facilitation of vision by touch observed in the lingual gyrus. In a subsequent fMRI study Macaluso, Frith and Driver (2001) identified the intraparietal sulcus and the temporo-parietal junction as multimodal brain regions that were involved in the controlling of spatial attention in both vision and touch. From these studies it is evident that there are a variety of subsystems involved in the cross-modal integration of vision and touch and that there are dominant supramodal high level regions.

## 1.5. Outline of Experimental Chapters

### 1.5.1. Localising the Extrastriate Body Area (EBA)

Fundamental to this thesis is the successful localisation of the EBA using fMRI and for this reason chapter two explores three alternative paradigms that seek to identify

this region of the occipito-temporal cortex. Each of the three paradigms explored in this chapter vary in both the stimuli and timing characteristics of the experimental procedure with the intention of finding a paradigm that could be used to successfully localise the EBA across observers reliably and quickly. Furthermore, using the most successful EBA localiser paradigm a whole brain analysis will be conducted to highlight other regions of interest that may show some selectivity to human body images. This will both validate the EBA's role in the visual processing of these images and reveal possible other areas that may play a part in body part perception in a more cross-modal capacity such as between the body and touch.

### 1.5.2. fMR-Adaptation and Repetition Suppression

A large majority of fMRI studies reported in the literature examine the differences in percentage signal change (PSC) observed in functional or cortical regions. However, while this technique is often the most suitable for the research question investigated, it is possible that because of the limited spatial resolution of fMRI (in the range of millimetres) there may be differences in selectivity between groups neurons underlying the response of the particular region. Therefore, in chapters three and four a relatively new method termed fMR-Adaptation (fMR-A; Grill-Spector and Malach, 2001) is employed that uses fMRI to allow inferences to be drawn regarding the selectivity of underlying neurons in a functional region. In order to ensure that the EBA is sensitive to this technique, in chapter three, we attempt to characterise a repetition suppression effect within the EBA by simply manipulating the number of different EBA sensitive (i.e. body part) images presented and measuring the degree of adaptation between them. Successful implementation of fMR-A would be indicated if more adaptation occurs in blocks with fewer different images. Characterising this effect is essential as it would demonstrate that fMR-A can be used further to investigate properties of the EBA that may otherwise go unnoticed using conventional methods of analysis.

### 1.5.3. Investigating the Visual Properties of the EBA using fMR-A

In chapter four fMR-A is used to help address the question of whether the EBA is able to distinguish between images of one's own body and another's. Whilst this question has been partly explored by Chan, Peleen and Downing (2004) it is possible that by using fMR-A we may be able to uncover evidence of separate selectivity for own and other body images, as the fMR-A technique will permit insights into possible sub-populations of neurons that may have gone undetected in previous studies. At a more general level the same technique will confirm whether the EBA distinguishes between different exemplars of the same body part category (a within category or subordinate level distinction).

### 1.5.4. Crossmodal Links between Vision and Touch

Cross modal links between vision and touch have been reported previously in the literature (for example see Macaluso, Frith and Driver, 2000) and furthermore the EBA has already been linked with the performance of motor actions (see Astafiev *et al.*, 2004). However, the EBA has not yet been explicitly implicated as a region in a cross-modal network, or more specifically a body-touch network, yet it would appear a candidate region for this role considering its selectivity for human bodies. In addition, results from chapter one reveal possible somatosensory activity to visual EBA stimuli further pointing towards some type of possible crossmodal involvement. In order to begin to address this question, chapter five investigates the effect of a crossmodal congruency (lab-based) paradigm using vibrotactile stimulation to the hand and foot and human body images (of the hand and foot) of the same type that the EBA has been shown to be selective to in previous chapters. This study is necessary to establish whether the visual body part stimuli evocative to the EBA can have an effect upon somatosensation before this issue is further explored using a more complex, costly and time consuming fMRI paradigm.

### 1.5.5. Somatosensory Cortex and the EBA

The final experimental chapter of the thesis integrates the multiple questions that have been addressed throughout the thesis by investigating not only the role of the EBA in a body-touch network but also the response of other brain regions to specific types of EBA selective images, in particular those from one's own and another's body. The previous chapter sought to establish the influence of human body part images upon somatosensation. Following this, the present chapter further develops this concept of crossmodal interaction by investigating three questions pertaining to such a network following localisation of primary and secondary somatosensory areas with a purpose built MRI compatible piezoceramic tactile stimulator. (1) Are these regions sensitive to body part images as measured by an event-related experiment using own and other hand and foot stimuli? (2) Is the EBA responsive to vibrotactile stimulation of the hand and foot? (3) Can a whole brain analysis based upon the data from the event-related own and other experiment be used to identify regions selective to (a) own and (b) other body images and are these regions sensitive to the vibrotactile stimulation of the hand and foot? Using this approach it is intended that we can establish what role the EBA may play in a body-touch network.

# Chapter Two: Localising the Extrastriate Body Area (EBA)

## 2.1. Overview of Chapter Two

In order to investigate the possible role and functions of the EBA it was first necessary to develop an economical (in the sense of time) and reliable experimental paradigm for the localisation of the EBA. The principle of localisation of function using fMRI is fundamental to this thesis and for this reason some time will be taken to explain the principles and methods of both fMRI as a tool for studying human brain function and localisation of function as a technique. Following this, three different experimental paradigms that were used to localise the EBA will be discussed in detail. These different paradigms increase in effectiveness as the author gained increased experience and knowledge of using fMRI.

## 2.2. Localisation of Function using fMRI

The core method of investigation used for this thesis was fMRI therefore this section will briefly describe the method of fMRI itself and more specifically demonstrate how it is used to localise functional brain regions. There are a number of different types of fMRI. However, the focus of this thesis will be on the use of blood oxygenation level dependent (BOLD) fMRI where imaging contrast is generated through changing levels of oxy- to deoxy-haemoglobin that accompanies neuronal activity (see Ogawa, Menon, Tank, Kim, Merkle, Ellermann and Ugurbil, 1993).

### 2.2.1. Principles of Blood Oxygenation Level Dependent (BOLD) fMRI

fMRI exploits the magnetic properties of the human physiological system and enables the observation of changes in regional cerebral blood flow. While the spatial resolution of fMRI is good, in the region of millimetres (although inferences can be made about the behaviour of individual groups of neurons at sub-millimetre resolution using the fMR-Adaptation technique; Grill-Spector and Malach, 2001; discussed extensively in chapter three), the temporal resolution is comparatively low.

However, the resultant BOLD response has a predictable temporal profile (figure 2.1; Ogawa *et al.*, 1993).

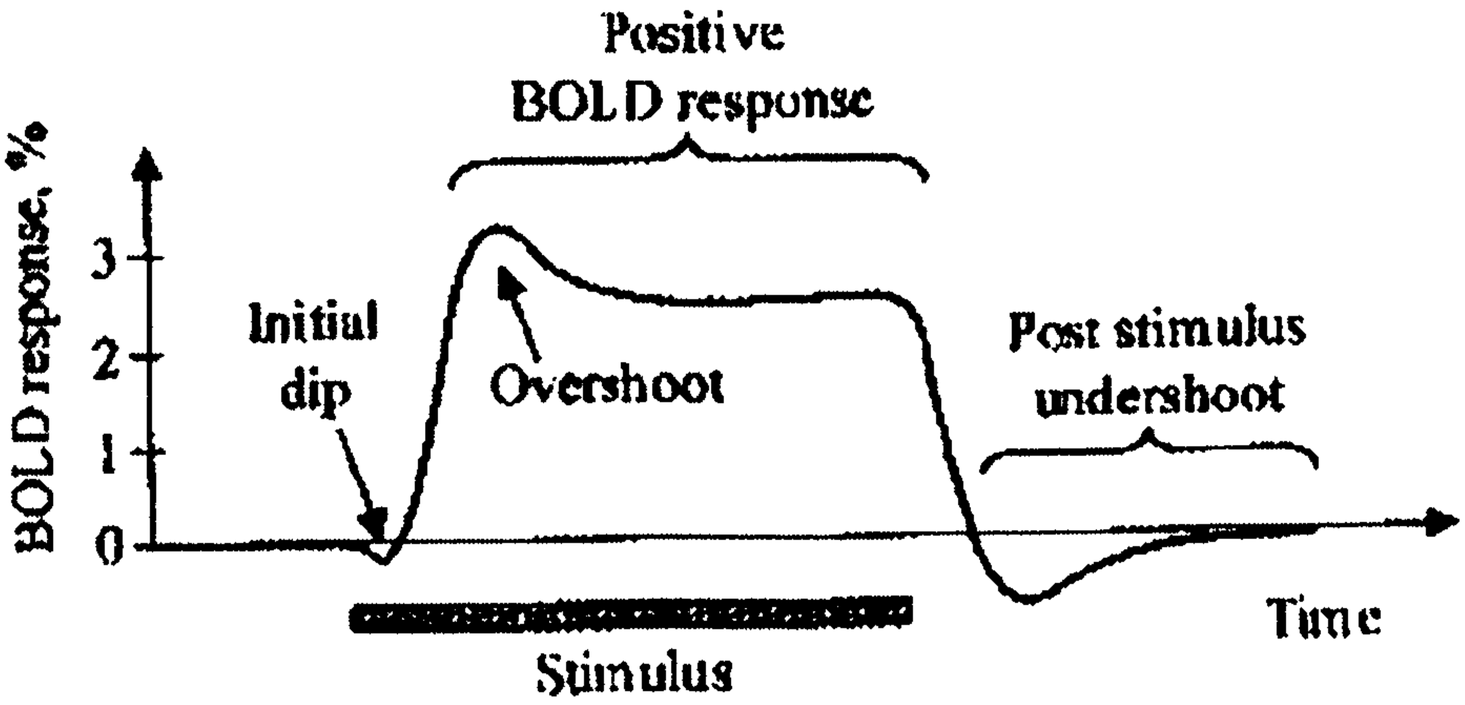



**Figure 2.1.** BOLD response from Ogawa et al. (1993), example of the BOLD response/HRF. Even after a brief stimulus the time from onset to final return to baseline may be in excess of 18s.

The measured changes in the BOLD response form the basis of the majority of functional brain mapping experiments. Furthermore, they are based on the assumption that there is a coupling between neuronal activity and changes in regional cerebral blood flow, a relationship that is still not fully understood (Jezzard, Matthews and Smith, 2002). Neuronal activity occurs in milliseconds and haemodynamic changes in seconds. Thus, following a 500ms stimulus presentation around a two second delay may occur until the haemodynamic changes characteristic of the BOLD response become evident lasting about 10-12 seconds (Blamire, Ogawa, Ugurbil, Rothman, McCarthy, Ellermann, Hyder, Rattner and Shulman, 1992; Boyton, Engel, Glover and Heeger, 1996). However, most important, as reported extensively in the literature (for example see Dale and Buckner, 1997). is the finding that haemodynamic responses within observers and within different regions of the cortex are extremely consistent. Therefore, despite the differences in timing of stimulation, the subsequent onset of the BOLD response and its timecourse are highly replicable allowing for comparisons across experimental runs and observers (Donaldson and Buckner, 2001).

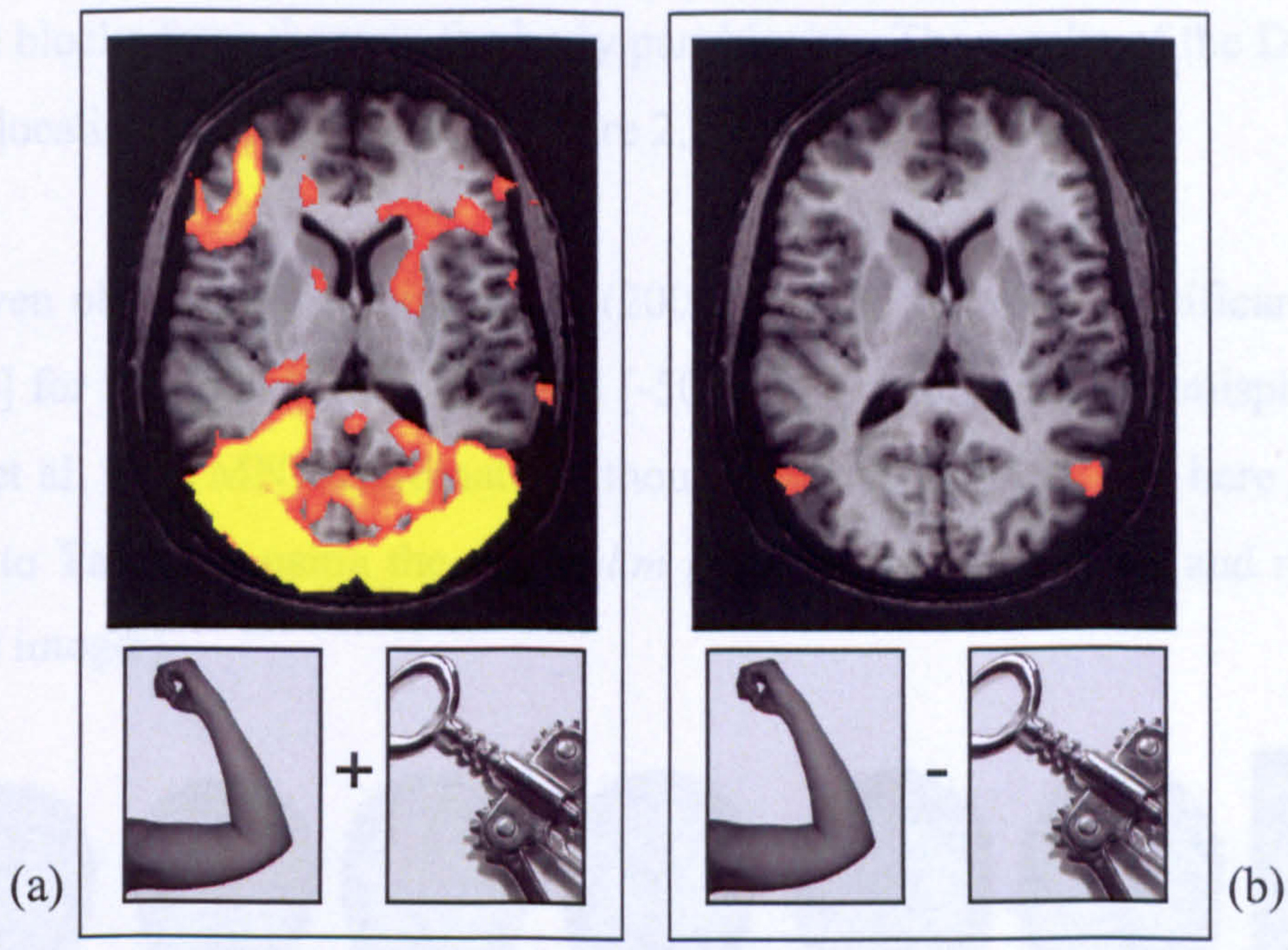
### 2.2.2. fMRI blocked paradigms

The most common type of fMRI experimental design, and the one used for the experiments discussed in the present chapter (and the majority of the thesis), is the blocked task paradigm. This design is similar to those initially used in Position Emission Topography (PET) and were the first used in fMRI (for example see Bandettini, Wong, Hinks, Tikofsky and Hyde, 1993). With this type of design experimental runs are composed of blocks (ranging from around 16 to 60 seconds) of stimulation with the intention of maximising the fMRI response to multiple stimuli occurring within a block (note: this does not mean showing a single stimulus for an extended period of time otherwise this will result in a habituation response, rather multiple examples of a stimulus may be presented).

Block paradigms contain multiple conditions (two or more) and typically also include a baseline/fixation only condition. The content of the conditions themselves is dependent upon the objective of the experiment. As will be explained in section 2.2.3, contrasting conditions are used to localise brain activity. Therefore, for that reason, the block content must be carefully chosen to ensure that any contrasts between conditions represent a direct change in activity resulting from the stimulus manipulation as opposed to some other random brain activity that is not a result of the conditions.

### 2.2.3. Localisation of function using fMRI

The use of blocked design fMRI paradigms is an established method to isolate a brain region based upon its functional role (the regions shown in figure 1.1 were identified using this method) rather than its anatomical location. The practice of localisation of function using fMRI typically utilises the method of 'cognitive subtraction'. This method (as demonstrated with a body minus object contrast in figure 2.2) simply subtracts all the activity recorded in condition A (the control condition) from that recorded in condition B (the experimental condition).




(a) (b)

**Figure 2.2.** Example of an EBA subtraction analysis (a) displays the total activation (sum of all blocks) of two conditions; body parts and object parts. (b) displays only the activation remaining after the total activation acquired in the object part blocks is subtracted from that acquired in the body part blocks.

Hypothetically, this will subsequently leave only the data in the experimental condition. For example, in the initial localisation of the LOC, Malach (1995) subtracted all the activation recorded when observers viewed scrambled images from the activation recorded when they viewed whole objects. However, it is important to note that one must be careful drawing inferences from such a result (an issue discussed extensively by Friston, Price, Fletcher, Moore, Frackowiak and Dolan, 1996). This method of localisation is typically used to define a 'Region of Interest' (ROI). A ROI is simply a predefined cortical area based on anatomical location or, more typically (and as used in this thesis), based on functional localisation that is then investigated further, looking at specific responses within this ROI.

### 2.2.4. Localisation of the EBA by Downing *et al.* (2001)

As was discussed in chapter one (section 1.3.1) Downing *et al.* (2001) provided evidence for a distinct cortical region in humans that responds selectively to images of either parts or the whole of the human body. This region was located in the lateral occipitotemporal cortex and was termed the 'extrastriate body area' (EBA) and was localised using the procedure described above by subtracting the data recorded in the

object part blocks from those in the body part blocks. The results of the Downing et al. (2001) localisation are evident in figure 2.3.

Across seven observers Downing et al. (2001) located the most significant voxel at [50, -69, 4] for the right hemisphere and [-50, -69, 11] for the left hemisphere (note: Downing et al. used MNI coordinates although the coordinates cited here have been converted to Talairach using the *mni2tal.m* program by Brett, 1999 and rounded to the nearest integer).

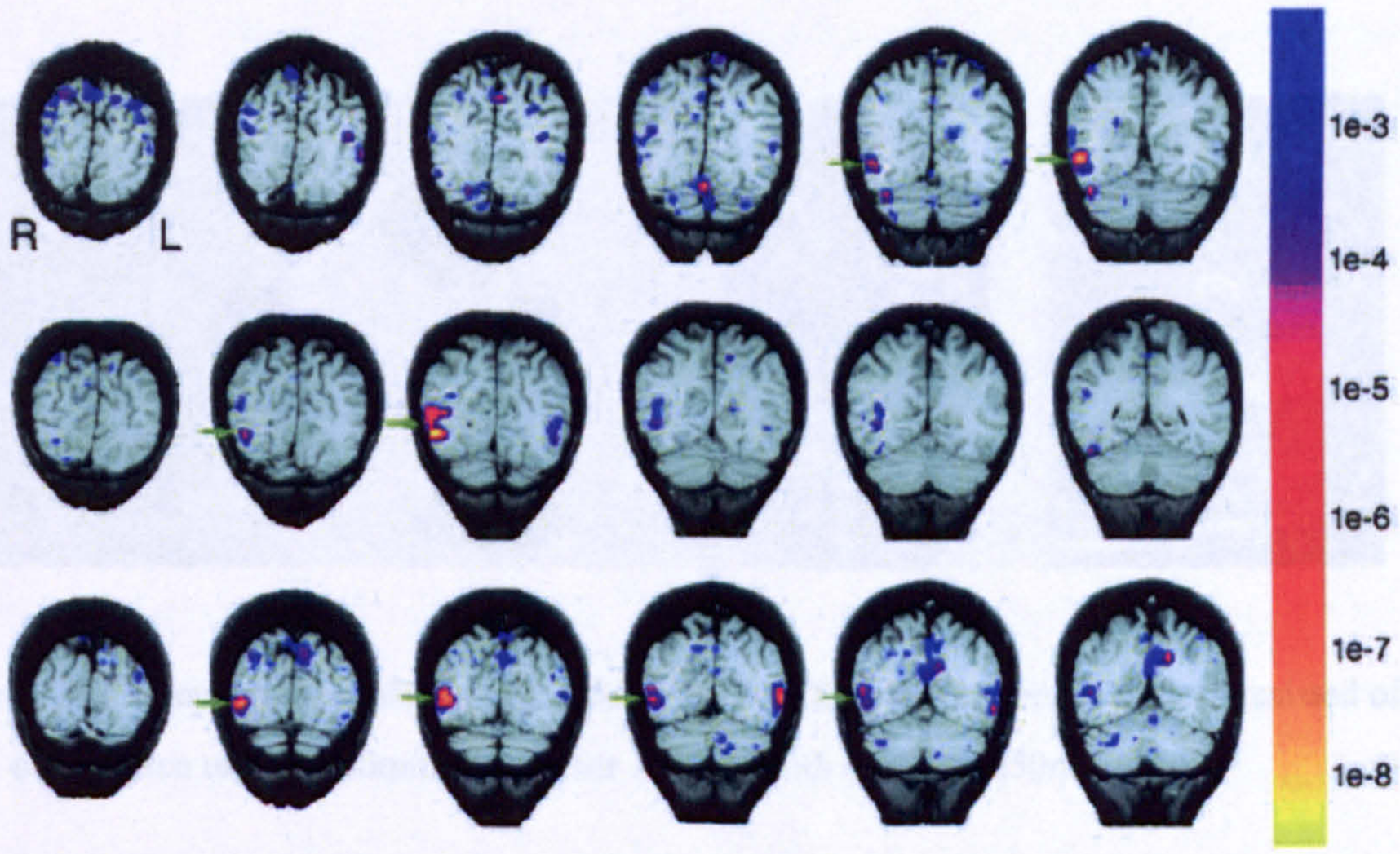



**Figure 2.3.** Localisation of the EBA from Downing *et al.* (2001). Each row represents coronal slices from three separate EBA localisations arranged posterior (left) to anterior (right) from the original Downing et al. study. Each statistical overlay represents voxels that were significantly more active for human body parts than object parts. The most significantly active region is constrained to the right occipitotemporal cortex of each subject. Scale indicates the *P* value of activations in coloured (significant) regions.

## 2.3. Localising the EBA: Experiment One

### 2.3.1. Method

#### *2.3.1.1. Observers*

Six observers (1 male and 5 females) with normal and corrected to normal vision volunteered for the study all of whom had passed primary and secondary screening

requirements in accordance with the imaging facility's standard protocols. Written consent was also obtained prior to scanning.

*2.3.1.2. Imaging protocol and experimental design*

The stimuli used were greyscale photographs (12.33° x 15.81° visual angle) of body parts, object parts, faces and scene images (for example images see figure 2.4 below).

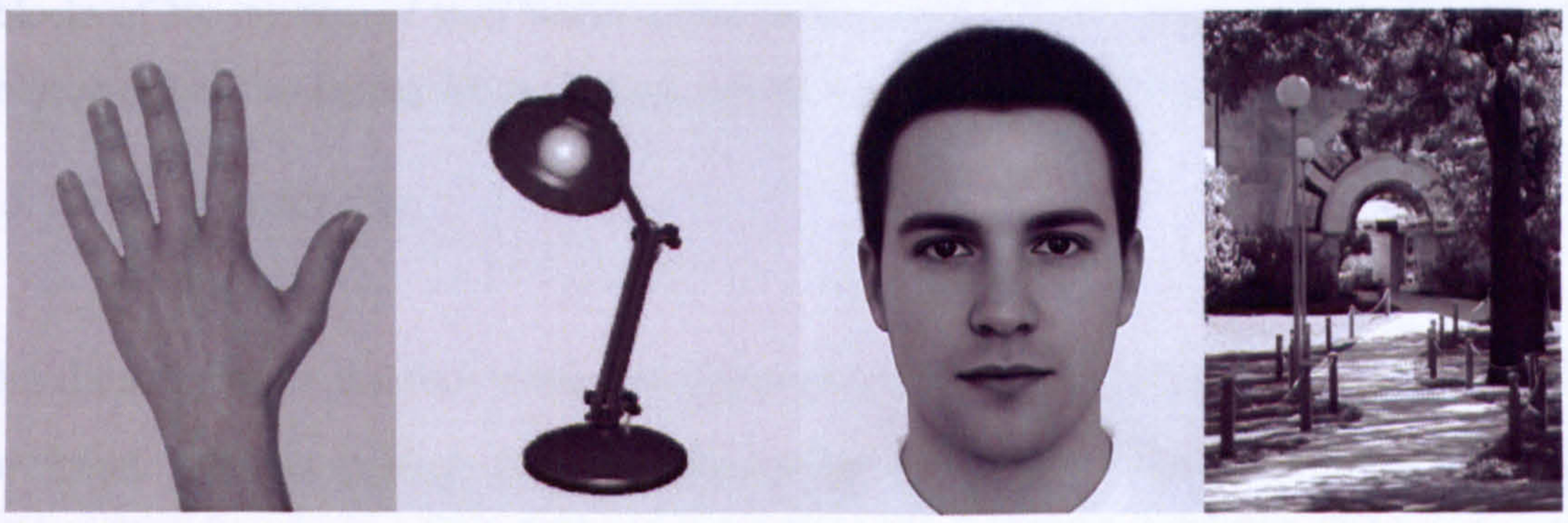


**Figure 2.4.** Example images shown in the first EBA localiser experiment. Blocks consisted of 20 body, object, face or scene stimuli shown for 1250ms with an ISI of 250ms.

Each run lasted 240s (96 volumes; TR = 2500ms; 36 axial slices; 3mm slice thickness; 64x64 inplane resolution; 3x3x3mm matrix) and comprised four blocks of experimental stimuli (bodies[B], objects[O], faces[F], scenes[S]) and four fixation blocks. Each experimental block lasted 30s (12 volumes) and contained 20 exemplars of the category. Fixation blocks consisted of a fixation cross (1.42° x 1.42° visual angle) with duration of 30s (12 volumes). There were four different run orders in total creating a counterbalanced design (i.e. F-S-B-O, S-O-F-B, O-B-S-F, B-F-O-S –see figure 2.5.) and each run was completed twice (8 runs in total). Each image was presented for 1250ms with an ISI of 250ms. Observers were instructed to fixate on the images and maintain attention by covertly naming each stimulus.

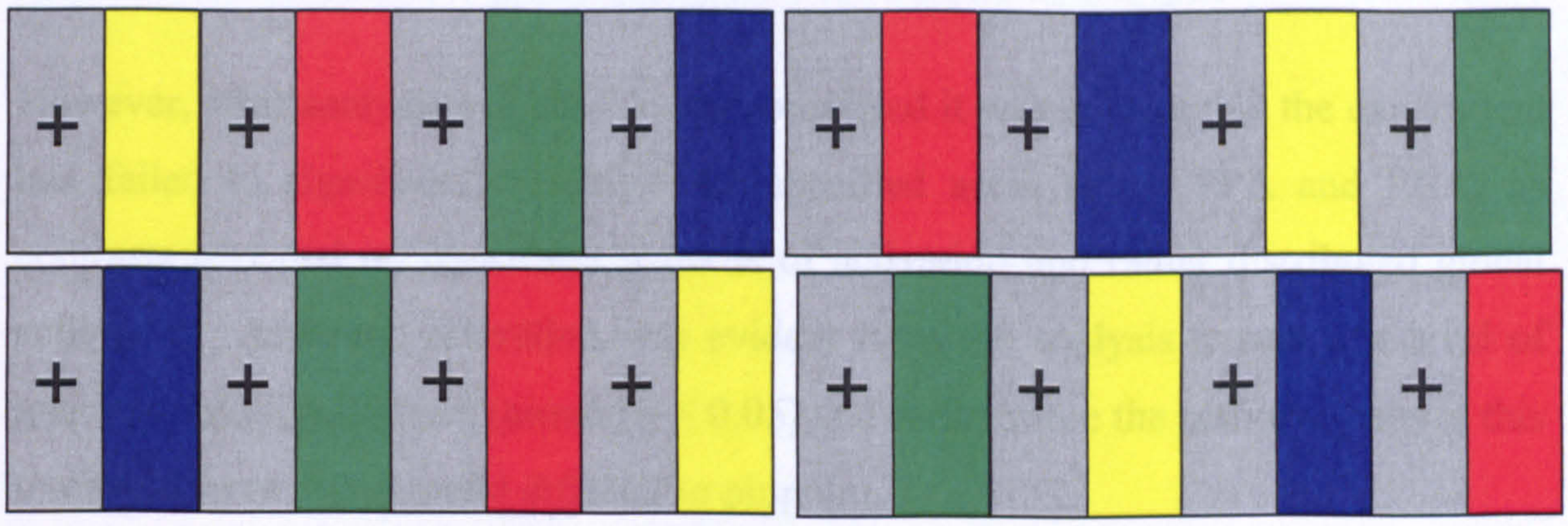


**Figure 2.5.** Four different run types as used in experiment one. Each run contained fixation only blocks of 30s interleaved with blocks of images of faces (yellow), scenes (red), bodies (green) and objects (blue) also lasting 30s each. Each subject completed each run twice.

### *2.3.1.3. Preprocessing*

The data for each subject were pre-processed using 3D motion correction to account for head motion (using trilinear interpolation), slice scan correction (ascending, interleaved), high-pass filtering (0.008Hz) and spatial smoothing using a Gaussian kernel of 6mm full width half maximum (FWHM). The functional data were then automatically aligned to a structural scan obtained from the same session. This structural scan was then aligned (automatically) to standard Talairach space and aligned with the transformed Talairach scan. This process was carried out using FSL Feat 5 including the BET procedure from brain extraction.

## 2.3.2. Results

The data from all six observers were first analysed using FSL's FEAT 5. After pre-processing was carried out each run was analysed using a standard FEAT 5 GLM analysis which used contrasts that were based on methods from previous research. The FFA was located using a face minus objects contrast (Kanwisher et al., 1997), PPA localisation used a scenes minus faces and objects contrast (Epstein and Kanwisher, 1998) and the EBA contrast used body parts minus objects (Downing et al., 2001). This first level analysis was carried out on each run and then passed on to a second level analysis that combined all eight runs per observer (note: this two level analysis is a standard procedure in FEAT 5).

However, after analysis in FEAT 5 was completed it was evident that the experiment had failed to significantly localise the specified areas (FFA, PPA and EBA) as contrasts revealed no consistent patterns of activation and rather distributed global activation. Although activation was evident from the analysis it was at a level of unacceptable significance (around $p \leq 0.05$) and furthermore the active regions at this threshold were dubious and difficult to pinpoint.

Following the unsuccessful FSL analysis the data were subsequently analysed using BrainVoyager 2000 (BrainInnovation, Maastricht, The Netherlands). However, this analysis also yielded comparably unsuccessful localisations.

### 2.3.3. Discussion of experiment one

A number of reasons were identified for the failure of the paradigm used in experiment one to localise the EBA. Firstly, it became evident that there were not enough repetitions of each experimental block within each run resulting in a sub-optimal level of power, despite having eight runs in total. Secondly, there was no fixation period following the final experimental block, consequently the haemodynamic response was not correctly captured for the last block in the sequence (due to the haemodynamic delay). Furthermore, the use of multiple repetitive runs may have resulted in participant fatigue, specifically lack of attention, tiredness and adverse head movements, all of which would significantly affect the data. Finally, the quality of the images was not tightly controlled for. For example the object images were whole objects rather than object parts and were computer generated rather than photographs of the objects themselves. In light of this a second EBA localiser was designed.

## 2.4. Localising the EBA: Experiment Two

Due to the design issues identified in the previous experiment a new localiser was developed to overcome these. First, repetitions of each experimental block were increased, which was intended to improve the power of the experiment were

increased. Second, fixation periods were reduced to 20 seconds, with the experiment ending in a fixation period to account for the haemodynamic lag. Third, in each 30 second experimental block 45 images were shown in random order (rather than 20). Furthermore, the object images used were tightly controlled and were all high resolution greyscale real photographs of object parts making them comparable to the body part images that were used. Face and scene stimuli were not used in this experiment.

### 2.4.1. Method

#### *2.4.1.1. Observers*

Two female observers with uncorrected vision volunteered for the study both of whom had passed primary and secondary screening requirements in accordance with the imaging facility's standard protocols. Written consent was also obtained prior to scanning.

#### *2.4.1.2. Imaging protocol and experimental design*

The stimuli were similar to those used by Downing *et al.* (2001) and were greyscale photographs (12.33° x 15.81° visual angle) examples of which are shown in figure 2.6. below.

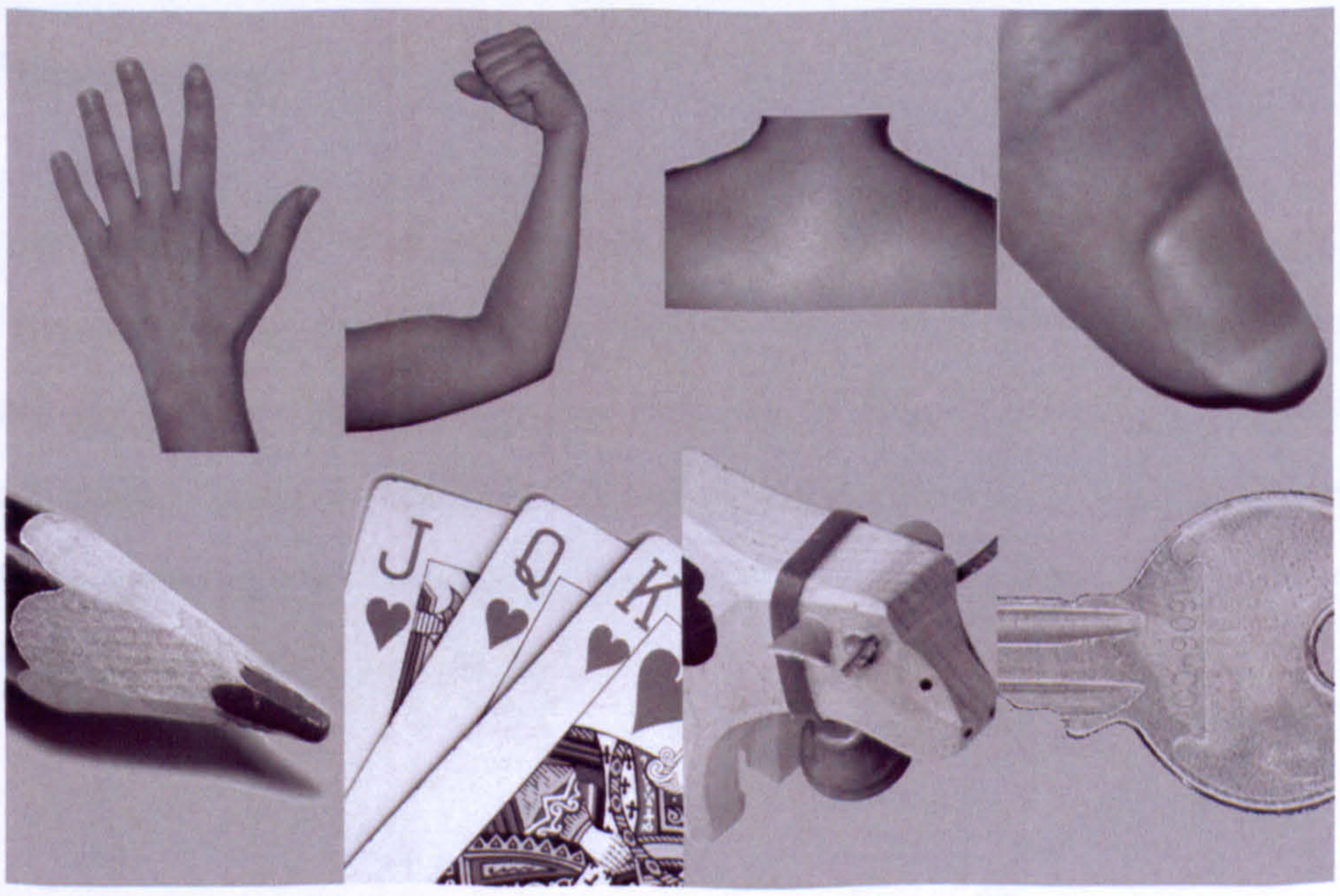


**Figure 2.6.** Example body and object images as used in EBA localiser experiment two and three.

Each run lasted 320s (128 volumes; TR = 2500ms; 36 axial slices; 3mm slice thickness; 64x64 inplane resolution; 3x3x3mm matrix) and was comprised of three blocks of greyscale body part stimuli, three blocks of greyscale object stimuli and seven fixation blocks. Each experimental block lasted 30s (12 volumes) and contained 45 exemplars of the category (20 of which were/contained the hand). Within blocks each stimulus was presented for 542ms, with an ISI of 125ms. Fixation blocks consisted of a fixation cross (1.42° x 1.42° visual angle) with a duration of 20s (8 volumes). Runs interleaved fixation between body and object blocks with two counterbalanced (between) run orders (with the first experimental block as either body or object images) as demonstrated in figure 2.7. Each subject completed three runs in total (i.e. repeating one of the runs twice).

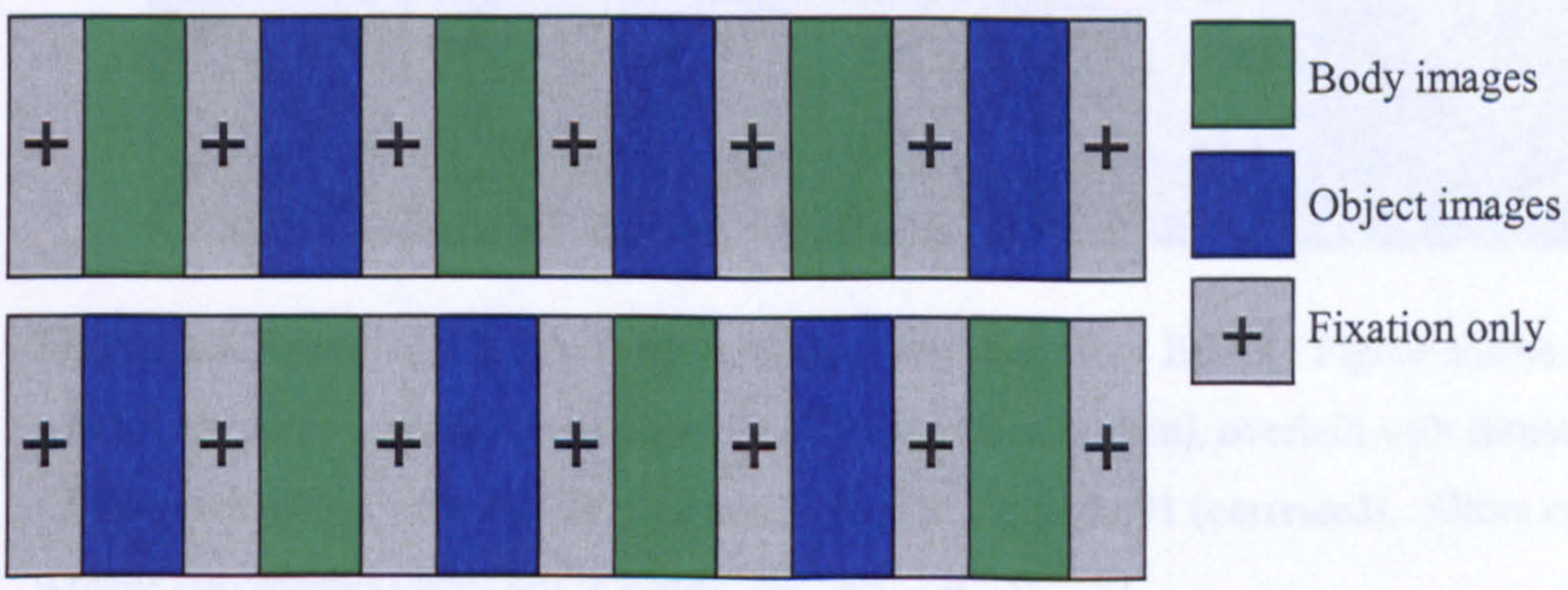



**Figure 2.7.** Run order for EBA experiment two. Counterbalancing is achieved between runs by the reversal of the run order. Experimental blocks (body and objects) lasted 30s containing 45 randomised greyscale images and fixation blocks lasted 20s.

### *2.4.1.3. Preprocessing*

The data for each subject was pre-processed using 3D motion correction to account for head motion (using trilinear interpolation); slice scan correction to correct the interleaved slice order (ascending interleaved), highpass filtering (0.008Hz) and spatial smoothing using a Gaussian kernel of 6mm FWHM. The functional data were then aligned to a structural scan obtained from the same session and subsequently transformed into Talairach space.

### 2.4.2. Results

Analysis for both observers was carried out using BrainVoyager 2000 (BrainInnovation, Maastricht, The Netherlands). The data from both observers (6 runs in total) were combined (with a fixed effects analysis) and a body minus object contrast was conducted to localise the EBA. Data were thresholded to a conservative $p<0.001$ (corrected) which revealed a region in the right [55, -57, 11] and left [-50, -69, -1] (Talairach coordinates of the most significant voxel) hemispheres corresponding to the EBA (see figure 2.8. below).

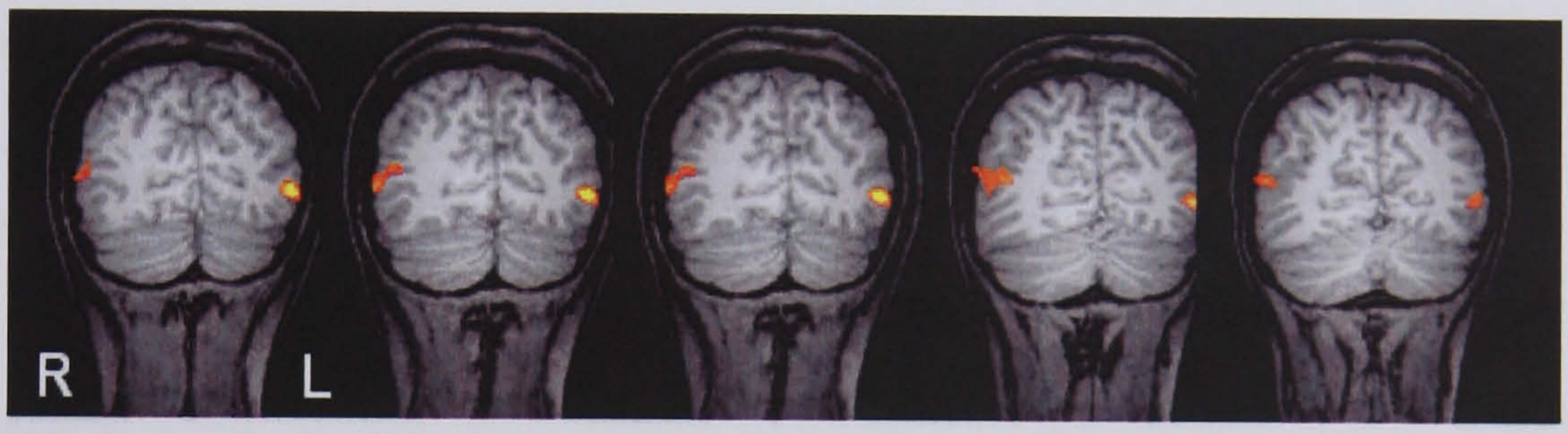



**Figure 2.8.** Resulting EBA of combined observers data from EBA2. Figure shows five coronal anatomical slices arranged from posterior (left) to anterior (right), overlaid with statistical maps of a body parts minus object parts contrast thresholded to $p<0.001$ (corrected). Slices correspond to y-plane coordinates (from left to right), -70, -65, -60, -55, -50.

### 2.4.3. Discussion

The paradigm used in experiment two appeared to have successfully localised the EBA. Successful localization here compared to the first localiser was likely to be due to the number of replications of conditions within runs, a factor which would substantially increase the power of the experiment. However, it was evident that there were a number of factors that could improve the localiser further. A great deal of scanning time consisted of fixation periods. While time is not such an issue with a short experiment such as simply localizing the EBA the intention was to use the localiser as part of a larger experiment that would localize then investigate the EBA itself. Because of this a more economical design was needed and also one that truly counterbalanced within and between runs.

## 2.5. Localising the EBA: Experiment Three

### 2.5.1. Method

#### *2.5.1.1. Observers*

Fifteen observers (3 males and 12 females) with normal vision volunteered for the study all of whom had passed primary and secondary screening requirements in accordance with the imaging facility's standard protocols. Written consent was also obtained prior to scanning.

#### *2.5.1.2. Imaging protocol and experimental design*

As previously, the stimuli were similar to those used by Downing *et al.* (2001) and were the same greyscale photographs (12.33° x 15.81° visual angle) used in experiment two, examples of which can be seen in figure 2.6.. Observers completed two runs. Each run lasted 340s (136 volumes; TR = 2500ms; 36 axial slices; 3mm slice thickness; 64x64 inplane resolution; 3x3x3mm matrix) and comprised four blocks of greyscale body part stimuli, four blocks of greyscale object stimuli and five fixation blocks. Each experimental block lasted 30s (12 volumes) and contained 45 exemplars of the category. Within blocks each stimulus was presented for 542ms, with an ISI of 125ms. Fixation blocks consisted of a fixation cross (1.42° x 1.42° visual angle) with a duration of 20s (8 volumes). Both runs were counterbalanced by reversing the block orders within the run and participants were instructed to silently name each stimulus in order to maintain attention during the task. Observers were either shown the group one or two run order (see figure 2.9.).

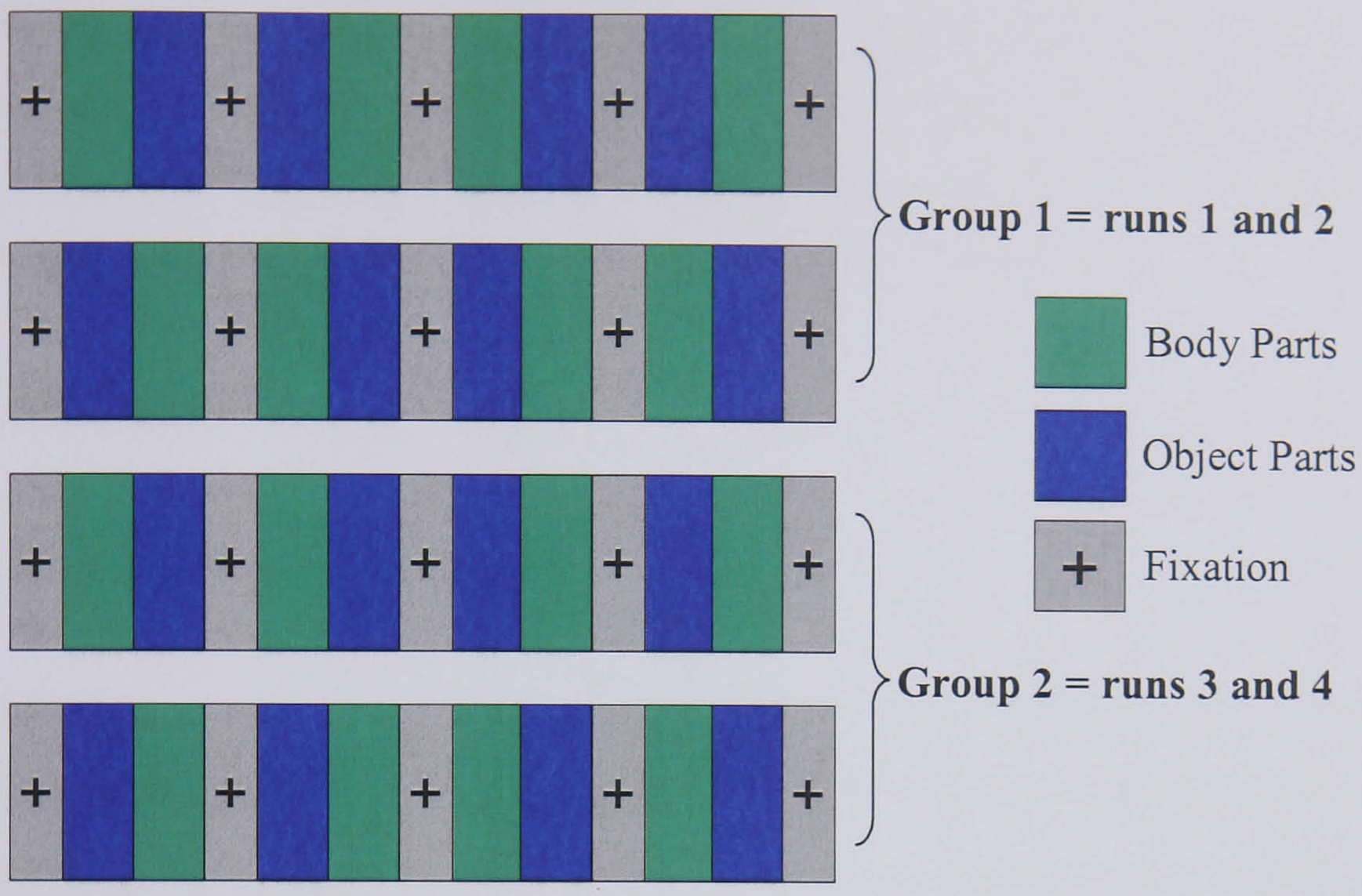



**Figure 2.9.** Two types of run orders used in EBA Localiser: Experiment 3. Fixation blocks lasted 20s (8 volumes) and experimental blocks 30s (12 volumes). Counterbalancing was achieved both in the run order itself and between the two runs (i.e. they were the opposite arrangement of one another).

Observers were given a 15 second test EPI sequence prior to the main scanning session in order to familiarise themselves with the scanning environment. They were instructed not to move their head or body when the scanning started. All observers were instructed to maintain fixation on the images at all times and to use a covert naming strategy[1] in order to maintain attention.

*2.5.1.3. Preprocessing*

Data were pre-processed using 3D motion correction with sinc interpolation and corrected for slice timing and scanning order (ascending, interleaved). Linear trend removal and a high pass filter (0.0088 Hz) were also applied. The functional data were aligned to a high resolution anatomical scan (1x1x1 mm matrix, 256x256 inplane resolution, TR 1900, TE 5.57) taken in the same session. This was

[1] Covert naming was used to minimise activations of other cortical regions involved in an attentional control such as a button response to a change in the visual stimuli. Such a task may have induced confounds in the data aquired in the EBA that we hypothesise may be responsive to tactile stimulation. The use of covert naming has also been used by Grill-Spector and Malach (2001) to help observers maintain attention.

subsequently normalised to a Talairach template (Talairach and Tournoux, 1988) and the parameters applied to the co-registered functional data. Spatial smoothing, using a 6mm FWHM Gaussian spatial filter, was then carried out in the 3D domain once the data had been aligned to the participant's 3D anatomical scan.

## 2.5.2. Results

### *2.5.2.1. Individual subject analysis*

Data were first analysed (using BrainVoyager 2000; BrainInnovation, Maastricht, The Netherlands) for each subject separately by running a simple body minus objects contrast. Figure 2.10. displays the un-thresholded results of this contrast in each subject. From this it is evident that eleven of the fifteen observers showed substantial activity in comparable locations in the right and left hemisphere. Four observers only showed activation in the right or left hemisphere.

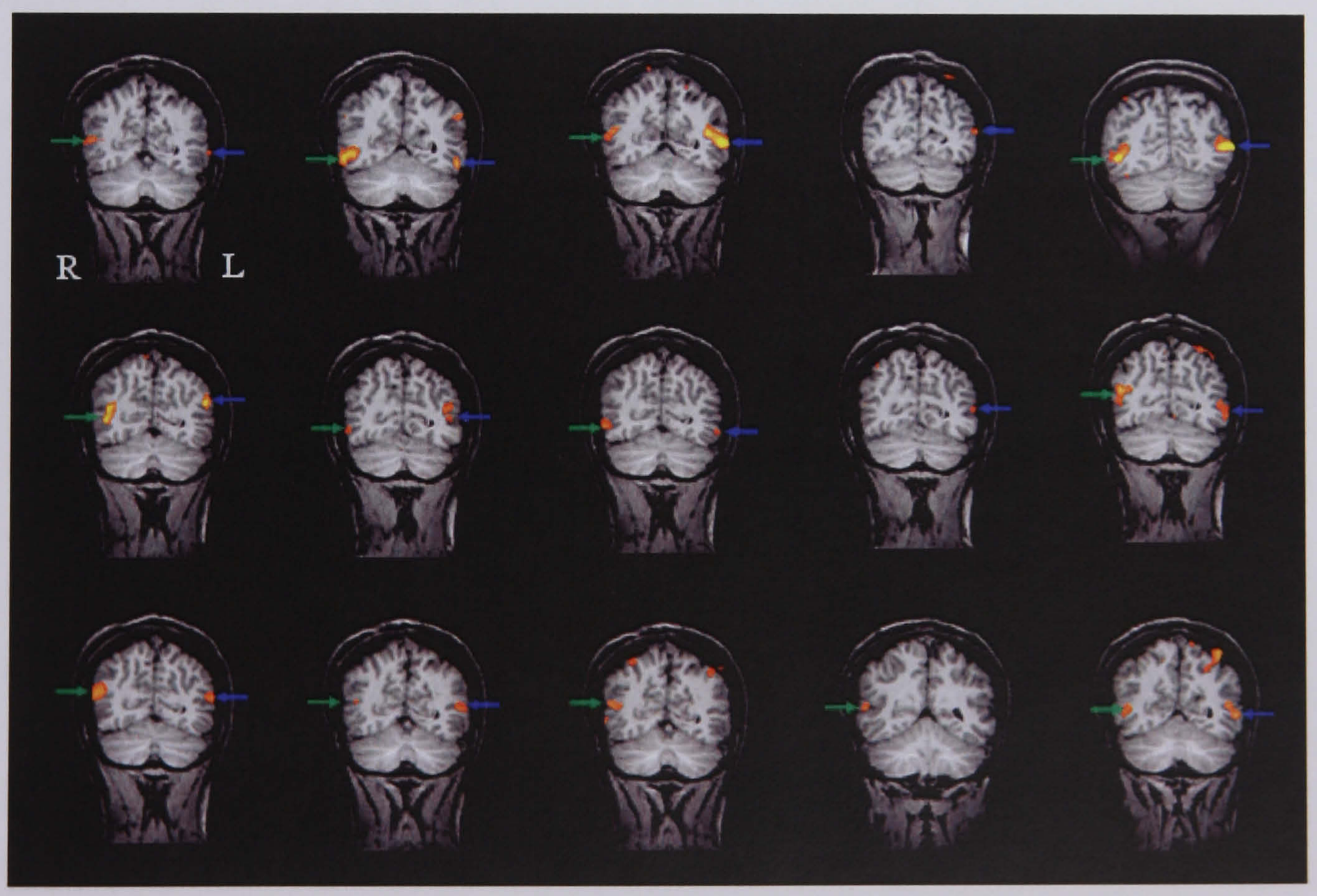



**Figure 2.10.** Coronal slices showing the EBA from each of the 15 observers in experiment three (un-thresholded). The EBA was identified using a body minus object contrast that combined both runs. Activation was found in both the right (indicated by the green arrow) and left (blue arrow) hemispheres in 11 out of 15 observers. Location of the peak voxel can be found below in table 2.1.

| | Right EBA | | | | Left EBA | | | |
|---|---|---|---|---|---|---|---|---|
| | Talairach Coordinate | | | | Talairach Coordinate | | | |
| **Observer** | **X** | **Y** | **Z** | **Voxel Count** | **X** | **Y** | **Z** | **Voxel Count** |
| **1** | 40 | 28 | 11 | 1335 | -53 | -69 | -1 | 133 |
| **2** | 54 | -55 | -5 | 1252 | -48 | -57 | -14 | 876 |
| **3** | 49 | -72 | -1 | 1018 | -50 | -57 | 2 | 5780 |
| **4** | 48 | -67 | -5 | 24 | -51 | -73 | 7 | 515 |
| **5** | 43 | -66 | -4 | 2833 | -59 | -66 | 8 | 2358 |
| **6** | 40 | -59 | 11 | 1668 | -47 | -63 | 17 | 1603 |
| **7** | 51 | -67 | -5 | 671 | -42 | -64 | 1 | 172 |
| **8** | 52 | -66 | -7 | 1767 | -53 | -66 | -7 | 165 |
| **9** | 51 | -67 | 10 | 1353 | -42 | -61 | 13 | 2960 |
| **10** | 51 | -64 | 19 | 948 | -56 | -61 | 0 | 1242 |
| **11** | 52 | 192 | 115 | 754 | -53 | -66 | 11 | 185 |
| **12** | 46 | -63 | 11 | 46 | -47 | -63 | 5 | 570 |
| **13** | 51 | -64 | 13 | 4817 | -42 | -70 | -2 | 6082 |
| **14** | 49 | -64 | 29 | 378 | -44 | -66 | 11 | 1687 |
| **15** | 51 | -58 | 1 | 4454 | -54 | -61 | -2 | 1211 |

**Table 2.1.**. Location of the peak EBA voxels in each of the fifteen observers in the right and left hemisphere as indicated in figure 2.10.

### *2.5.2.2. Group subject analysis*

Data from each of the 15 observers were entered into a group analysis and a simple body minus objects contrast was conducted. The results of this contrast revealed distinct occipito-temporal regions in the right and left hemisphere respectively corresponding to the EBA. Data were thresholded to $p<0.001$ corrected and from investigating the right and left EBA ROI's it was found that the peak voxel in the right hemisphere EBA was [47 -60 8] and in the left hemisphere EBA was [-45 -59 10]. Figure 2.11. below shows the relative percentage signal change (PSC) from baseline for the object and body stimuli respectively in both the right and left EBA (EBA thresholded to $p<0.001$ corrected). The difference between the body and object conditions was found to be significant in both the right ($t(15) = 7.046$, $p < 0.0001$) and left ($t(15) = 7.772$, $p < 0.0001$) hemispheres. Interestingly the inverse contrast of objects minus bodies identified a region consistent with the LOC and

found significant preference for object images in both the right (t (15) = 5.357, $p < 0.0001$) and left (t (15) = 4.752, $p < 0.0001$) hemispheres.

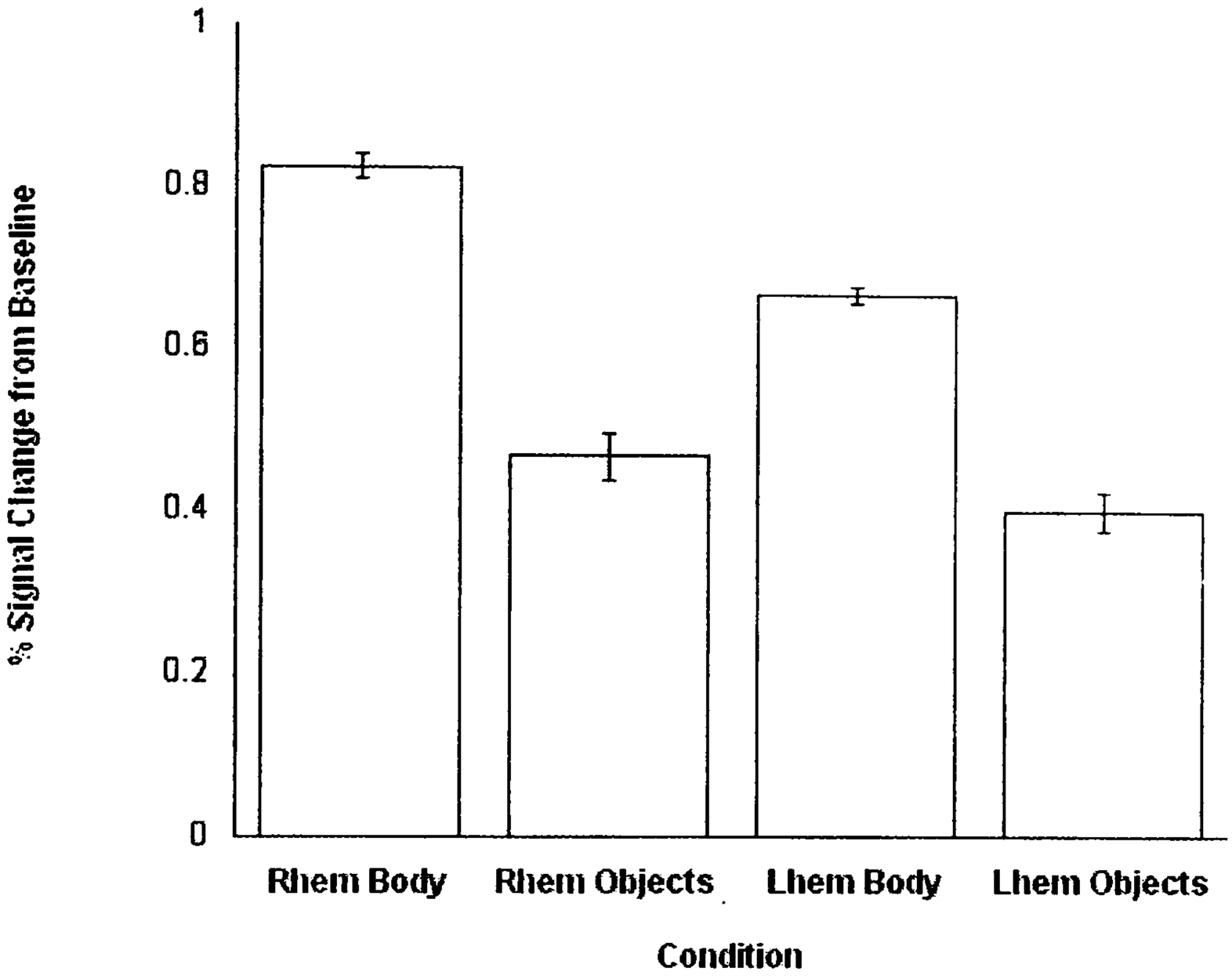



**Fig.2.11.** Response of the right and left EBA (defined by peak voxel from body minus object localiser) to both body and object stimuli (error bars represent the SE).

Further to the localisation of the EBA the body minus object localiser identified a number of additional brain regions sensitive to the contrast (thresholded to a conservative $p<0.001$ corrected). Table 2.2. below reports the brain regions sensitive to this contrast and the Talairach coordinates of the most significant voxel in regions that exceeded a $50mm^3$ voxel cluster size threshold. Figure 2.12. shows these overlaid onto a standardised Talairach template.

| Key | Region | Talairach Coordinate X | Y | Z | Voxel Count |
|---|---|---|---|---|---|
| | R.Middle Temporal Gyrus* | 47 | -60 | 8 | 6846 |
| | R.Inferior Parietal Lobule, Brodmann area 40 | 47 | -33 | 46 | 1409 |
| | R.Temporal Lobe, Brodmann area 21 | 43 | -16 | -13 | 167 |
| | Culmen | 32 | -55 | -23 | 67 |
| | L.Middle Temporal Gyrus* | -45 | -59 | 10 | 6005 |
| | L.Inferior Parietal Lobule, Brodmann area 40 | -40 | -38 | 46 | 4807 |
| | L.Superior Parietal Lobule, Brodmann area 7 | -17 | -62 | 57 | 308 |
| | L.Postcentral Gyrus, Brodmann area 3 | -46 | -16 | 48 | 234 |
| | L.Medial Frontal Gyrus, Brodmann area 6 | -3 | -11 | 61 | 52 |

**Table.2.2.** Main clusters of activation (exceeding 50mm$^3$) as identified by the body minus objects EBA localiser thresholded to $p<0.001$ corrected. Talairach coordinates for the peak voxel in each region are shown along with the associated brain region and voxel (3x3x3mm) count of each cluster. Note that (*) denotes that this region was identified as the EBA in the right or left hemisphere. Key corresponds to colour coded regions of figure 2.10.

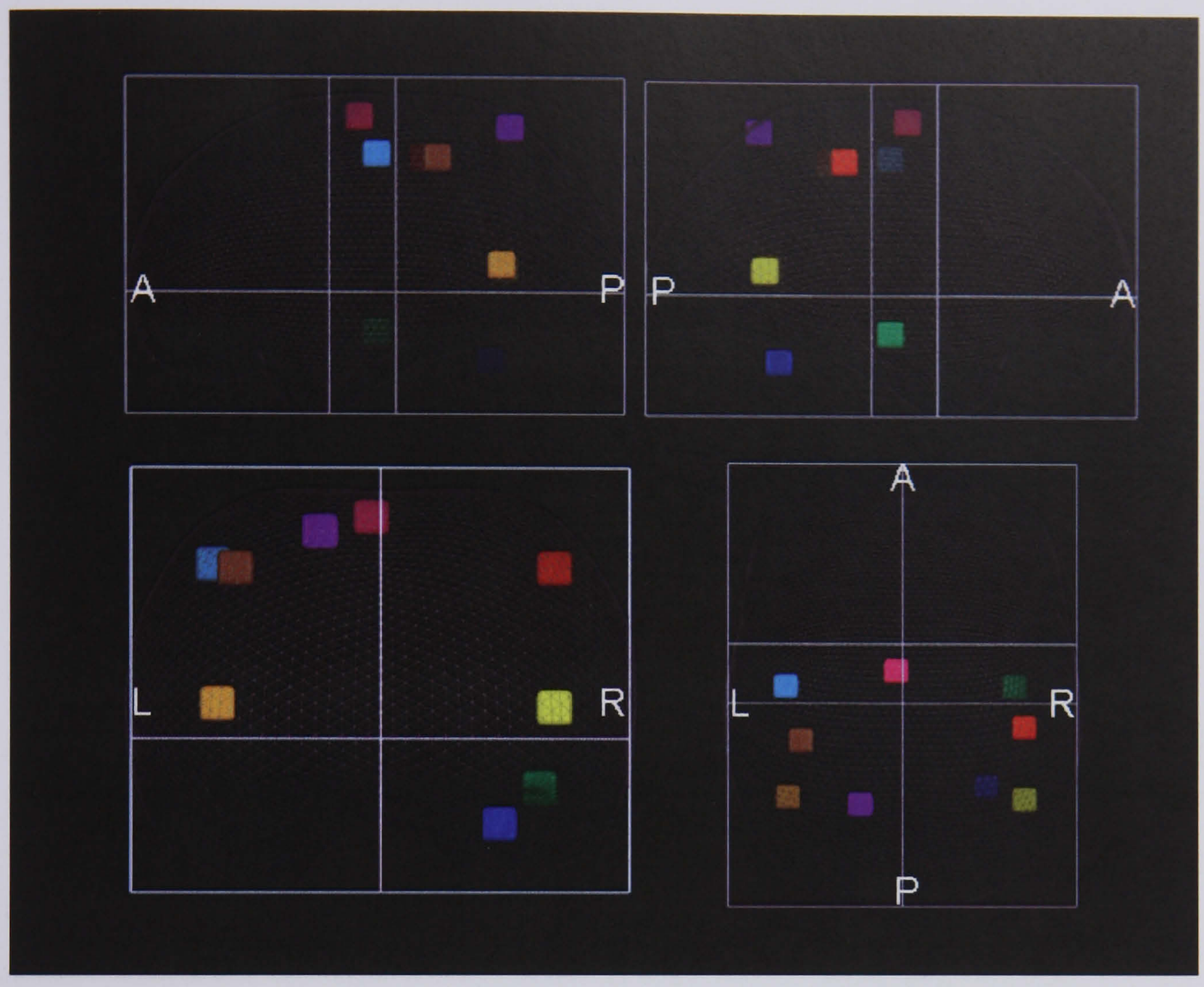



**Fig. 2.12.** Whole brain analysis from EBA experiment 3. Images show brain areas activated at $p<0.001$ corrected after a whole brain body minus objects contrast performed on the group data. Clusters shown exceed the $50mm^3$ cut-off. Brain areas have been overlaid onto a standardised Talairach (glass brain) template. Colour coded key for this figure can be found in table 2.1. (a) and (b) represent the left and right hemispheres respectively, (c) shows a frontal view and (d) a dorsal view. Note: size of coloured regions are for illustrative purposes only and do not represent the size of the functional region at the chosen threshold.

### 2.5.3. Discussion

The design of the third EBA localisation experiment improved upon the shortcomings of the previous two experiments. The power of the localiser itself was increased dramatically by increasing the number/duration of experimental blocks (a significant problem in the first localiser). This was possible by decreasing the number of fixation periods (a problem evident in the second localiser). These factors combined allowed the EBA to be localised using two short runs (although just one run could potentially be sufficient).

The results of the region of interest (ROI) analysis of the right and left EBA revealed a slightly stronger response in the right over the left EBA, a finding that has been previously reported (for example see Downing *et al.*, 2001). As well as the EBA, the body minus objects contrast revealed a number of brain areas activated during the body condition even after a conservative $p<0.001$ corrected threshold (and exceeding the $50mm^3$ voxel cluster size cutoff).

Using the BrainMap software (see Laird, Lancaster and Fox (2005) and http://www.brainmap.org) we were able to cross-reference the Talairach co-ordinates in table 2.1. above with other studies (using a $3mm^3$ bounding box centred upon our chosen Talairach reference point). This enables us to offer a justified explanation for the activity in the cortex as a result of the body minus objects contrast other than in the EBA itself. Table 2.3 below proposes the functional role of corresponding cortical regions that were identified using the body minus object EBA localiser (this does not include the right and left EBA themselves).

| Region | Functional Role | Studies |
|---|---|---|
| R.Inferior Parietal Lobe, BA40 | Attentional modulation | Sergent et al. (1992); Stanescu-Cosson et al. (2000) |
| R.Temporal Lobe, BA21 | Verbal labelling/Naming | Phillips et al. (1998); Cabeza et al. (2003) |
| R.Anterior Lobe, Culmen | Explicit memory | Mazard et al. (2002); Calhoun et al. (2001); Owen et al. (2005) |
| L.Inferior Parietal Lobe, BA40 | Attentional modulation | Bodegard et al. (2001); Sadato et al. (1998) |
| L.Superior Parietal Lobe, BA7 | Visuo-motor inc. imagery | Gerardin et al. (2000); Simon et al. (2002); Bonda et al. (1995) |
| L.Postcentral Gyrus, BA3 | Tactile stimulation (hand) | Francis et al. (2000); McGlone et al. (2002) |
| L.Medial Frontal Gyrus, B6 | Object naming | Hirsch et al. (2001) |

**Table.2.3.** Functional roles that have been attributed by other studies that were identified using the body minus objects EBA localiser (note: this does not include the right and left EBA).

This technique is flawed in that it does not account for the size of a functional region and/or the threshold chosen, furthermore it assumes that a perfect Talairach alignment has been performed. However, the this approach does have the advantage of allowing possible correlations to be found between studies that have reported activation in similar areas although it is important to be aware of the possible confounds. Of the regions identified beyond the EBA itself many of these would be expected to be engaged in a task where observers were required to covertly name body and object images. It may be argued that many of these should not have been activated by the contrast as they should have been engaged in both conditions (e.g. attentional modulation) and hence be subtracted out in the contrast. However, as has been discussed in chapter one, evidence suggests that bodies, like faces, are a special class of image and therefore one might expect an enhanced attentional salience.

Activation of the left superior parietal lobe has previously been linked to motor imagery. For example Wolbers, Weiller and Buchel (2003) identified the superior parietal lobe as a cortical region activated in motor imagery tasks involving the mental imagery of hands. With regard to the present study it is probable that this activation is a result of the high frequency of hand images that were presented in comparison to the other types of body parts shown.

The activation of the postcentral gyrus was also unexpected. Classically, the postcentral gyri are the location of primary somatosensory cortices (SI) and the areas that we found activated in the left postcentral gyrus have been attributed to digit somatotopic areas (McGlone et al., 2002). Although not entirely clear, this again may be linked to the higher prevalence of hand images. The possible link between the EBA and SI has not previously been explored and therefore will be in chapter six, as will the EBA's response to tactile stimulation.

The primary aim of this chapter was to design a paradigm to successfully localise the EBA using fMRI. Of the three experiments detailed in this chapter the third was the most successful and in subsequent experiments in this thesis where the EBA needs to be localised this paradigm will be used. In the next chapter, using this paradigm a

method for examining the underlying sensitivity of groups of neurons is introduced and used to explore the EBA further.

# Chapter Three: fMR-Adaptation and the EBA

## 3.1. Overview of Chapter Three

The previous chapter outlined the role of the extrastriate body area (EBA), a functional region in the occipito-temporal cortex that had been shown previously by Downing *et al.* (2001) to respond preferentially to images of the human body and furthermore detailed a robust fMRI paradigm for localising the EBA. Differences in PSC are often used to investigate differences between experimental conditions within a cortical region. However, it may be that this is not the most suitable method for every research question. Therefore, in the current chapter we adopt the relatively new technique of fMR-Adaptation (fMR-A; Grill-Spector and Malach, 2001) that from the fMRI response, allows us to infer the selectivity of underlying groups of neurons within a functional region that may yield results that may have otherwise been overlooked in a standard analysis. However, in order to successfully utilise this method it must be ensured that the region (in this case the EBA) to be investigated is sensitive to adaptation effects (or rather that they can be detected). Therefore the central aim of the experiments within this chapter is to use fMR-A to characterise the effects of repetition suppression within the EBA.

## 3.2. fMR-Adaptation as a tool in fMRI

### 3.2.1. Validating adaptation as a tool in fMRI research

While investigating the response of V1 to orientation changes in gratings Tootell, Hadjikhani, Vanduffel, Liu, Mendola, Sereno and Dale (1998) discovered a relationship between the BOLD response and underlying neuronal adaptation. They found that V1 was most responsive to orthogonal changes in gratings and smaller changes in orientation. This suggested that the new orientations excited sub-populations of neurons. This finding is supported by numerous fMRI (for example Engel, 2005) and electrophysiological research (from example Movshon and Ferster, 1998).

In a recent paper Krekelberg, Boynton and van Wezel (2006) attempted to validate the use of adaptation in fMRI studies by comparing new functional imaging evidence with existing single-cell recording research while maintaining the assumption that the BOLD signal is a general measure of neural activity rather than questioning the underlying mechanisms of the BOLD signal itself. They comment that multiple factors can affect the level of adaptation including the timescale of the stimulus duration. From examining the results of studies using different stimulus durations (such as Boyton and Finney, 2003) it was concluded that temporal issues greatly influence the susceptibility of a cortical area to adaptation, a finding that is not so much of an issue when adaptation results are reported but more so when they are not. The presence of a null result, according to the paper, must be approached with a great deal of caution as this may not simply be because the cortical area was invariant to the stimuli (although this could of course be the case) but may instead be due to an inappropriate time scale. Further, this is complicated by the response of neurons in the region of milliseconds and the significantly slower BOLD response that operates within a timescale of seconds.

Overall, Krekelberg, Boyton and van Wezel (2006) surmise that the use of adaptation as a technique in fMRI has the potential of allowing new insights into human brain function without the complications of invasive methods (such as single cell recording). However, like any method of investigation (even fMRI itself) there are multiple issues such as those discussed here that must be considered when designing paradigms and interpreting results. Furthermore, the inferences from fMRI adaptation results must be drawn with caution due to the underlying complexity of the neural processes themselves and also the unclear link of the BOLD response and the activity of neurons. Therefore, it appears that the use of adaptation in fMRI research is a useful technique but one that must be interpreted together with accompanying evidence.

### 3.2.2. Adaptation as a method to overcome spatial resolution problems in fMRI

Currently the majority of MRI scanners used in research have a magnetic strength of between 1.5 and 3 Tesla (T), a factor that has been shown to affect spatial resolution

(for example see Forder, Nayak and Pohost, 2002). The resolution refers to the 3-Dimentional (3D) size of a single voxel. A voxel is a 3D version of a pixel (2-Dimensional) of finite volume within 3D space. The imaged area of cortex is divided into a 3D array of voxels of predetermined size; it is from each of these voxels that data is recorded during an fMRI scanning session.

With MRI scanners of 1.5 to 3T, the spatial resolution of a voxel is typically defined as $3mm^3$, where spatial resolution refers to the smallest point between two distances within the cortex that can be distinguished as separate details/neural activity. Therefore this defines the size of voxels within a scanning session. However, Schimidt, Pruessmanni, Jaermann, Lamerichs and Boesiger (2002) have demonstrated that by using a modified scanning procedure (known as SENSE-EPI, EPI or Echo Planner Imaging being the standard imaging method used with fMRI research) it is possible to reduce the spatial resolution at 3T to $1mm^3$. Furthermore at increased magnetic strength it is possible to achieve much higher spatial resolution. For example Pfeuffer, Steudel, Merkle and Logothetis (2004) successfully imaged at 0.5 x 0.5 x $3mm^3$ at 7T.

However, even at high strength the resolution of fMRI is still within the region of millimetres, data extracted from just a single voxel is reflecting the mean response of hundreds to thousands of neurons contained within the voxel itself. Furthermore, in fMRI, data is extracted from clusters (groups) of active voxels that makeup a functional region such as the EBA that would contain potentially millions of neurons. Contained within these clusters, or even single voxels, there may be distinct populations of neurons that are differentially sensitive to changes in stimuli. For example the EBA has been shown to be responsive to images of the human body. However, it may be that populations of underlying neurons within the EBA differentiate between different types of body parts (e.g. hand or foot).

Despite the constraints of spatial resolution, a number of techniques have been documented in the literature that exploit the neuronal mechanism of adaptation and allow the response of the underlying populations of neurons within a functional region/cluster/voxel to be inferred (for an overview of these techniques see Henson.

2003). One such technique that is used throughout this thesis is fMR-Adaptation (fMR-A), a technique developed by Grill-Spector and Malach (2001) that has been used previously to explore the behaviour of neuronal populations within the LOC. fMR-A is based upon the well documented phenomena of neuronal adaptation (as discussed in chapter one), a phenomena that is observed through repetition suppression. Repetition suppression refers to an effect occurring when a neuronal population's response to subsequent presentations of an identical stimulus (or a stimulus that the neuronal population is insensitive to [discussed later]) result in a decreased response. The following sections of chapter 3.2 outline the fundamental principles of fMR-A and further the (assumed) underlying mechanism of neuronal adaptation.

### 3.2.3. Repetition Suppression

fMR-Adaptation is based upon repetition suppression, a frequently reported phenomena in the neurophysiological literature. The basic premise of repetition suppression is that repeated presentation of a stimulus results in decreasing neuronal activity, a finding that has been observed on the neural level in single cell recordings from monkeys (for example see Li, Miller and Desimone, 1993) and the haemodynamic level evident from functional imaging research (for example see Demb, Desmond, Wagner, Vaidya, Glover and Gabrieli, 1995). This effect has also been widely observed across multiple areas of human and monkey cortex making it of particular relevance to the study of brain function. However, despite the robust nature (in terms of replicability) of repetition suppression the underlying neuronal mechanisms themselves are not clearly understood. This is similar to the BOLD response itself in that both of these mechanisms of underlying brain function are not fully understood yet produce predictable changes in the fMRI signal that allow reliable inferences to be drawn from experimental manipulations.

In a recent paper Grill-Spector, Henson and Martin (in press) highlight the importance of repetition suppression as a tool in fMRI to allow pseudo-improved spatial resolution (i.e. fMR-A). Further, they attempt to address the explanatory gap of the underlying mechanisms of repetition suppression and here Grill-Spector *et al.*

review three possible models in an effort to resolve this conundrum; the fatigue, sharpening and facilitation models.

*3.2.3.1. Fatigue model*

The basic premise of the fatigue model is that after the initial presentation of a stimulus, responsive neurons show a proportional reduction in their firing strength to repeated presentations of the same (initial) stimulus. Here the pattern of response across neurons and the temporal window (number of neurons fired in x amount of time) remains the same yet the rate of firing declines i.e. the population of neurons fatigue at a constant rate proportional to the level of the initial response. Further, the fatigue model would predict that repetition suppression will be greater in neurons that respond optimally to a stimulus than in other neurons (i.e. the most responsive neurons will be the fastest to adapt as they are optimally tuned to the stimulus). Because of this the population of neurons will be more sensitive to any stimuli different from that which is repeated and therefore act as a type of novelty detector.

*3.2.3.2. Sharpening model*

According to the sharpening model (Desimone, 1996) only neurons which code features irrelevant to identification of the stimulus exhibit the characteristics of repetition suppression to subsequent presentations of the initial stimulus. This concept is very different from the fatigue model as here the optimally tuned neurons show the *least* amount of response reduction whereas in the fatigue model it is these neurons that show the *greatest* repetition suppression effects. Subsequently this results in a neural 'sharpening' as the response of the optimally tuned neurons becomes more sparse among the majority of neurons which are exhibiting repetition suppression effects.

*3.2.3.3. Facilitation model*

In the facilitation model, repetition suppression is related to the decreased (faster) processing time of stimuli and thus a shortening of the duration of the neural firing.

As the haeomdynamic response in fMRI is related to the temporal duration of neural firing (i.e. the BOLD response is an effect of accumulated neural firing) the amplitude of the fMRI signal (BOLD response) will be suppressed.

To summarise; the fatigue model, recovery occurs as a new non-fatigued population is accessed and in the sharpening model, this occurs because a whole new population of less narrowly tuned neurons become active following a stimulus change. Finally, according to the facilitation model, recovery occurs because the newly active population have a longer firing duration. This thesis will not choose between these models, but rather they are detailed to demonstrate that all three predict that where sub-populations of neurons differ in their degree of selectivity, repetition suppression will be observed in the BOLD response to the same stimulus, that will in turn then recover from this when the stimuli is changed.

### 3.2.4. fMR-Adaptation as a tool to investigate human brain function

The neuronal phenomenon of repetition suppression, as has been discussed, is the foundation of a relatively recent technique that uses fMRI to infer the selectivity of groups of neurons despite the limited spatial resolution of fMRI. Developed by Grill-Spector and Malach (2001; also see Grill-Spector *et al.*, 2000), the basic premise of fMR-Adaptation (fMR-A) is that after repeated presentation of an identical stimulus a property of the stimulus is changed, neurons that are invariant to this change will continue to adapt (where adaptation could be fatigue, sharpening, or facilitation). However, if the neurons are sensitive to a change in stimulus then neurons will recover from their adapted state following such a change and new populations of neurons in the same region will become active.

For example, figure 3.1. outlines a hypothetical situation whereby observers are presented with four arrow stimuli each rotated 90°, as the stimuli are presented groups of neurons will behave in one of two ways 1) Continued adaptation indicating that the neurons are invariant to rotation (i.e. the neurons are not sensitive to a change in orientation) or 2) each orientation change excites a separate neuronal population.

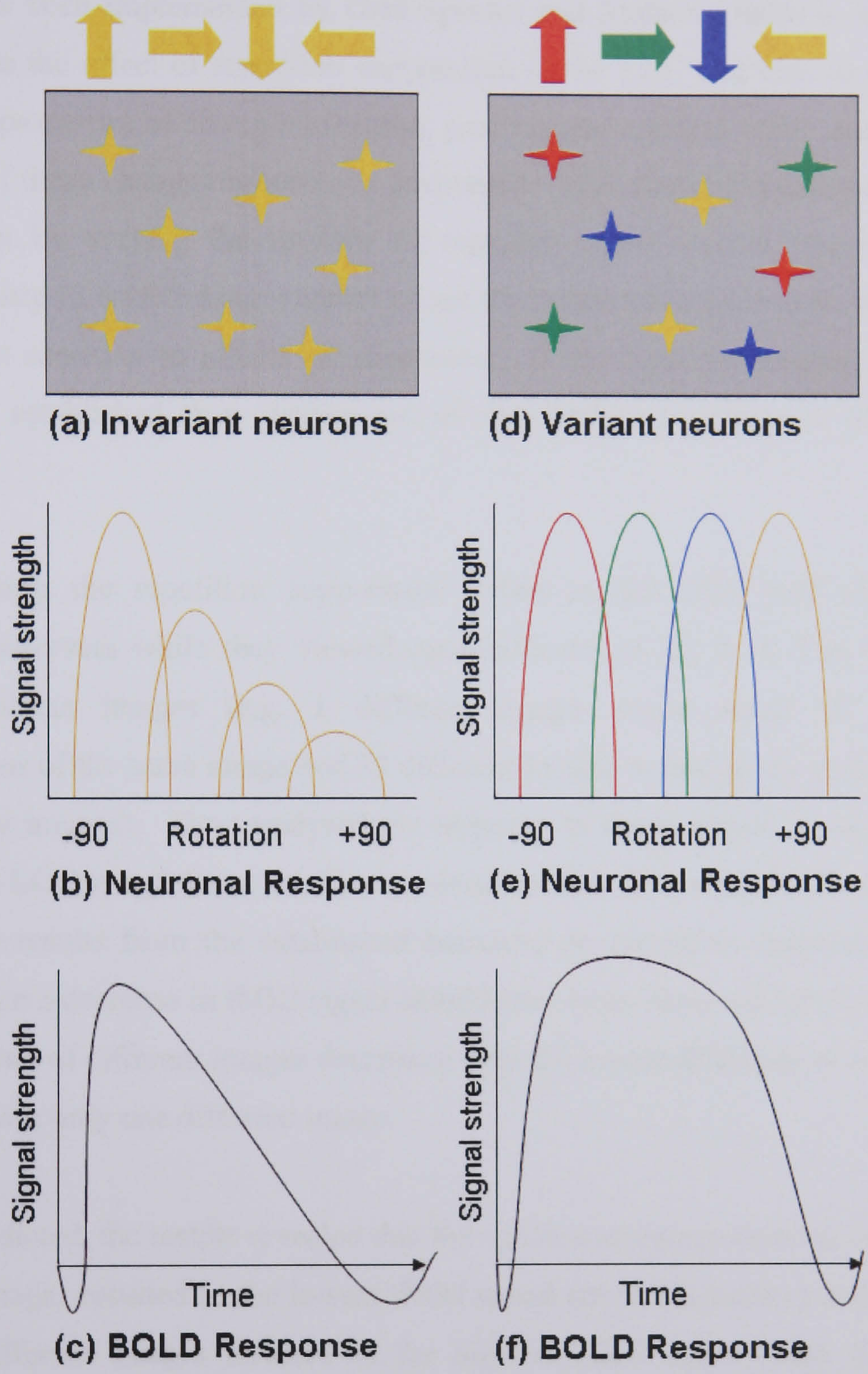



**Figure. 3.1.** Hypothetical behaviour of neuronal populations. Figure adapted from Grill-Spector and Malach (2001). Groups of neurons will behave in one of two ways to four different orientations of arrow stimuli 1) Continued adaptation indicating that the neurons are invariant to rotation (i.e. the neurons are not sensitive to a change in orientation and are treating both stimuli as simply 'an arrow' rather than '0°,90°, 180°, 270° arrow') this is evident in (a) where all stimuli are treated as if they are the same. Here the neuronal response decreases with each subsequent presentation (b) which results in an overall mean suppressed fMRI response (c). 2) Each stimuli excites a separate neuronal population (d) and subsequently each separate population responds maximally (e), here the fMRI signal will recover from the adapted state thereby indicating that the neurons in the ROI are sensitive to the particular stimulus orientation (i.e. all orientations are treated as separate stimuli) subsequently is manifested in a high fMRI response (e).

fMR-A has been implemented by Grill-Spector and Malach (2001) in this way to characterise the effect of repetition suppression in the LOC and then to manipulate the object properties of size, illumination, position and rotation while measuring the response of these changes in terms of adaptation. The characterisation of repetition suppression by varying the number of repeated object stimuli was deemed an important step in establishing whether or not the functional region to be investigated (LOC) was sensitive to effects of adaptation. If the repetition suppression effect cannot be established then further use of the fMR-A paradigm is likely to be ineffective.

Characterising the repetition suppression effect in the LOC was achieved by scanning observers while they viewed epochs/blocks of 32, 8, 4, 2 or 1 different repeated object images (e.g. 1 different image would equal 32 sequential presentations of the same image and 32 different images would be the presentation of 32 different images). They analysed the response to these stimuli in the LOC (the ROI of the LOC was defined as objects minus textures in a separate localiser scan). Due to the results from the established literature on repetition suppression it was expected that a decrease in fMRI signal should have been observed across each block as the number of different images decreased with the lowest fMRI signal occurring in the block with only one different image.

As was predicted, the results revealed that the epoch containing identical images (one different image) resulted in the lowest fMRI signal (most adaptation) and the epoch with 32 different images resulted in the highest fMRI signal (least adaptation). Furthermore, the most dramatic adaptation effects occurred in the higher repetition epochs (e.g. one and two different images) with the adaptation reduced in the four and eight different image epochs therefore indicating a monotonic decrease. Changes between epochs were represented in terms of their 'adaptation ratio'. This simply expresses the difference in signal relative to the least adapted epoch (i.e. 32 different images) and is calculated by dividing the percentage signal change (PSC) from baseline in each condition by the PSC in the most adapted epoch e.g. (PSC from [1,2,4,8] different image)/(PSC from 32 different images). Hence, a ratio of 1.0

(i.e. for the 32 different images block) assumes for the purpose of comparison no, or rather the least amount of, adaptation.

## 3.3. Characterising Repetition Suppression in the EBA

Using the method of fMR-A we sought to characterise the effect of repetition suppression in the EBA using the same technique as Grill-Spector and Malach (2001) used to investigate the LOC. Establishing whether the EBA is sensitive to repetition suppression effects is essential if we are to further use this technique to explore the functional properties of the EBA itself.

### 3.3.1. Method

#### *3.3.1.1. Observers*

Twelve Observers were recruited for the repetition suppression experiment (4 male). All Observers had normal or corrected-to-normal vision. Scanning took place on the Siemens Trio 3T scanner at the CUBIC imaging facility, Royal Holloway University, UK. Observers were screened in accordance with the imaging facility's standard protocols and written consent was also obtained prior to scanning. Ethical approval was granted by the University of Surrey Ethics Committee.

#### *3.3.1.2. EBA Localiser: Imaging protocol and experimental design*

Two EBA localiser runs were used for each subject to localise the EBA as detailed in experiment three in chapter two. The stimuli were similar to those used previously to localise the EBA (Downing *et al.*, 2001) and were greyscale photographs (12.33° x 15.81° visual angle). Each run lasted 340s (136 volumes; TR = 2500ms; 42 axial slices; 3mm slice thickness; 64x64 inplane resolution; 3x3x3mm matrix) and comprised four blocks of greyscale body part stimuli, four blocks of greyscale object stimuli and five fixation blocks. Each experimental block lasted 30s (12 volumes) and contained 45 exemplars of the category. Within blocks, each stimulus was

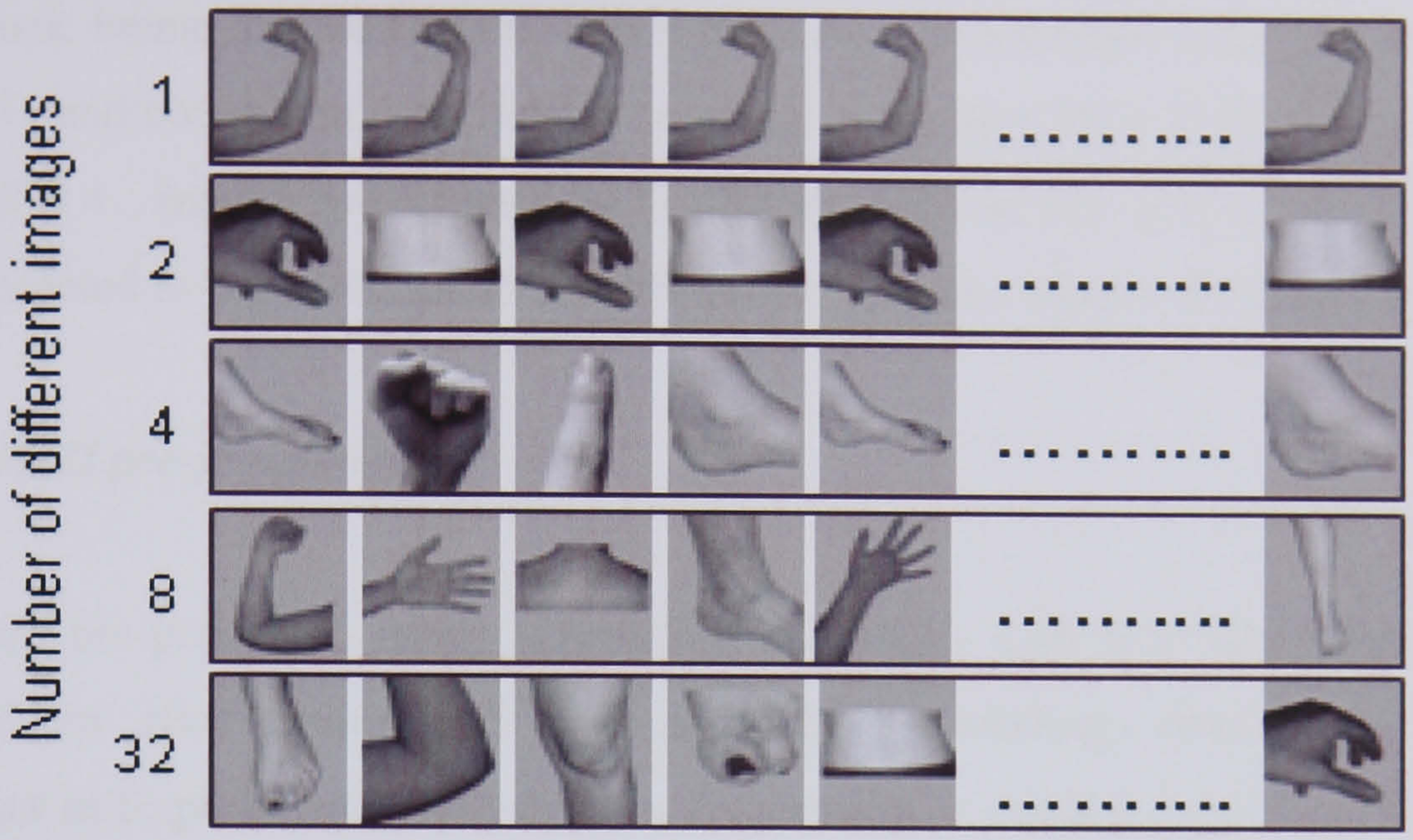



**Figure 3.2.** Diagrammatic example of one repetition suppression run (after Grill-Spector and Malach, 2001). Details the contents of each experimental block within one run. Each block was made up of 1, 2, 4, 8 or 32 different body part images presented twice within each run interspersed with blocks of fixation.

presented for 542ms, with an ISI of 125ms. Fixation blocks consisted of a fixation cross (1.42° x 1.42° visual angle) with a duration of 20s (8 volumes). Both runs were counterbalanced by reversing the block orders within the run and Observers were instructed to covertly name each stimulus in order to maintain attention during the task.

*3.3.1.3. EBA repetition suppression*

This experiment (shown in figure 3.2. above) followed the adaptation method developed by Grill-Spector and Malach (2001), although here we used 32 body part stimuli (similar to those used in the EBA localiser experiment) as opposed to object stimuli. Images were greyscale photographs (12.33° x 15.81° visual angle). Observers completed two experimental runs (counterbalanced by reversing the block order). Each run comprised of ten experimental blocks (TR = 2000ms; 34 axial slices; 3mm slice thickness; 64x64 inplane resolution; 3x3x3mm matrix) lasting 32s (16 volumes) and 7 fixation blocks lasting 20s (10 volumes).

The experimental blocks consisted of 1, 2, 4, 8 or 32 different body part images (each block being repeated twice within each run) interspersed with fixation only blocks (+) and counterbalanced within runs e.g. + [2][8] + [4] + [32][1] + [1][32] + [4] + [8][2] +. Images were presented for 875ms with an ISI of 125ms. Observers were instructed to pay attention to the differences between stimuli during the task.

#### *3.3.1.4. fMRI pre-processing*

Data were pre-processed using 3D motion correction with sinc interpolation and corrected for slice timing and scanning order (ascending, interleaved). One participant in Experiment 1, and three in Experiment 2, needed to be removed from further analysis due to excessive head motion. Linear trend removal and a high pass filter (cut-offs: 0.0088 Hz (EBA Localiser); 0.0078 Hz (Repetition Suppression)) were also applied. Functional data were aligned to a high resolution anatomical scan (1x1x1 mm matrix, 256x256 inplane resolution, TR 1900, TE 5.57) taken in the same session. This was subsequently normalised to a Talairach template (Talairach and Tournoux, 1988) and the parameters applied to the co-registered functional data. Spatial smoothing, using a 6mm FWHM Gaussian spatial filter, was then carried out in the 3D domain once the data had been aligned to the participant's 3D anatomical scan.

### 3.3.2. Results

#### *3.3.2.1. EBA localiser: region of interest definition*

Prior to analysis of the repetition suppression effect, a region of interest (ROI) for each participant was established in both the right and left hemispheres using the data acquired from two EBA localiser scans. The EBA was localised in each participant using the body minus objects contrast detailed in chapter two (experiment three), combining the data from the two runs. The data were thresholded to $p<0.0001$ (uncorrected for multiple comparisons) and from this the most significant voxel in both the right and left hemispheres was identified (peak EBA voxel). The location of the mean EBA peak voxels across Observers were [49 ± 5mm, -64 ± 3mm, 5 ± 5mm]

in the right hemisphere and [-49 ± 7mm, -62 ± 7mm, 10 ± 6mm] in the left hemisphere. These Talairach coordinates correspond to an area of the middle temporal gyrus in the posterior end of the temporal lobe.

A number of studies have shown that the EBA is in close physical proximity to other functional areas (for example Downing *et al.*, 2001). Consequently, the EBA ROI was established by setting a very conservative $3mm^3$ box centred on the peak EBA voxel to ensure that an area of maximal response to body images was localised whilst minimising inclusion of other functional areas. This combined with the reliable independent paradigm for localising a maximally responsive area to human body images made it highly probable that the EBA and not an adjacent region was being defined as the ROI.

*3.3.2.2. Repetition suppression results*

The aim of this experiment was to characterise the adaptation effect in the EBA and compare it to results previously reported from the LOC (Grill-Spector and Malach, 2001). As has been mentioned previously, successful demonstration of adaptation related to repetition suppression in the EBA is a pre-requisite for using this technique to explore the functional role of the EBA in subsequent experiments.

The timecourses from each of the two runs were extracted from the predefined ROI based upon the EBA localiser scans. Each time-course was then shifted forwards 3 TRs (6 seconds) to reflect the delay in hemodynamic response. Next we converted the value at each timepoint into percentage signal change (PSC) using the average signal of all the baseline (fixation) blocks within a run. The converted PSC data were then averaged across runs by block type (1, 2, 4, 8, 32 different images).

Figure 3.3a displays the mean PSC across observers for each block type containing 1, 2, 4, 8 or 32 different body part images for the right and left hemispheres respectively and 3.3b shows an example of the timecourses for each block type from one observer.

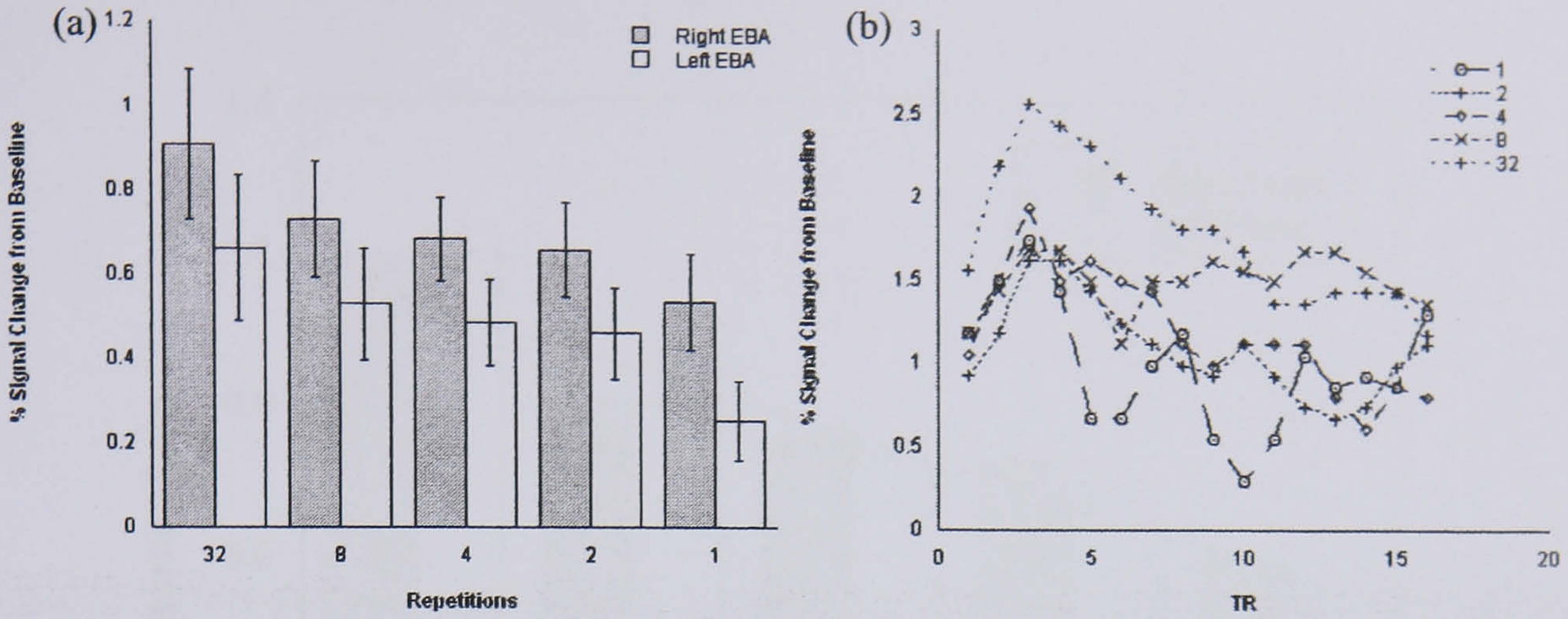



**Figure 3.3.** (a) displays the mean PSC response in the right and left EBA to each of the repetition conditions (32, 8, 4, 2, 1 different images). PSC was highest when the greatest number of different images was shown reflecting the higher overall PSC as a reflection of the least amount of adaptation (error bars show the standard error of the mean). (b) shows an example of timecourses for each condition for one observer, the blue and red lines indicate the most different conditions (red = 1 different images; blue = 32 different images). Here the overall lower and differences in

Data have been taken from the second half of each block (i.e. scans 9-16) to allow for one full image cycle to have occurred and are displayed in terms of their adaptation ratio (Grill-Spector and Malach, 2001) in figure 3.4.. Adaptation ratio is the amount of activity relative to the maximally non-adapted block (32 different images) calculated as average percent signal change (PSC) of the second half of the block (1, 2, 4, 8 or 32) divided by average PSC of the second half of the 32 different image block. Note that a decrease in the adaptation ratio signifies a relative increase in the degree of adaptation (i.e. suppression) of the BOLD response (PSC shown at the bottom of each bar with SE of the PSC response in brackets).

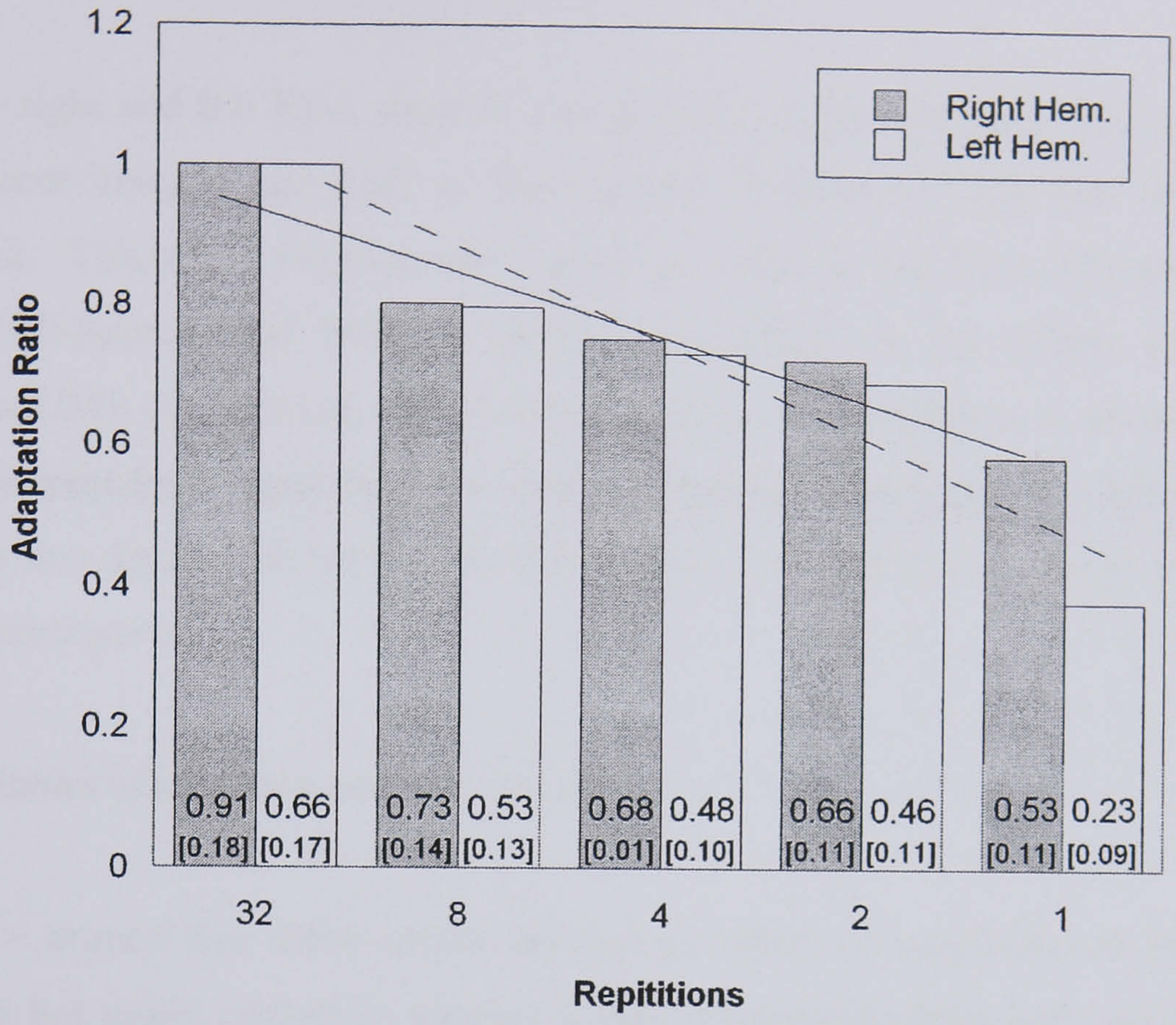



**Figure. 3.4.** Effect of repetition suppression in the EBA of the right and left hemisphere. Both show a monotonic decrease in the adaptation ratio as a function of the decrease in number of different images presented. This was also reflected by a decrease in overall PSC (shown by the figure at the base of each bar with the SE of the PSC in brackets below). In addition, there was significantly greater overall activation (measured by PSC) in the right hemisphere ($t(10)=2.157$ $p(1\text{-tailed})<0.05$). For comparison with Grill-Spector and Malach (2001) a linear trend line has been fitted to the adaptation ratio data (right hemisphere: solid line, $r^2 = 0.91$; left hemisphere: dashed line, $r^2 = 0.90$).

Figure 3.4. shows a clear decrease in the adaptation ratio as the number of different body part images presented within a block decreases. A 2-way ANOVA on the data (Hemisphere [Right and Left] x Block [1, 2, 4, 8 and 32 different parts]) showed a significant effect of Block ($F(4,40)$, 5.306, $p<0.01$). Post hoc tests showed that the 1 different part block was significantly more adapted than the 4 ($p<0.05$), 8 ($p<0.05$) and 32 ($p<0.0001$) different parts blocks (note: no significant interactions were found). Furthermore the 2 and 4 different parts blocks were both significantly more adapted than the 32 ($p<0.05$). Overall, these data provide clear evidence that neural populations within the EBA are susceptible to the effects of stimulus repetition in a similar way to those in the LOC, and that they distinguish between different body part categories.

### 3.3.3. Discussion

Both the right and left EBA showed a clear decrease in adaptation ratio (relative to 32 different images) and PSC as the number of different body part images was decreased. This result suggests that neural networks in the EBA, like those in the LOC (Grill-Spector and Malach, 2001), are sensitive to the effects of stimulus repetition (fMR-A). Further, the observation that less adaptation is observed when many different body parts are presented supports the notion that the EBA contains networks that distinguish between different body parts rather than simply responding to body parts *per se*.

#### *3.3.3.1. Issues of attention and adaptation*

It may be argued that these results are not an effect of adaptation as induced by condition but rather caused by varying levels of attention dependent on the varying number of different images. If we assume that attentional load increases as the number of different images increases (i.e. 32 different images would sustain the most attention and one different image would require the least attention) then our data indicate that an increase in attention resulted in less adaptation. However, this runs contrary to many findings in the physiological and psychophysical literature. In a classic illustration Chaudhuri (1990) used the motion after-effect (MAE; after adapting to a stimulus moving in one direction a stationary stimulus will appear to move in the opposite direction) to demonstrate that diverting attention away from the moving stimulus significantly weakened observer's MAE. Further, by investigating the MAE using an attentional manipulation Chaudhuri had demonstrated that adaptation increased with attention. This finding has been extended recently by Rezec, Krekelberg and Dobkins (2004) who show that the duration of the MAE is increased by a factor of 1.4 when the stimulus is attended. Further, they develop a quantitative model, based on the known properties of directionally selective MT neurons, which can explain these findings be assuming that attention enhances adaptation a phenomenon that they term adaptation gain.

Clearly, these types of findings make predictions opposite from those observed here. In the present experiment, conditions which would be classically defined as having a high attentional load (e.g. 32 different images) show the least amount of adaptation. This argues that the differences in adaptation observed here cannot be explained by differences in attention but instead reflect the selectivities of the underlying neurons as specified in the theory of fMR-A.

### *3.3.3.2. Conclusion*

The aim of this chapter was to characterise repetition suppression using fMR-A and hence demonstrate the EBA's sensitivity to this technique. The results from the present study demonstrate very clear effects of repetition suppression in both the right and left hemisphere that are directly comparable to those reported from the LOC (Grill-Spector and Malach, 2001). Building upon these results, the next chapter will utilise this technique to explore the functionality of the EBA with regard to discriminating different examples of the same body part and discriminating own and other body stimuli.

# Chapter Four: Investigating the Visual Properties of the EBA using fMR-A

## 4.1. Overview of Chapter Four

The previous chapter outlined how fMRI can be used to infer the function of neurons using fMR-A (Grill-Spector and Malach, 2001). Furthermore, we demonstrated that the basic effects of repetition suppression could be demonstrated within the EBA and were independent of possible attentional confounds. Based upon these results, the experiments discussed within this chapter exploit the fMR-A paradigm to investigate the possible functional role the EBA plays in the perception of images of the observer's own body compared to images of another's. Furthermore, fMR-A is used to extrapolate the responsiveness of the EBA to different body part images.

## 4.2. The use of fMR-Adaptation in functional exploration

The basic principles of fMR-A have been outlined in the previous chapter as well as the effects of repetition suppression within the LOC. The following section details a number of studies that have used the technique of fMR-A to investigate human object recognition (such as objects and faces) with the intention of demonstrating the flexibility of fMR-A as a tool to explore human brain function.

### 4.2.1. fMR-A and the LOC

Following the characterisation of the basic repetition suppression effect of objects in the LOC, Grill-Spector and Malach (2001) used fMR-A to investigate the functional properties of the LOC (that was subdivided into lateral occipital, LO and posterior fusiform sulcus, pFs), namely its response to changes in object size, position, illumination and orientation using face and car stimuli, in an attempt to reveal subtle functional and anatomical details that would typically be difficult to observe with standard fMRI analyses.

Based upon the findings of a previous repetition suppression experiment, which showed that the LOC was sensitive to the fMR-A/adaptation effect, observers were adapted using blocks containing repeated presentation of an identical image except that one image parameter (e.g. viewpoint) was systematically varied within each block. For example, the condition of viewpoint was manipulated by showing the same object at orientations of -34°, -17°, 0°, 17° and 34° within a block. Using this example, if neurons within the LOC ROI (LO/pFs) were sensitive to viewpoint each separate viewpoint would be responded to as if it were a new stimulus (e.g. car (a), car (b), car (c), car (d), car (e)) and yield a high fMRI response comparable to a non-adapted condition such as 32 different images (as in the previous experiment). However, if the LOC was invariant to viewpoint it would respond to the image at each viewpoint as if it were an identical object (e.g. car (a), car (a), car (a), car (a), car (a)) yielding a low fMRI response and hence comparable to the identical image condition (one different image condition) used to adapt observers.

The results of these experiments revealed that the pFs and the LO (note the response was weaker in the LO across conditions) was significantly more invariant to size and position compared to orientation and illumination. These findings were found to be inline with those reported previously in studies of macaque inferotemporal cortex (for example Ito, Tamura, Fujita and Tanaka, 1995). Thus, using fMR-A Grill-Spector and Malach (2001) had demonstrated how the function of populations of neurons can be inferred from the BOLD response using fMRI. However, from this it is unclear to what extent this technique can be extended to other functional regions or rather would other selective processing areas such as the FFA be sensitive to fMR-A analysis. The following sections discuss this question with reference to both the FFA and PPA.

### 4.2.2. fMR-A and Face Processing

The mechanisms underlying human face recognition are unclear. Faces are rarely identified statically (e.g. a picture) and therefore the visual system must account for variations in size and shape upon the retina as we approach/move away from others etc. As has been previously discussed with reference to object processing in general

(see chapter three) mechanisms underlying such a network have been attributed to both modular processing (for example Malach *et al.*, 1995) or a distributed pattern of responses throughout the temporal lobe (Haxby, Gobbini, Furey, Ishai, Schouten and Pietrini, 2001).

Using fMR-A Andrews and Ewbank (2004) hypothesised that regions involved in facial identity would produce a repetition effect to repeated presentations of the same face and that this reduction in response would be invariant to changes in image size or viewpoint. However, areas representing changeable aspects of faces would be predicted to not show repetition suppression and furthermore would be sensitive to changes in viewpoint.

As was predicted, repetition suppression effects to repeated presentation of an identical face were observed in the face selective region of the fusiform gyrus. These findings were comparable to those of Grill-Spector and Malach (2001) where size but not viewpoint invariance was demonstrated in the LOC. Furthermore all regions that were responsive to faces were tested for repetition suppression though it was reported that only face-selective regions (i.e. the FFA) demonstrated the drop in signal after repeated presentation of the same face (repetition suppression). Regions in the superior and inferior temporal lobe were largely size invariant but were face selective. Furthermore, there was a significant lack of fMR-adaptation in the object-selective regions of the visual cortex (LOC). This finding further supports the theory of domain-specificity with distinct modules rather than a distributed network of object selective regions. The use of fMR-A in this study demonstrates the advantage over standard fMRI analysis techniques that would not have revealed the subtle differences in processing between face responsive areas.

### 4.2.3. fMR-A and the PPA

In an attempt to investigate whether the parahippocampal place area (PPA) represented scenes in a viewpoint-specific or viewpoint-invariant manner Epstein, Graham and Downing (2003) assessed the response of the PPA to changes in viewpoint using fMR-A. Observers were presented with tabletop scenes that had two

possible relationships to one another (1) completely identical (no-change); (2) same layout and viewing angle but different object (object-change); (3) same layout and viewing angle, different viewpoints (viewpoint-change); (4) same object, different surrounding environment (place-change). It was predicted that if the PPA is viewpoint-invariant then changes in scene rather than viewpoint would yield a greater response (less adaptation) as the populations processing two different scenes would overlap less than those processing the same scene presented from different viewpoints. Conversely, if the PPA is viewpoint-specific then the fMRI response will be similar for both scene and viewpoint only changes.

Overall the results suggested that the PPA was viewpoint specific and responds as strongly to changes in viewpoint as to those in scene layout both of which are significantly stronger than changes to objects i.e. two views of the same scene are as different as two different scenes.

### 4.2.4. fMR-A: LOC, FFA and PPA

In a recent paper Ewbank, Schluppeck and Andrews (2005) addressed the modular vs. distributed networks for object recognition debate using fMR-A to analyse the FFA, PPA and LOC. Specifically, they investigated whether adaptation occurred in object selective areas to stimuli the area was not selective for (e.g. object stimuli in the FFA or the PPA).

Contrary to the findings of their previous study (Andrews and Ewbank, 2004) results supported the theory of a distributed network of object recognition (for inanimate objects and places) not restricted to areas showing maximal sensitivity/selectivity to specific object categories (i.e. FFA, LOC and PPA). For example adaptation to inanimate objects was shown not only in the LOC as would be predicted (see Grill-Spector and Malach, 2001) but also the FFA and PPA. All of these areas were invariant to changes in the object size and viewpoint, contrary to the viewpoint selectivity found in the PPA by Epstein, Graham and Downing, 2003 (although this may be affected by greater changes in viewpoint in the aforementioned study). However, such distributed adaptation should not be taken as clear evidence against

modular object recognition processing. For example, objects are embedded within scenes and are strongly associated with the context in which they are shown and the context which the object is perceived to belong to (Silva, 2005). Furthermore, adaptation to places was found in the LOC (as well as the PPA) but not the FFA, a finding supporting the idea of object context, but perhaps raising more questions about the role of the FFA.

The findings of the studies reviewed above do not provide conclusive evidence for either the concept of modular or distributed network approaches to object processing. However, for the purpose of this thesis they demonstrate the wide range of areas that can be studied using fMR- A. Further, in the previous chapter we discussed an experiment that demonstrated this effect in the EBA (a result not previously demonstrated). The studies discussed in this chapter explore how repetition suppression can be further used to explore the micro-functionality of the EBA.

## 4.3. Selectivity of the Extrastriate Body Area

Chapter one implicated the EBA as a candidate area for the processing of human body images and furthermore in mechanisms involved in the perception of specific aspects of the human body such as the perception of action (Downing, Peleen, Wiggett and Tew, in press), performance of action (Astafiev, Stanley, Shulman and Corbetta, 2004) and the perception of the self and others (Chan, Peelen and Downing, 2004).

The experiments detailed in the current chapter manipulate specific properties of EBA sensitive, human body part, images that are then analysed using fMR-A. They address two separate probable functions of the EBA. The first of these is *within-category repetition suppression* and the second is *own body recognition*. Within-category repetition suppression addresses whether the EBA is sensitive to different exemplars of the same body part (hand) or whether it is insensitive to this manipulation. In the second experiment we investigated the EBA's selectivity to recognition of one's own body; directly comparing images of the observer's own

hand against another's. Before the details of these experiments are discussed the rationale for these manipulations will be examined.

### 4.3.1. Within-Category Repetition Suppression

The EBA has been shown to be sensitive to repetition suppression. This finding also reveals that the EBA distinguishes between different body parts e.g. hand, arm, foot, leg, torso etc. This might be expected from the other experiments discussed that have reported comparable results with faces in the FFA (Andrews and Ewbank, 2004), scenes in the PPA (Epstein, Graham and Downing, 2003) and objects in the LOC (Grill-Spector and Malach, 2001). However, from this it is unclear whether the EBA responds to each exemplar of the same category (for example hands) differently in a way that is comparable to how it responds to images of different body parts (hand, foot, arm, torso etc.). Selectivity to within-category stimuli has been reported within the FFA for different faces whereas no difference was found for objects within the FFA (Grill-Spector, Knouf and Kanwisher, 2004) indicating that the FFA is selective for different exemplars of the same class/category of stimuli. Furthermore, Grill-Spector, Kushnir, Edelman, Avidan, Itzchak and Malach (1999) have also reported that the LOC showed no adaptation to objects of the same semantic category (e.g. dogs). From this it might be predicted that the EBA will show no adaptation to different exemplars of the same body part (hand) category relative to the same body part image shown repeatedly. Conversely, if the EBA shows such adaptation it could support the EBA's role in not only identity recognition but also may implicate it in social perception.

### 4.3.2. Own Body Recognition

The most direct study of the EBA's involvement in recognising one's own body was conducted by Chan, Peleen and Downing (2004) who investigated the response within the EBA to allocentric and egocentric stimuli of observers' own and others' bodies. However, the results of this study did not find a clear distinction between the self and familiar others in the EBA of either the right or left hemisphere. It is possible that these findings imply that the EBA does not play a significant role in

early social vision and further that connections to the representation of the human body and the self are dealt with by the STS. However, it is also possible that the method used in this study was not sensitive to different neuronal populations in the EBA. Therefore, by using fMR-A, a method that is sensitive to the selectivity of groups of neurons in a functional region (i.e. the EBA) it may be that different results may emerge.

## 4.4. Exploring the role of the EBA using fMR-A

In this experiment we explored the selectivity of the EBA to both within-category body part stimuli and images of the self using fMR-A, a technique as already discussed, that has been shown to reliably allow inferences to be made regarding the selectivity of groups of underlying neurons in a functional region. In order to achieve this five types of stimuli were used: Identical hand (same hand repeated throughout the block); Different Hands (six different people's hands); Own/Other (observer's own hand and another individual's hand); Other/Other (two unfamiliar individuals' hands); Different Parts (six different body part images).

### 4.4.1. Method

#### *4.4.1.1. Observers*

Fifteen observers were recruited to take part in the experiment (6 male). All observers had normal or corrected-to-normal vision. Scanning took place on the Siemens Trio 3T scanner at the CUBIC imaging facility, Royal Holloway University, UK. Observers were screened in accordance with the imaging facility's standard protocols and written consent was also obtained prior to scanning. Ethical approval was granted by the University of Surrey Ethics Committee.

*4.4.1.2. Task and Procedures*

**The EBA localiser**

An EBA localiser was conducted to identify the EBA for each observer (detailed in chapter two and also used to identify the EBA in the experiment detailed in chapter three of this thesis). The stimuli were similar to those used previously to localise the EBA (Downing *et* al., 2001) and were greyscale photographs (12.33° x 15.81° visual angle).

Each run lasted 340s (136 volumes; TR = 2500ms; 42 axial slices; 3mm slice thickness; 64x64 inplane resolution; 3x3x3mm matrix) and comprised four blocks of greyscale body part stimuli, four blocks of greyscale object stimuli and five fixation blocks. Each experimental block lasted 30s (12 volumes) and contained 45 exemplars of the category. Within blocks each stimulus was presented for 542ms, with an ISI of 125ms. Fixation blocks consisted of a fixation cross (1.42° x 1.42° visual angle) with a duration of 20s (8 volumes). Both runs were counterbalanced by reversing the block orders within the run and observers were instructed to covertly name each stimulus in order to maintain attention during the task.

**Discrimination within body-part categories experiment**

This experiment consisted of two counterbalanced runs (260 volumes; TR = 2000ms; 34 axial slices; 3mm slice thickness; 64x64 inplane resolution; 3x3x3mm matrix) each containing 10 experimental blocks lasting 30s (15 volumes) and 11 fixation blocks lasting 20s (10 volumes). Fixation blocks were presented either side of each experimental block. The experimental blocks consisted of five types: Identical hand (same hand (same photograph) repeated throughout the block); Different Hands (six different people's hands); Own/Other (observer's own hand and another individual's hand); Other/Other (two unfamiliar individuals' hands); Different Parts (six different body part images). Each block type was repeated twice within each run. All images were colour photographs (12.33° x 15.81° visual angle) and were presented for 750ms with an ISI of 250ms. All hand images were presented from the perspective

of the back of the hand examples of which can be seen in appendix two. As before, observers were instructed to pay attention to the differences between stimuli during the task.

#### *4.4.1.3. fMRI Pre-processing*

Data were pre-processed using 3D motion correction with sinc interpolation and corrected for slice timing and scanning order (ascending, interleaved). One observer in Experiment 1, and three in Experiment 2, needed to be removed from further analysis due to excessive head motion. Linear trend removal and a high pass filter (cut-offs: 0.0088 Hz (EBA Localiser); 0.0083 Hz (main experiment)) were also applied. Functional data were aligned to a high resolution anatomical scan (1x1x1 mm matrix, 256x256 inplane resolution, TR 1900, TE 5.57) taken in the same session. This was subsequently normalised to a Talairach template (Talairach and Tournoux, 1988) and the parameters applied to the co-registered functional data. Spatial smoothing, using a 6mm FWHM Gaussian spatial filter, was then carried out in the 3D domain once the data had been aligned to the observer's 3D anatomical scan.

### 4.4.2. Preliminary Analysis

#### *4.4.2.1. EBA localiser: region of interest definition*

A region of interest (ROI) for each observer was established in both the right and left hemispheres using the data acquired from the two EBA localiser scans. The EBA was localised in each observer by using a body minus objects contrast (Downing *et al.*, 2001; also see chapter two), combining the data from the two runs. The data were thresholded to $p<0.0001$ (uncorrected for multiple comparisons) and from this the most significant voxel in both the right and left hemispheres was identified (peak EBA voxel). The location of the mean EBA peak voxels across observers were [48 ± 6mm, -63 ± 6mm, 6 ± 6mm] for the right hemisphere and [-48 ± 4mm, -62 ± 6mm, 13 ± 8mm] for the left hemisphere. These Talairach coordinates correspond to an area of the middle temporal gyrus in the posterior end of the temporal lobe. A

number of studies have shown that the EBA is in close physical proximity to other functional areas (Downing *et al.*, 2001). Consequently, the EBA R[illegible] was established by setting a very conservative 3mm$^3$ box centred on the peak [illegible]xel to ensure that an area of maximal response to body images was localised whilst minimising inclusion of other functional areas.

*4.4.2.2. Discrimination within body-part categories experiment*

From each observer's 3mm$^3$ ROI centred on their peak EBA voxel (established from the EBA localiser scans taken in the same session) we extracted the average timecourses for each of five block types. These data were converted to PSC using a condition-based averaging method (Brain Voyager QX; Brain Innovation, Maastricht, The Netherlands) which calculated the PSC using the fixation period preceding each block as the baseline. The converted PSC data were then averaged across runs by block type (Identical, Other/Other, etc.).

## 4.4.3. Results

The current experiment has been subdivided into two parts (*A* and *B*). Experiment *A* addresses the question of within-category repetition suppression; whether the EBA is sensitive to different exemplars of the same body part (hand) category. Experiment *B* considers the conditions manipulating the observer's view of their own body and that of another's.

*4.4.3.1. Statistical Analysis*

Testing for the assumptions of normality was conducted to screen the data [illegible] skewness and kurtosis prior to parametric testing. All conditions except Identical Hand, Different Hands and Own/Other, in the left hemisphere showed [illegible] than the criterion $z$ of 3.29 ($p = 0.001$) recommended for small to moderate sizes (Tabachnick and Fidell, 1996). Consequently, statistical analyses conducted using either t-tests (1-tailed due to specific predictions from research) for single pair wise comparisons or Analysis of Variance to

Type 1 errors, where multiple comparisons are made, with post hoc analysis to explore significant effects conducted using Fisher's LSD test to maximise power. All significant effects from the ANOVA analyses are reported.

*4.4.3.2. Experiment A: within-category repetition suppression*

Figure 4.1. displays the adaptation ratio (calculated relative to the Different Hands block) for blocks in which 1 (Identical), 2 (Other/Other) or 6 different hands (Different Hands) were presented for each hemisphere's EBA.

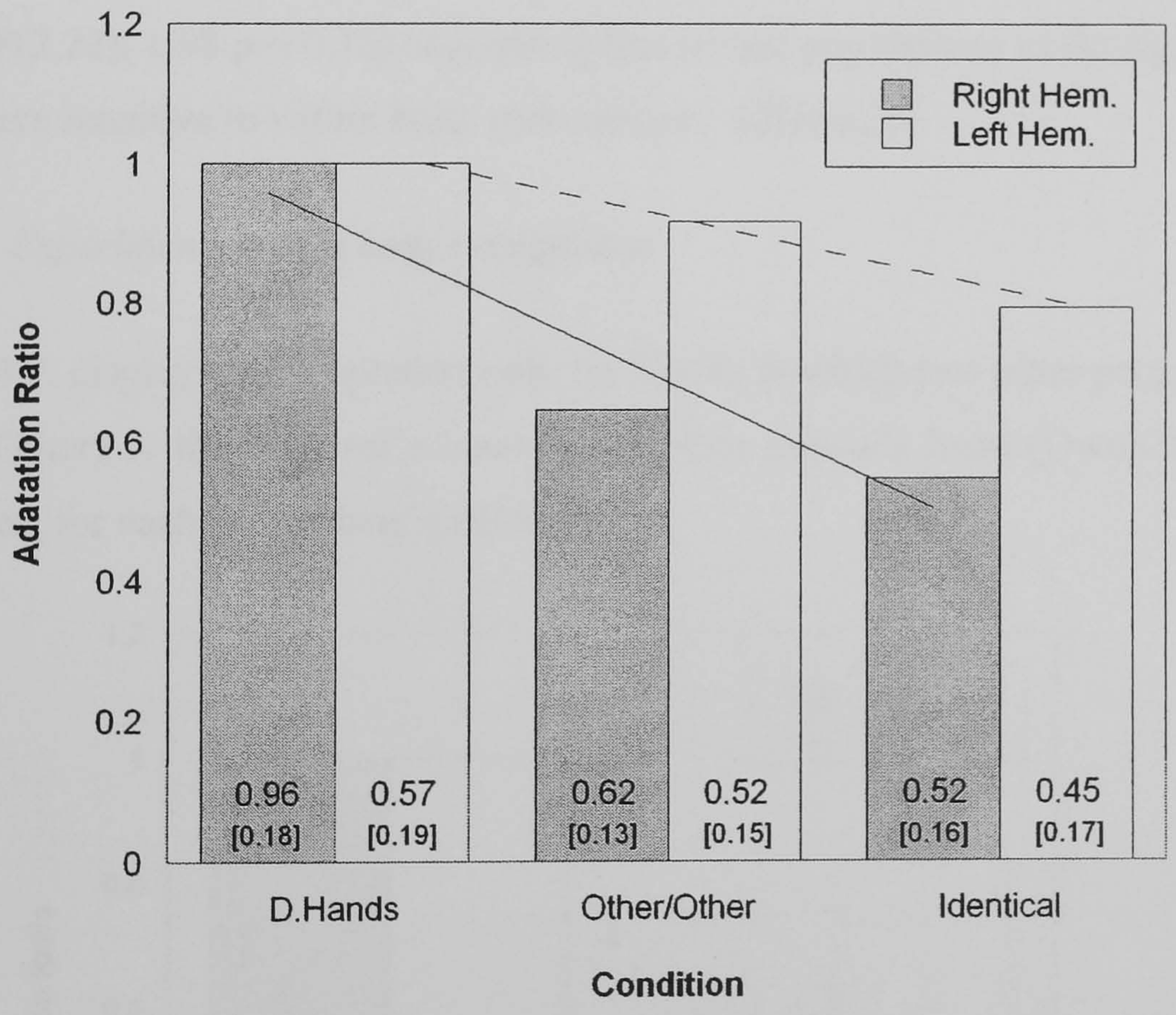



**Figure 4.1.** Repetition suppression within a body-part category for each hemisphere. The adaptation ratio decreases as the number of different hands shown decreases; 6 different hands (Different Hands); 2 different hands (Other/Other); 1 hand (Identical). A linear fit to the data for both the right (solid line) and left (dashed line) hemisphere EBA is shown. PSC for each condition/hemisphere is shown at the base of each bar and under it the SE of the PSC in brackets. There was significantly greater overall activation (measured by PSC) in the right hemisphere ($t(11)=2.673$ $p(1\text{-tailed})<0.05$).

It is evident that there was a clear monotonic decrease in the adaptation ratio (and hence PSC) as the number of different hand images in an epoch was reduced. A 2-way ANOVA (Hemisphere [Right and Left] x Block [Different Hands, Other/Other and Identical]) showed a main effect of Block ($F(2,22)$, 5.56, $p<0.01$). Post Hoc analysis (Fisher's LSD) showed that the Identical and Other/Other blocks were significantly more adapted than the Different Hands block ($p<0.01$ & $p<0.05$ respectively). These findings show that the fMR-A effect, characterised in the experiment discussed in the previous chapter, is also evident within a single body part category (i.e. hands). Furthermore, the effect of hemisphere was found not to be significant ($F(1,11)=0.8$ $p=0.39$) as was the interaction between hemisphere and block ($F(2,22)$, 1.98 $p = 0.16$) suggesting that neural populations in the right and left EBA were sensitive to within body part category differences.

*4.4.3.3. Experiment B: own body recognition*

Figure 4.2. displays the adaptation ratio for blocks in which two other peoples' hands (Other/Other) or the observer's hand and another person's hand (Own/Other) were presented, for each hemisphere's EBA.

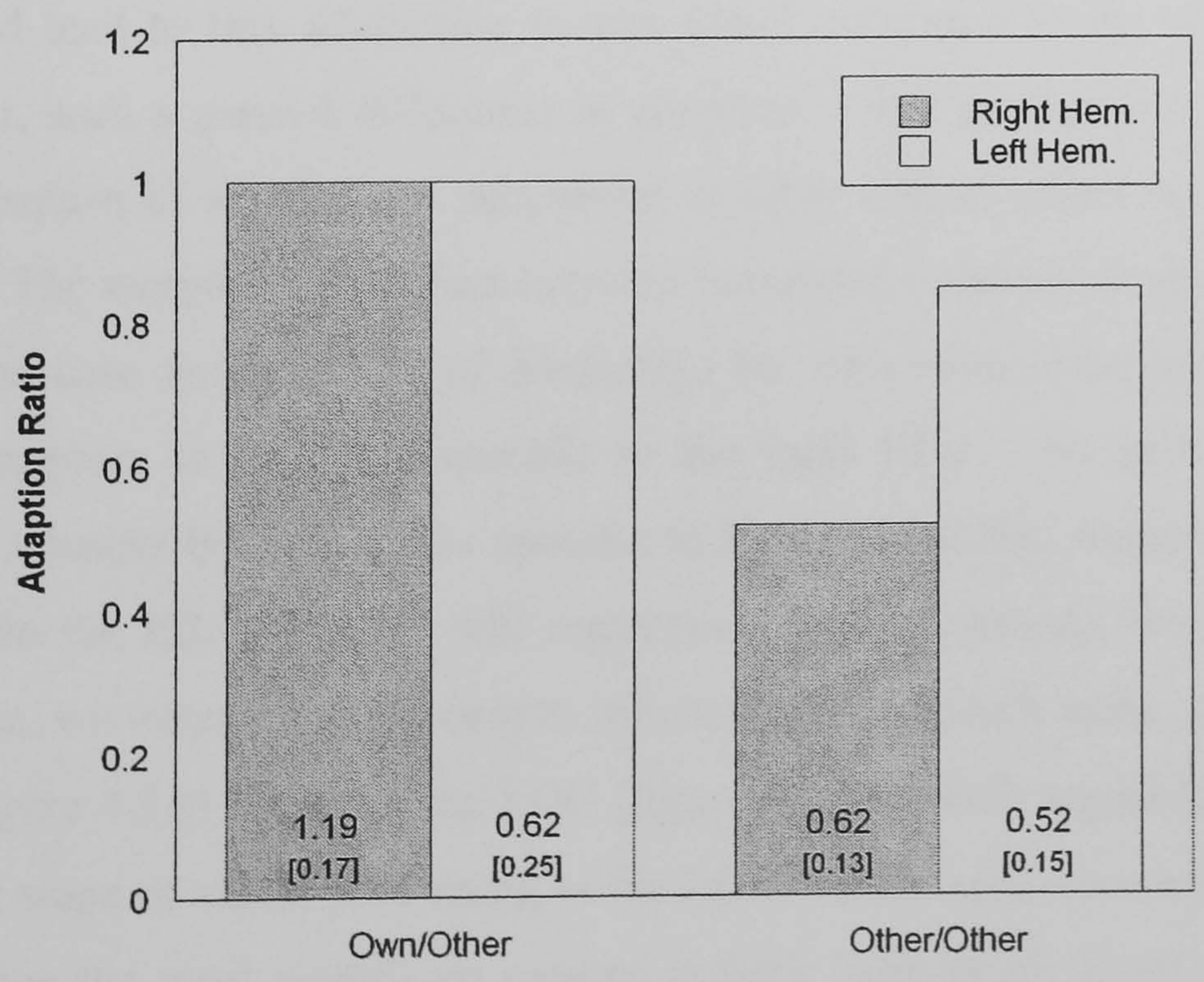



**Figure 4.2.** Adaptation ratio for the own/other and other/other conditions is plotted for the right and left hemispheres. There is greater adaptation in the other/other blocks. The value of the mean PSC is shown above each bar and under it the SE of the PSC in brackets. There was a non-significant ($p$(1-tailed)$>0.05$) trend for greater activation in the right hemisphere.

Here the own/other condition is established as the 'non-adapted' condition due to firstly the a priori hypothesis that the EBA will be selective to own body stimuli and the result (shown at the base of each bar) reveals this condition to have a dramatically higher PSC hence supporting this hypothesis. From this there appears to be greater adaptation in the other/other block. A 2-way ANOVA (Hemisphere [Right and Left] x Block [Own/Other and Other/Other]) confirmed the statistical significance of this observation (effect of Block: $F(1,11)$, 10.02, $p<0.01$) suggesting that neural populations within the EBA particularly distinguish one's own body parts. Furthermore, the effect of hemisphere was found not to be significant ($F(1,11)=2.08$ $p=0.178$), however, the interaction between hemisphere and block was marginally significant ($F(1,11)=4.71$ $p=0.053$) in line with a more pronounced adaptation effect in the right hemisphere.

*4.4.3.4. Control for attention*

It is possible that observers pay less attention to their own hand (due to its great familiarity) than to others' hands. If so, then we would predict that observers would pay less attention in the own/other block, which following the discussion in chapter 3, should lead to less adaptation in this block compared to the other/other block. However, such a general difference in attention would predict that we should see a similar pattern of activity and adaptation in other brain regions responsive to these stimuli. The marginal interaction between hemisphere and block above suggests this is not the case as the effect of adaptation for own/other compared to other/other stimuli appears to be fairly specific to the right EBA. Nevertheless, to further confirm whether the effect was specific to the (right) EBA, timecourses in regions other than the EBA, that are still responsive to these stimuli, were examined. In particular, we extracted time course information from both early visual processing areas (figure 4.3.a) and from the LOC (figure 4.4.b), which arguably is positioned at a similar stage of visual processing to the EBA. Early visual cortices were localised by locating the most significant regions in both hemisphere to all visual stimuli in EBA localiser (body plus objects), this resulted in a cluster in the right(14, -86, 1, voxel count = 285) and left (-11, -92, 5, voxel count = 106) hemispheres. Localisation of the LOC was achieved using an objects minus body contrast which

identified a region in both the right (29, -49, -8, voxel count = 304) and left (-26, -45, -8, voxel count = 355) hemispheres corresponding to the LOC.

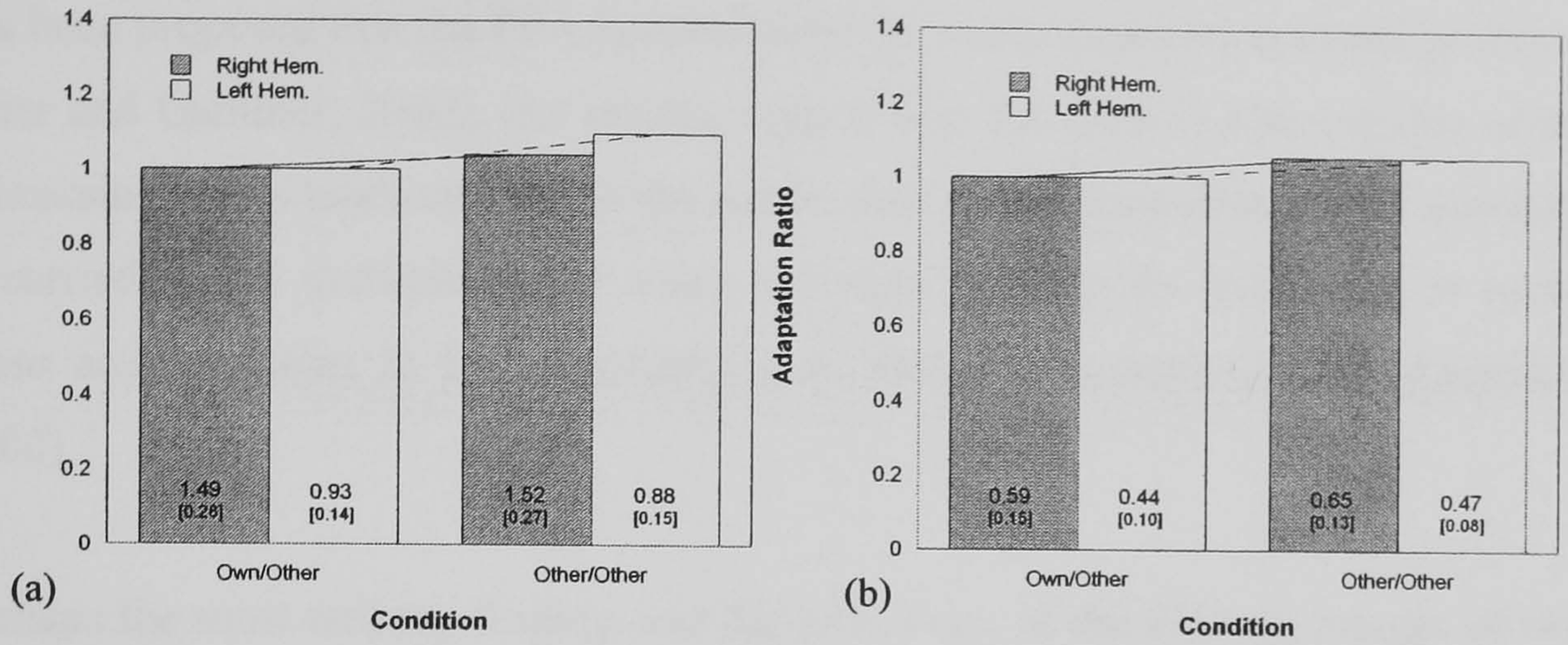



**Figure 4.3.** Adaptation ratio in the bilateral early visual processing areas (a) and LOC (b). Data from both regions showed no significant differences in the degree of adaptation between own/other and other/other conditions. The value of the mean PSC is shown above each bar and under it the SE of the PSC in brackets.

Critically, a 2-way ANOVA (Hemisphere [Right and Left] x Block [Own/Other and Other/Other]) confirmed that there was no effect of block in either the early visual cortices ($F(1,10)$, 3.054, $p=0.819$) or the LOC ($F(1,10)$, 0.866), $p=0.37$). Only a main effect of hemisphere was observed in this analysis for the early visual cortices ($F(1,10)$, 8.07, $p<0.05$). From figure 4.3(a) this is evident from the larger PSC response from both blocks in the right hemispheres (shown at the base of each bar with the standard error of the mean in brackets below).

### 4.4.4. Discussion

The within-category repetition effect reported in Experiment *A* showed a monotonic trend for repetition suppression as a function of variation in the number of within category exemplars (here images of the hand) comparable to that found in the repetition suppression experiment detailed in the previous chapter that used 1,2,4,8 and 32 different body part images. This result implies that networks within the EBA are also capable of distinguishing exemplars within a single body-part category and may facilitate discrimination of identity from body part images. The selectivity to

within category differences observed in the second experiment is paralleled by related findings with faces (Phelps, 2001; Henson, Shallice and Dolan, 2000) and objects (Tyler, Stamatakis, Acres, Abdallah and Moss, 2004). Furthermore, whilst it has been proposed that the FFA is specialised for subordinate-level visual processing (Tarr and Gauthier, 2000), our results suggest that the EBA is also capable of such processing. This lends support to the notion that subordinate level visual processing is carried out in multiple visual areas, although the domain specificity of each of these areas remains to be determined (see Tarr and Gauthier, 2000; Kanwisher, 2000).

Perhaps the most striking finding was the selectivity of the EBA to images of one's own body parts found within Experiment *B*. The own/other condition (which contained an image of the observer's own hand) was significantly less adapted than the other/other condition (containing two unfamiliar hand images) suggesting the possibility that more distinct neural populations process own vs. others' body part images, whilst more overlapping populations process different images of others' body parts (both within and between body part categories). In other words, the difference between these two conditions implies that a function of the EBA may be differentiating images of one's own body parts from those of others.

The findings of the present study run contradictory to those that have been reported in a recent study (Saxe, Jamal and Powell, 2006) investigating egocentric (perspective as if looking at one's own body) vs. allocentric (perspective as if looking at another's body) views. Saxe *et al.* (2006) reported that the right EBA was selective for allocentric images but not egocentric i.e. other vs. own/self. However, this study did not use actual images of the subject's body parts but rather manipulated the viewpoint of the body part presented. Therefore, although it was shown that the right EBA was sensitive to allocentric processing our findings clearly suggest that the EBA is highly responsive to actual images of one's own body. In addition, Chan, Peleen and Downing (2004) similarly investigated the role of the EBA in egocentric and allocentric processing but used images of the subject's own body photographed in a variety of whole body (excluding head) and part body (e.g. torso) poses. In this study they reported, as previously, that the EBA was more

responsive to allocentric than egocentric images. Furthermore, they report that the EBA was not selective for images of the self.

These results appears to run contrary to the findings of the current experiment that the EBA responds selectively to images of one's own body compared to another's. One possible reason for this disparity is that in the present study we directly compared the same isolated body part i.e. own hand vs. other hand whereas Chan et al. used a combination of poses that included a variety of body parts (in a more holistic image) that may have reduced the selectivity of the EBA to images of one's own body as a larger population of neurons would be involved in processing multiple body part images. However, the most significant difference between the two studies is that in the present one the technique of fMR-A was used. This may have allowed insights into the selectivity of neurons within the EBA that would have been overlooked by a simple contrast between own and other body images. The latter is capable of revealing when an area preferentially processes one type of stimulus (for example own) over another, but it will not be sensitive to the possibility that an area contains two different, equally balanced, neural sub-populations. In this case, one responsive to own body part images and another responsive to other body part images. The present fMR-A analysis suggests that this may be exactly the case in the EBA.

The present finding that the EBA may recognise oneself promotes the EBA as a candidate area to facilitate the priming of somatosensory processing by relevant visual information seen in psychophysical studies. For instance, the increased somatosensory selectivity observed when the site of tactile stimulation is viewed (Kennett, Taylor-Clarke, and Haggard, 2001). Furthermore, it is consistent with recent findings that place the EBA in part of a functional network with motor cortex in the performance of body movements (Astafiev, Stanley, Shulman and Corbetta, 2004).

It may be argued that the adaptation results here are not an effect of adaptation induced by condition but rather caused by varying levels of attention dependent on the relevance (e.g. own vs. other) or varying number of different images. However,

it has been discussed in the previous chapter that the findings are more likely a result of the intended manipulations across condition rather than attention (for example, they run contrary to the theory of adaptation gain; Rezec, Krekelberg and Dobkins, 2004). In the case of Experiment A in this chapter, we would predict that observers will pay more attention when viewing multiple different hands and less attention when viewing the same hand repeatedly, leading to less adaptation in the latter case. This was exactly the opposite of the present findings suggesting the adaptation cannot be explained by differences in attention to the stimuli. However, this argument is not valid for Experiment B where we might reasonably predict less attention (and so less adaptation) to blocks in which an observer's own hand appeared. Arguing against this explanation, was the interaction between block and hemisphere. Any effects of global attention should be noticeable across both hemispheres rather than differences between the hemispheres as was observed in experiment B. Furthermore, we have shown here that the adaptation effects observed in the own/other conditions were exclusive to the EBA and did not occur in either the LOC or early visual cortex of the right and left hemispheres.

Finally, in their initial work Downing *et al.* (2001) reported a stronger response from the right hemisphere EBA, which has resulted in other researchers focusing on the EBA in this hemisphere (for example see Urgesi, Berlucchi and Aglioti, 2004). Further, evidence from disorders of face recognition such as prosopagnosia are typically the results of damage to right hemisphere regions (De Renzi, 1997) and imaging evidence of the FFA also suggests right hemisphere dominance in the perception of faces (Kanwisher, McDermott and Chun, 1997). Similar to previous work on the EBA and FFA, we found that overall levels of activation (measured by PSC) were significantly greater in the right hemisphere. However, we still found significant activation in the left hemisphere EBA and some evidence that the left and right EBA do not have the same selectivity. This underlines the potential importance of continuing to explore the role of the EBA in both hemispheres lest more subtle left hemisphere effects are missed.

In conclusion, the results of the present experiments suggest that the EBA differentiates not only between different body part stimuli, as was reported in the

previous chapter, but also that this differentiation is within categories (between different examples of the same category i.e. hands). Furthermore, there is evidence to suggest that the EBA may hold some type of unique visual representation of one's own body with which it is able to distinguish from another's. In relation to previous literature we can therefore propose that the EBA may be a candidate area for aiding other brain areas in tasks that relate visual and somatosensory information.

# Chapter Five: Crossmodal Links between Vision and Touch

## 5.1. Overview of Chapter Five

The previous chapters have addressed some of the possible roles of the Extrastriate Body Area concerning its visual properties especially those pertaining to the own/other body distinction. However, Downing, Jiang, Shulman and Kanwisher (2001) commented that stimulation in modalities other than vision may activate the EBA. This possibility that was explored by Astafiev, Stanley, Shulman and Corbetta (2004) in relation to the motor system who reported the response of the EBA to motor actions (although this has been disputed; see Peleen and Downing, 2005). In this and the subsequent chapter we will investigate the possible role the EBA may play in a somatosensory crossmodal network as it has been previously demonstrated that there are crossmodal links between vision and touch (for example see Macaluso, Frith and Driver, 2000). However, as yet the EBA has not been implicated in such a network though results from chapter two did reveal apparent somatosensory activation to visual EBA stimuli, hinting at the possible links between the two areas. Here we explore this question using a lab-based crossmodal congruency paradigm. Although there are no shortage of studies that have demonstrated the effect of congruency between vision and touch (for example see Spence, Pavani and Driver, 1998) there are no studies that can be drawn upon (to the author's knowledge) that demonstrate such effects using the same stimuli that are used here to evoke the EBA (i.e. human body part images). Therefore it is necessary here to establish whether some of the present stimuli used to localise the EBA can have an effect upon somatosensation before this issue is further explored using a more complex, costly and time consuming fMRI paradigm.

## 5.2. Crossmodal Integration between Vision and Touch

Crossmodal integration refers to the combining of information between multiple modalities that subsequently permit effective interaction with our world. Without such a process carrying out even the simplest of tasks such as picking up an object

would be near impossible. This section examines research that has explored the various mechanisms underlying the integration between two sensory modalities, that of vision and somatosensation/touch.

### 5.2.1. Orientating without proprioception: Body part familiarity

In a study conducted by Tipper, Lloyd, Shorland, Dancer, Howard and McGlone (1998) it was demonstrated that vision of a body part (hand), independent of proprioceptive orienting (orienting of the head to the stimulated location), can significantly affect somatosensation thereby illustrating cross-modulation of touch by vision. This result persisted even when the hand was viewed, via a video-camera and monitor, from the perspective of a third party (comparable to an allocentric viewpoint; see Chan, Peleen and Downing, 2005) and hence the viewpoint was not one that could be gained from orienting of the eyes and the head to the hand (an egocentric viewpoint; See Chan, Peleen and Downing, 2005). In a subsequent study Tipper, Phillips, Dancer, Lloyd, Howard and McGlone (2001) compared the facilitation of target detection provided by vision of both familiar, frequently viewed, areas such as the hand and unfamiliar, infrequently viewed, areas such as the back of the neck. Results from this manipulation revealed that viewing the stimulated body part of a familiar region (via camera) yielded significantly faster reaction times than viewing the unfamiliar body area. Findings from both of these studies suggest that internal personal body representations may act cross-modally to aid the somatosensory system, with more familiar representations providing the greatest assistance. However, from these studies it is not clear what type of mechanism may guide this visual identification, although the EBA may be a candidate area given its increased response to human body part images (see chapter one and Downing *et al.*, 2001 for details).

### 5.2.2. Vision aids somatosensation

Building upon the results of Tipper *et al.* (1999, 2001) Kennett, Taylor-Clarke and Haggard (2001) measured observer's two-point touch discrimination thresholds from the forearm. Observers were instructed to view the location of their forearm at all

times while visibility of the arm itself was manipulated (by means of an occluding box where just prior to stimulation LEDs inside the box were turned off occulding the arm). Therefore, unlike in Tipper *et al.* (1999, 2001) proprioceptive orienting was permitted but was not manipulated. Also only the site of the stimulation could be seen, i.e. the forearm, not the solenoids that delivered the tactile stimulation whereas in Tipper *et al.* (2001) the vibrotactile stimulator was visible in the online images provided by the video camera. The results of this study revealed that spatial resolution to touch was significantly improved when the arm was visible and even more so when the arm was magnified immediately prior to somatosensory stimulation. Furthermore, viewing an object in the same location yielded no improvement revealing that the result was a consequence of viewing the relevant body part rather than improved spatial orienting/proprioception, i.e. the viewing of the actual body part itself rather than being able to look at the location.

In a subsequent study, Taylor-Clarke, Kennet and Haggard (2002) recorded brain activity using event-related potentials (ERPs) while observers judged two-point discrimination stimulation on the forearm. The vision of the stimulated forearm was manipulated as in their previous experiment. Results from the previous (2001) study were replicated; however, ERP recordings also revealed that vision modulated somatosensory cortex activity. Specifically, in SI (primary somatosensory cortex) activity was enhanced by task relevant visual stimulation whereas SII showed a degree of modulation by vision regardless of task (SI and SII were recorded from C3 and C4 in the international 10/20 ERP system).

Haggard, Taylor-Clarke and Kennet (2003), with reference to work by Taylor-Clarke *et al.* (2002), suggest that the neural integration of vision and touch may be essential for developing and maintaining a sense of bodily self (often referred to as 'body schema'). The importance of the representation of the body appears evident in a variety of clinical disorders such as heterotopagnosia caused by left parietal damage that subsequently causes loss of spatial organisation of parts of one's own body (Pavani, Spence and Driver, 2000). Evidence from such research implies that as touch maybe modulated by vision then if the EBA truly represents/processes visual

images of the human body (whether it be one's own or another's) then it may be possible that the EBA plays an important role within this visual-tactile network.

In another example, cross-modulation between vision and touch has been shown to involve multiple brain regions. Here Macaluso, Frith and Driver (2000), in an fMRI study, demonstrated that areas classically labelled as unimodal visual areas, such as the lingual gyrus, respond to visual stimulation significantly stronger when paired with concurrent tactile stimulation on the same side as the visual stimulation (e.g. right visual stimulation and right tactile stimulation). From this it was proposed that an 'effective connectivity network' existed that indicated reciprocal connections between the occipital cortex, posterior parietal cortex and inferior parietal lobe, and that it was this network that was responsible for the crossmodal facilitation of vision by touch observed in the lingual gyrus. In a subsequent fMRI study Macaluso, Frith and Driver (2001) identified the intraparietal sulcus and the temporal-parietal junction as multimodal brain regions that were involved in the controlling of spatial attention in both vision and touch. From these studies it is evident that there are a variety of subsystems involved in the cross-modal integration of vision and touch and that there are dominant supramodal high level regions, although the role of the EBA within this, if any, is yet to be established.

### 5.2.3. Crossmodal Cueing Paradigms

It is evident from current research that the concepts of bodily representation and levels of familiarity, like the EBA itself, have not yet been considered as part of a crossmodal network. Studies such as Macaluso *et al.* (2000) have demonstrated methods that may reveal possible crossmodal networks and there is also an established methodology outside of the fMRI scanner for the use of classical psychophysical cueing paradigms in crossmodal research to infer links between different systems (for example: Spence, Pavani and Driver, 1998; Pavani, Spence and Driver, 2000; Spence, Kingstone, Shore and Gazzaniga, 2001).

Crossmodal cueing paradigms such as those mentioned above are based upon the widely used classical cuing paradigm developed by Posner (1980) whereby observers

were required to respond to the occurrence of a stimulus after a pre-cue. At the beginning of each trial in Posner's paradigm observers were presented with a cue' either a peripheral flicker (i.e. occurring peripheral to fixation) or a central arrow, indicating the possible location of the target. Following a short delay the target was presented in either the cued location or the miscued location (i.e. the opposite location from where the cue indicated). The results revealed that observers' performance was significantly enhanced in the cued rather than miscued trials. Further, as the proportion of valid cues increases so the effects of miscuing become more pronounced.

Crossmodal studies investigating the links between vision and touch often pair tactile stimulation (such as a vibrotactile device) with visual distracters (such as LED's). One such study, conducted by Pavani, Spence and Driver (2000), used this method. In their study observers were instructed to identify the location of a tactile target presented on the top or bottom of a foam block held (underneath the table) in the thumb and forefinger of either hand and to ignore distracter lights at each location. When distracter lights were presented (on top of the table) incongruent with the tactile stimulation location reaction times were significantly slower than in congruent trials. This effect was subsequently increased when 'rubber hands' were placed upon the table holding the distracter lights, but only when they were spatially aligned with the observer's real hands.

Findings such as these demonstrate, as previously discussed that vision can modulate somatosensation. In the present study we adopt a basic cueing paradigm as has been outlined. The central aim of this study is to demonstrate that the images that have been used previously (both in previous chapters and by other authors investigating the EBA) to evoke a significant response from the EBA can also be used to manipulate processing of touch information crossmodally.

## 5.3. Visual-Tactile Cueing Experiment

### 5.3.1. Method

#### *5.3.1.1. Observers*

Twenty participants were recruited to take part in the experiment (five male). All participants had normal or corrected-to-normal vision and gave full written consent to participate in the study. Ethical approval was granted by the University of Surrey Ethics Committee.

#### *5.3.1.2. Equipment*

Figure 5.1. below details the experimental equipment used to deliver tactile stimulation to the hand and foot of observers. A digital output control box was used to control the stimuli (National Instruments BNC-2090) that was itself controlled by a PC with a custom written program.

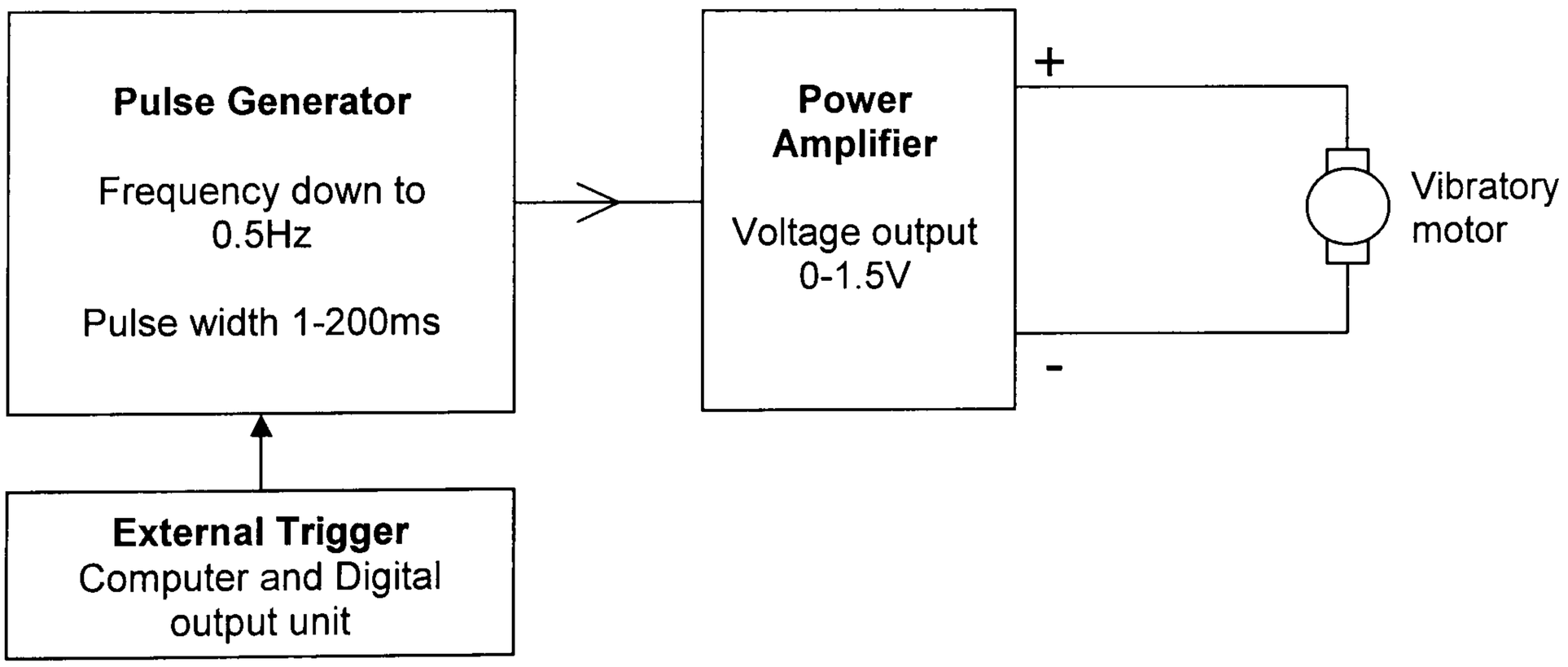



**Figure 5.1.** Diagram illustrating the purpose built vibrotactile stimulator. The vibrotactile motors were attached to the medial side of the dominant hand and at just above the ankle. The stimulator was controlled via an external digital trigger unit (National Instruments BNC-2090) that was in turn controlled by a purpose written program run from a PC.

*5.3.1.3. Task and Procedures*

Observers were seated in front of a 21" computer monitor and a vibrotactile stimulator (see section *5.3.1.2*) was attached with surgical tape to the medial side of the dominant hand and another to the medial side of the leg/foot (just above the ankle).

Each experimental trial followed the same sequence (see figure 5.2.): fixation for 1500ms; visual cue (either an image of a hand or a foot, 350 x 450 pixels) presented for 350ms; temporal gap that randomly lasted between 850-1850ms (to prevent anticipation effects); vibrotactile stimulation to either hand or foot that lasted for 80ms. The observer was instructed to fixate on the centre of the screen at the location of the fixation cross where images would appear and to press a response button when the vibrotactile stimulus delivered was detected. Observers completed 400 trials (80% congruent, 20% incongruent) composed of 160 congruous hand trials (hand picture/hand stimulation), 160 congruous foot trials (foot picture/foot stimulation), 40 incongruous hand trials (foot picture/hand stimulation) and 40 incongruous foot trials (hand picture/foot stimulation). Trials were shown in a completely random order for each observer. Furthermore, prior to the experimental run observers completed twenty practice trials during which the experimenter was present.

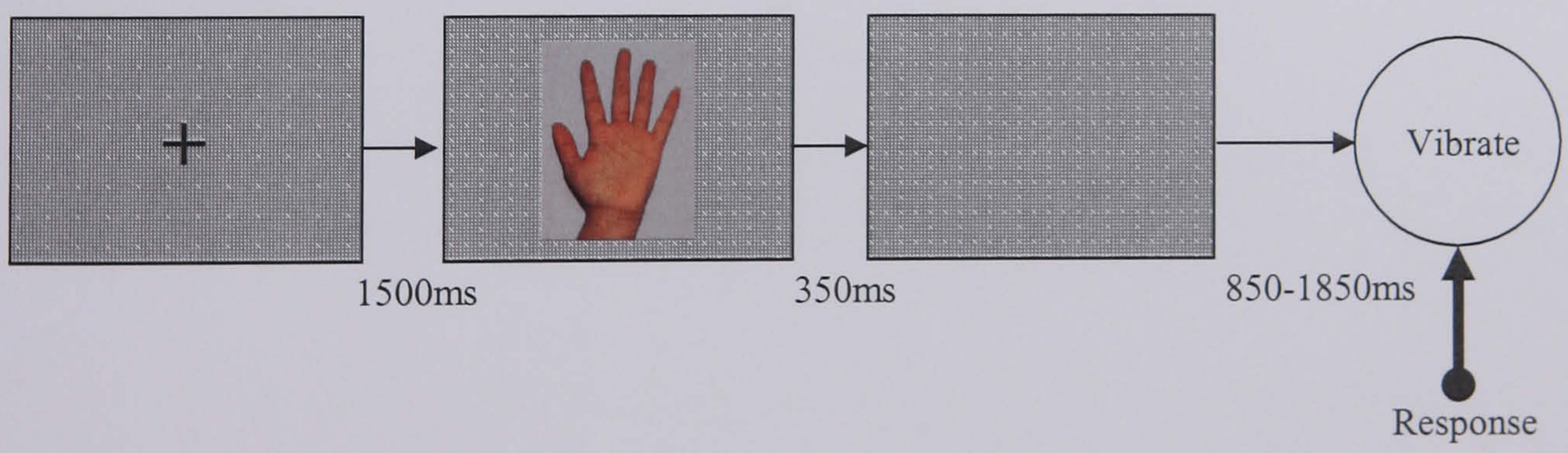



**Figure. 5.2.** Example trial sequence for vibrotactile run. After a fixation only period of 1500ms a foot or hand image was presented for 350ms this was followed by a temporal delay lasting between 850ms and 1850ms. After this period vibrotactile stimulation was delivered to a location on the hand or foot that was either congruous on incongruous with the image previously shown. Observers were instructed to respond by pushing a response button when the stimulus was detected.

### 5.3.2. Results

#### *5.3.2.1. Preliminary analysis and data screening*

Observers' results were individually grouped by condition (*hand*/hand, *foot*/foot, *foot*/hand, *hand*/foot (*visual cue*/tactile stimulus location) with any reaction time greater than three times the standard deviation of the mean of the total sample (representing trials in which the subject was not fully attending) being excluded from further analysis as were any reaction times less than 150ms (anticipatory responses). In addition to this, one observer's data were removed from the analysis altogether due to the abnormally high frequency of reaction times above the cut-off value.

#### *5.3.2.2. Effects of condition*

The mean reaction time was calculated for each of the remaining nineteen subjects and grouped by condition. A 2-way ANOVA (congruency [congruent and incongruent]) x (body part [hand and foot]) revealed a significant effect of congruency ($F(1, 18), 12.21, p<0.003$) and body part ($F(1, 18), 6.25, p<0.01$). From inspecting figure 5.3. (a) and (b) below it is evident the mean reaction for the congruent conditions is significantly shorter than incongruent for both the hand (a) and foot (b) locations as is the overall mean effect of congruency (c).

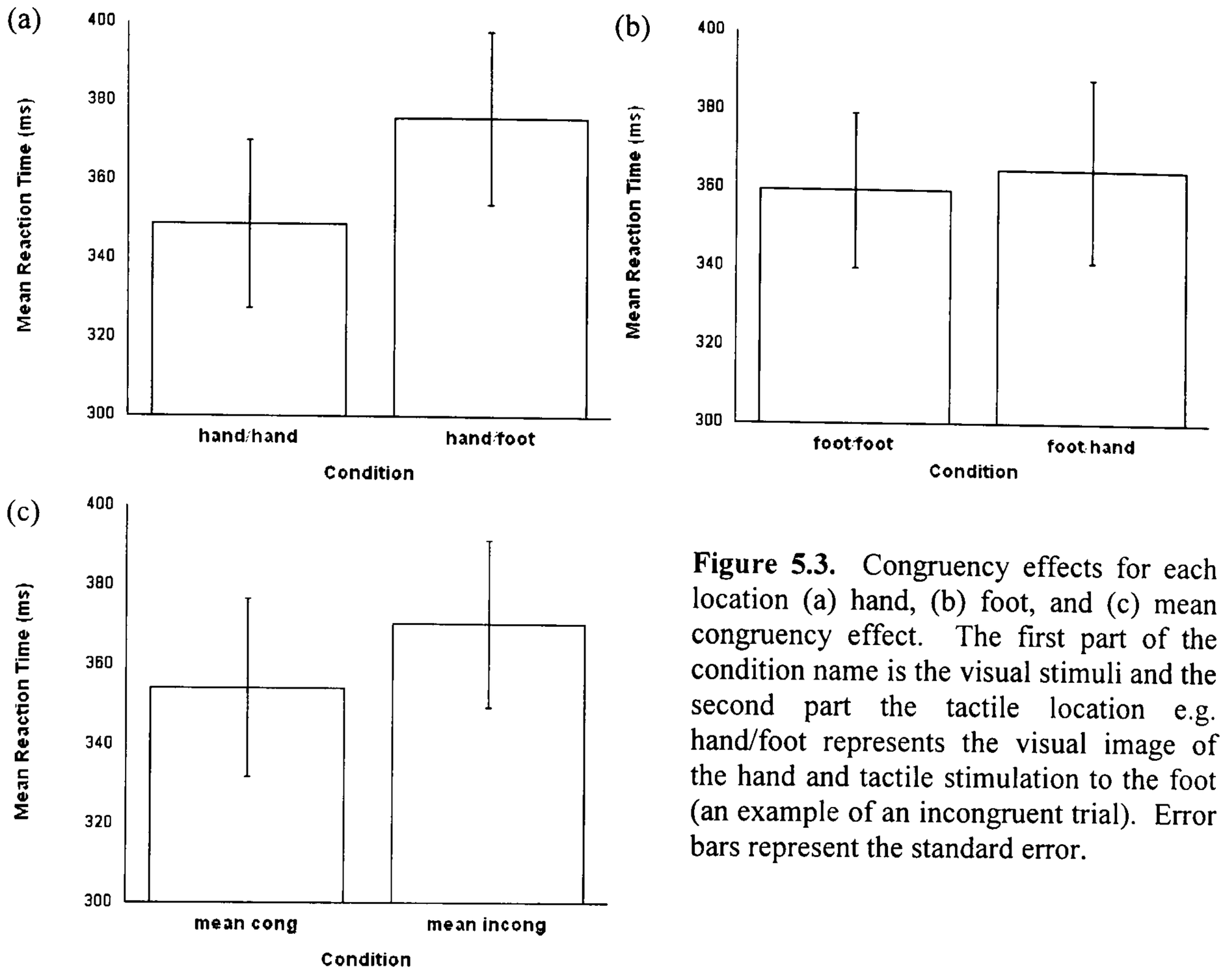



**Figure 5.3.** Congruency effects for each location (a) hand, (b) foot, and (c) mean congruency effect. The first part of the condition name is the visual stimuli and the second part the tactile location e.g. hand/foot represents the visual image of the hand and tactile stimulation to the foot (an example of an incongruent trial). Error bars represent the standard error.

## 5.3.3. Discussion

The results reveal a clear effect of body part cue congruency that would be predicted from the basic cuing paradigm of Posner (1980) whereby the presentation of an invalid cue results in a significantly longer reaction time compared to when a valid cue is presented, a finding that was the same for both stimulation to the hand and the foot. Furthermore, these findings echo those of previous studies such as Pavani, Spence and Driver (2000) that reaction time to a tactile stimulus is faster when the visual cue (LEDs in their study) is congruous with the site of stimulation.

This initial finding of congruency reinforces the concept of a visual-tactile cross-modal network and further, taken with the results of Kennett, Taylor-Clarke and Haggard (2001), reinforces the finding that visual feedback of a specific body part that is the site of tactile stimulation aids somatosensation. The findings from the current experiment can be interpreted alongside those of Kennet, Taylor-Clarke and Haggard (2001), despite the differences between the two studies (i.e. the present

study did not involve direct viewing of a body part but rather viewing a 'generic' example of the part to be stimulated), as it was the sense of vision that was guiding tactile perception in Kennet, Taylor and Haggard (2001) and tactile detection in the present study. Furthermore, the visual feedback in both studies was noninformative, that is they did not show the stimulation of the body site itself but rather the body site prior to stimulation.

The results of the present experiment are also comparable to those of both Tipper *et al.* (1998) and Tipper *et al.* (2001). In the first of these studies visual feedback (without proprioception) aided tactile detection when body parts were viewed (among other conditions) non-directly (via-video camera) and from allocentric viewpoints. Suggesting that cueing of the body part itself, rather than its viewpoint can have a strong effect upon somatosensation when it is not in conflict with contralateral body parts (e.g. right vs. left hand; discussed later with reference to Thomas, Press and Haggard, 2006).

The congruous hand condition compared to the congruous foot condition in the present experiment revealed significantly faster reaction times. We may speculate that it is possible that this difference may have occurred due to greater familiarity of hand images in agreement with the familiarity effects reported by Tipper *et al.* (2001). However, the cues in the current experiment were generic hand and foot images and further the task was not dependant upon identification of the observer's own body part over another's making this speculation difficult to substantiate further. Another possible explanation for this result is that the afferent connections from the foot to the central nervous system are simply longer than for the hand with increased conduction and hence reaction times for foot stimuli (Halliday and Mingay, 1964). Furthermore, the hand is represented by a substantially larger area in the somatosensory cortex representing the hand's greater level of sensitivity compared to the foot (Penfield and Boldrey, 1938). Therefore, the apparent differences in the reaction times of the congruent conditions may be caused by physiological factors rather than stimulus manipulations.

In a recent paper Thomas, Press and Haggard (2006) explored the concept of interpersonal body representation (IBR), the relationship between self and other body events (see also Haggard, Taylor-Clarke and Kennet, 2003). An example of this given in the paper is that if I saw you bang your knee on a table leg I may associate this with a tactile representation of the feeling I may have in my knee if I did the same thing. It is further suggested that the visual-tactile links such as those discussed in the present chapter not only are important for representing own bodies but also the bodies of others. This concept of IBR was investigated by Thomas, Press and Haggard (2006) using a cuing paradigm whereby a visual event cue was presented onto a corresponding anatomical location on a model's body. When this cue was congruous with the site of tactile stimulation on the observer's own body, reaction times were significantly faster.

This finding further builds on the concept of a specialist visual-tactile network where the image of the body, rather than simply a visual cue or orienting to the location of stimulation (see Kennet, Taylor-Clarke and Haggard, 2001), is an important factor within a crossmodal network between vision and touch. The key aim of this experiment was to demonstrate that images for which the EBA is selective can elicit an effect that demonstrates cross modal integration between these body images and touch. While it may be argued that the same results would occur if any type of cue was used, for example, words (e.g. 'hand' and 'foot') or LEDs and it is the effect of valid/invalid cues that is producing the results. The present findings demonstrate that images the EBA has been previously shown to be selective to can elicit a crossmodal effect (vision-somatosensory), regardless of whether other stimuli may also have produced this effect i.e. it is necessary to demonstrate that the body images can be used as cues. However, from this it is not clear where exactly the EBA in placed in such a network. While it has been demonstrated extensively in the literature and previous chapters that the EBA is highly selective for human body part images and is differentially selective for own and other body part images these functions have not been tied together and placed within a body-touch network. Therefore, the final chapter of this thesis will address this issue by looking at the response of the somatosensory systems, the EBA and other associated areas to attempt to establish a body-touch network.

# Chapter Six: Somatosensory Cortex and the EBA

## 6.1. Overview of Chapter Six

The experiment in the previous chapter demonstrated the clear link between the visual and somatosensory systems, the foundations of a crossmodal network in which visual cues have a direct influence upon responses derived from somatosensation. Such findings were consistent with those from the established literature that has shown viewing a body part while it is stimulated can aid somatosensation (Kennet, Taylor-Clarke and Haggard, 2001) and that there are different levels at which cues can aid somatosensation, for example, levels of familiarity (Tipper *et al.*, 2001). In the current chapter we explore what possible role the EBA may play in the network of vision and touch. Using an event related fMRI design we examine the response of the EBA and somatosensory cortex (SI and SII) to both observer's own vs. others' body part stimuli (of the hand and foot) and to tactile stimulation delivered to comparable sites on observers' bodies.

## 6.2. Structure and organisation of human somatosensory cortex

It has been established that cross-modal networks exist between visual and somatosensory systems and the role of the EBA among such a network has been implied. The following section provides a brief overview of the somatosensory cortex and the discriminative touch pathways. Following this, studies investigating the functional nature of the somatosensory system (with a focus on those using fMRI) will be discussed (including the organisation and role of the primary and secondary somatosensory cortices).

### 6.2.1. The basic somatosensory pathway

The somatosensory system is comprised of three pathways, namely discriminative touch, pain and temperature, and proprioception. Of these, only discriminative touch, which is of greatest relevance to the current thesis, will be described.

Discriminative touch refers to touch, pressure and vibration perception and is diagrammatically illustrated in figure 6.1.

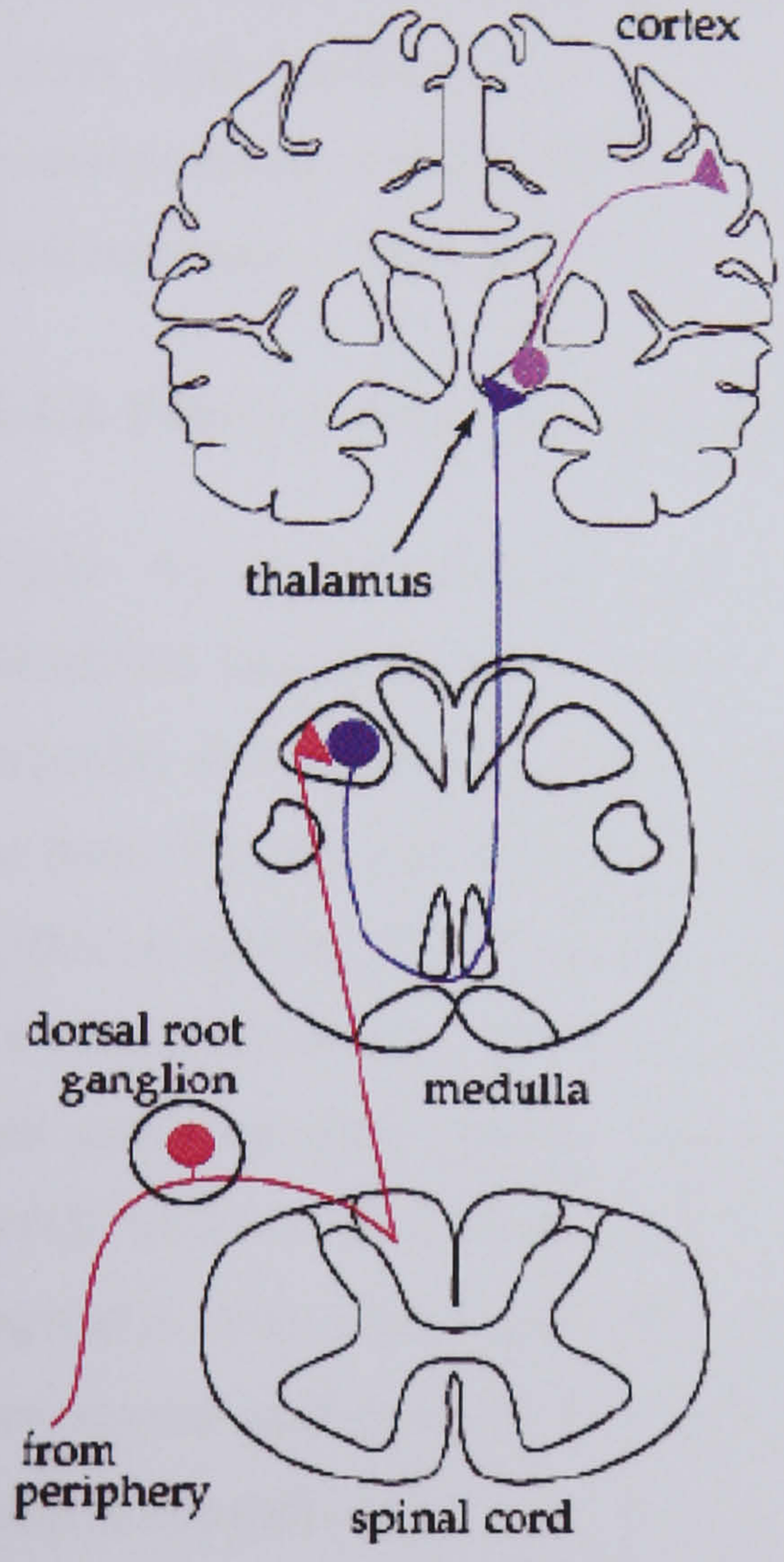



**Figure 6.1.** The basic somatosensory pathway. The path from bottom to top of tactile sensation from the periphery (pink), through the spinal column (purple) and into the cortex (lavender) (diagram from from Molavi, 1997)

With reference to figure 6.1., touch initiates responses from mechanoreceptors that are situated at different levels within the skin and are divided into four different categories: Meissner's and Pacinian corpuscles that are rapidly adapting and Merkel's disks and Ruffini endings that are slowly adapting. These peripheral tactile sensations enter the sensory axons from outside the spinal cord via the dorsal root ganglion. Every spinal nerve has one such ganglion. However sensory neurons are unique as, unlike most neurons, the signal does not pass through the cell body but rather passes directly to the dorsal part of the spinal cord and continues towards the brain via the primary afferents (shown in pink) which are the same axons that brought the signal to the cord itself.

The primary afferents synapse at the medulla where they become the secondary afferent (shown in purple). At this point the secondary afferents now cross the brainstem and form a new tract that ascends to the thalamus. It is here that the second synapse occurs and the final neuron (shown in lavender) passes on into the cortex and terminates at the appropriate homunculian location in the primary somatosensory cortex (SI) in the postcentral gyrus and also the secondary somatosensory cortex (SII).

### 6.2.2. Functional organisation of human somatosensory cortex

Early electrophysiological studies (for example Penfield and Boldrey, 1938) identified two main areas sensitive to somatosensory input. While these regions arguably still receive the greatest amount of attention, McGonigle (2004) states that at least five areas have been identified in primates. For example, Kaas and Collins (2001) identified SI, SII, a parietal ventral area anterior to S2 named PV, and 'bands' of cortex flanking SI. Furthermore, connectivity analysis has implicated as many as ten somatosensory regions (Burton and Sinclair, 1996) with somatosensory cortex subdivided into four anterior areas (Brodmann's Areas (BA) 3a, 3b, 1 and 2), two posterior areas (BA 5 and 7b), and four lateral regions (S2 anterior, S2 posterior, retroinsular and granular insula) all of which can be seen in the colour Brodmann map in appendix one.

#### *6.2.2.1 Primary somatosensory cortex – anterior regions (3a, 3b, 1 & 2)*

Primary somatosensory cortex is located on the post-central gyrus on the lateral bank of the right and left hemispheres posterior to the central sulcus and the posterior part of the central lobule on the medial surface and corresponds to Brodmann cytoarchitectural areas 3a, 3b, 2 and 1 (shown in the colour Brodmann map in appendix one). However, Kaas (1983) has commented that only area 3b should be considered as the true primary somatosensory area. Receptive fields in 3b are the smallest and become progressively larger from anterior to posterior (in the order of 3b-1-2; Sur et al., 1980). For the purpose of this thesis and the later definition of functional regions the term SI will be used to cover the activated regions of the postcentral gyrus rather than cytoarchitectural delineations (although Brodmann

areas will be referred to in order to aid analytical explanations in experimental chapters).

Through electrical stimulation of these regions Penfield and Boldrey (1938) created a somatotopic map of human SI the structure of which was determined by the functional importance of the body part and its sensitivity. This organisational structure is known as the 'homunculus'. Figure 6.2. (left) clearly shows the homunculus of the somatosensory cortex (and for comparison the motor cortex on the right of the figure) where the disproportionately large areas of the hand (notably thumb and forefinger) and lips can be seen reflecting the greater degree of sensitivity and hence larger somatotopic representation.

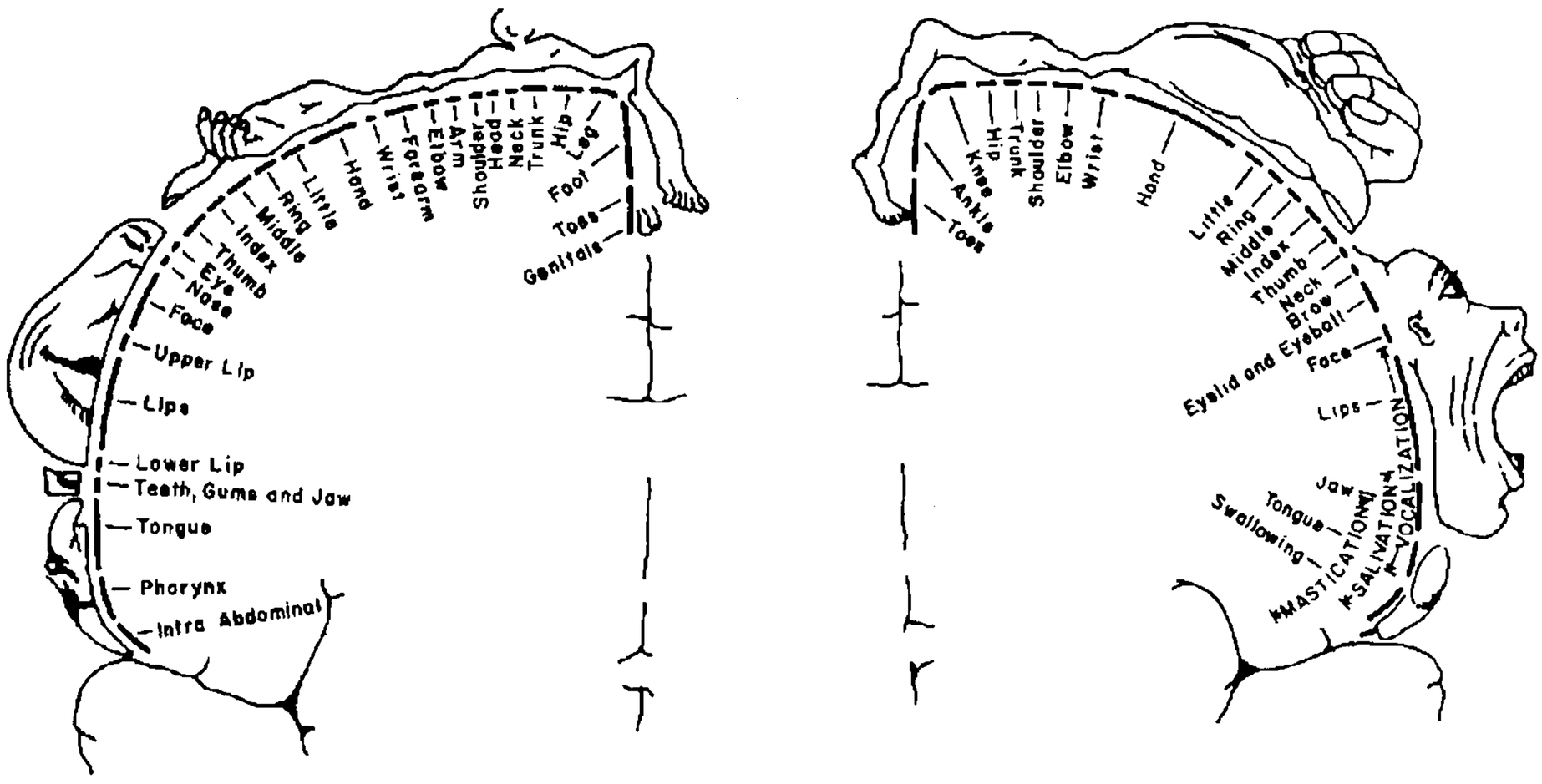



**Figure 6.2.** The somatosensory and motor homunculus. Penfield and Boldrey (1938) somatosensory (left) and motor (right) homunculus. Somatosensory cortex is located in the postcentral gyrus of the right and left hemispheres with the motor cortex anterior to this in the precentral gyrus of both hemispheres. Regions of the body are illustrated relative to the degree of representation they have cortically. In somatosensory cortex this is relative to how sensitive each region is to tactile stimulation with regions such as the lips and hand with the largest cortical representation.

*6.2.2.2. Posterior somatosensory regions (5 and 7b)*

Posterior to primary somatosensory areas 3a, 3b, 2 and 1 is area 5, which is itself anterior to area 7 (see appendix one). Located in the parietal cortex on the anterior bank of the intraparietal sulcus (IPS), area 5 has been identified as a somatosensory association region (Hyvarinen, 1982) and a region involved in motor actions involving visual guidance (Mountcastle et al 1975). The role of area 7a and 7b is less well defined. While it has been implicated in the integration of multiple modalities such as vision and touch, the exact nature of this process is unclear, although along with area 5, area 7 has been established in a network with SII (Wall, 1988). However, perhaps most relevant to this thesis is the report by Darian-Smith et al. (1996) that areas 7a and 7b are connected to the extrastriate areas of the temporal lobe (the location of the EBA).

*6.2.2.3. Secondary somatosensory cortex – the lateral regions (SII)*

The secondary somatosensory area (SII) was first reported in data acquired in studies on cats by Adrian (1940). In humans, SII is located on the dorsal wall of the lateral sulcus. In line with the post-central gyrus, this region does appear to have a rough somatotopic organisation but not to the same degree as SI (see Maeda, Kakigi, Hoshiyama and Koyama, 1999; and Ruben, Schwiemann, Deuchert, Krause, Curio, Villringer, Kurth and Villringer, 2001). However, more recent research has indicated that there are at least another two areas of the lateral sulcus separate from SII; S2p (Burton et al., 1995) and PV (parietal ventral area; Krubitzer et al., 1995). Both of these are responsive to tactile stimulation and, like SII, unilateral stimulation results in bilateral rather than unilateral activation.

### 6.2.3. fMRI compatible apparatus for investigating somatosensory brain function

Unlike the investigation of vision, audition and to an extent motor function, the investigation of the human somatosensory system involves a central difficulty pertaining to the apparatus used to deliver tactile stimulation to observers within the

fMRI scanner. Outside the scanner, studies that have investigated touch have used a variety of mechanised (such as solenoids; see Kennet, Taylor-Clarke and Haggard, 2001) and vibrotactile stimuli such as those used in the experiment in the previous chapter and also, for example Tipper *et al.* (1998, 2001). However, none of these stimuli may be used within the fMRI scanner because of the metallic components, most of which are magnetic and those that are not will at the very least conduct radio frequency that will increase the probability of artefacts within the images themselves. While this could be overcome by using a non-magnetic based imaging method such as Position Emission Topography (PET) such methods have there own disadvantages (e.g. poor resolution) that an experimenter may be looking to avoid by using fMRI.

However, recently there have been a number of studies in the literature that have used an MRI compatible fMRI tactile stimulator, each of which has satisfied the basic safety requirements for use in a magnetic environment. These devices may be grouped into; direct human manipulation, pneumatic, air-puff and Piezoceramic electric stimulators.

*6.2.3.1. Direct human manipulation*

The most basic delivery method for tactile stimulation in an fMRI experiment is via direct manual stimulation whereby an experimenter delivers the stimuli to the observer directly while standing next to them as they are being scanned. In a somatotopic mapping experiment Kapfer, Stippich, Hempel, Jansen, Heiland and Sartor (1999) delivered stimulation to the observer's toes via a brush controlled by the experimenter. This method of stimulation carries the advantage of being easy to organise and apply (no specialist equipment need be built for example), however, a number of difficulties may arise using this method.

Any tactile stimulus delivered in this method is under the control of the experimenter and therefore it is their responsibility to start and stop the stimulation at the correct time. Although this can be cued (such as an auditory cue) it limits the design of the experiment making more complex designs such as event-related ones (discussed later in this chapter) problematic, if not impossible. In addition, there are further

complications such as frequency and pressure of stimulation that if not held constant may confound the data. For example, it has been demonstrated with vibrotactile stimulation that varying the frequency of the stimulus activates different regions of the somatosensory cortex (i.e. SI or SII; see Francis, Kelly, Bowtell, Dunseath, Folger and McGlone, 2000). However, direct human manipulation may be preferable for some tactile fMRI studies such as those that have investigated the effects of acupuncture (for example see; Hui, Liu, Makris, Gollub, Chen, Moore, Kennedy, Rosen and Kwong, 2000).

*6.2.3.2. Pneumatically-driven tactile device (PDT)*

Mechanical, electronically, controlled tactile stimulators are most frequently used in tactile fMRI research, although equally are the most difficult to implement for reasons previously considered (such as the limitations on materials considering the magnetic field of the MRI scanner). One such stimulus device is that which is pneumatically driven (i.e. pressure driven e.g. air or liquid) and is referred to as a pneumatically-driven tactile device (PDT). In a recent paper Zappe, Maucher, Meier and Scheiber (2004) detail and evaluate the design of a specific PDT for use with fMRI that has been used previously in a study by Stolle, Aman, Baudendistel, Hoelzl, Kleinboehl, Maucher, Meier, Meyer and Schad (2001; note that this was using the design specified in a draft version of the Zappe *et al.*, 2004 paper).

As described in Zappe *et al.* (2004) tactile contact with the observer's skin is made via air-driven (pneumatic) pistons. Here only the air-tubes and pistons are within the magnet itself. The absence of ferromagnetic parts overcomes not only the safety issues but also problems of equipment induced artefacts that may occur when the equipment is so close to the subject and within the main field disrupting the image data acquired. The pressure timing is controlled by an interface unit within the faraday cage (the enclosure surrounding the room the MRI scanner that creates a shield against electromagnetic fields) but several meters from the scanner and the remainder of the computer controls are outside the faraday cage, within the scanner control room itself.

Using pressure of around 3-6 bar driven from an external compressor (and regulated within the faraday cage as described) drives 64 pistons in an 8 x 8 matrix. These produce a force of 1.3-2.7 N upon the skin which is reported to be detectable by observers (pistons automatically retract via a spring mechanism – this is a factor that must be considered in pneumatic designs).

Zappe *et al.* (2004) mention that there are a number of limitations with such a design one of which is the temporal resolution of the delivery device whereby patterns in the matrix can only be altered in 50ms steps and frequencies below 6Hz are undetectable (and thus a vibration frequency of 6Hz also). However, despite this limitation Zappe *et al.* detail a small experiment with the PTD, as described, whereby they delivered stimulation to observer's right and left abdomen. The results of this study revealed robust activation of the both the left and right somatosensory cortex, both SI and SII (slightly higher in SII).

It is apparent that the PTD is a suitable device for delivering tactile stimulation within an MRI environment, especially in experiments that may require 2D tactile displays such as those used in Braille. However, PTD may not be suitable for those requiring large ranges of frequency changes (to individually activate SI and SII) and in addition the expense and complexity of the build design for such a stimulator may make alternative devices preferable.

*6.2.3.3. Air-puff stimulators*

A method used in fMRI tactile stimulation, similar to the pneumatic device design, are air-puff stimulators. Here, compressed air not only drives the tactile stimulation but is the foci of tactile stimulation itself, i.e. small puffs of air are delivered to the observer via a delivery system. One such study that has used this method was conducted by Overduin and Servos (2004). Pulses of air were delivered to the hand via an array of 1152 tubes with a diameter of 1mm, fixed in place by a Plexiglass frame that was constructed to allow air to escape after it was delivered (an important feature allowing continuous pulses to be delivered, comparable to the retraction of the pistons in the Zappe *et al.*, 2004 PDT). Using this equipment, it was possible to

investigate digit somatotopy by attaching 16 of the 1152 mounted on the Plexiglass frame to each digit. Here, air delivery was controlled by computer housed outside the faraday cage (i.e. in the scanner control room) that maintained the pressure at between 35 to 45 p.s.i. This pressure was chosen to be the optimal balance between maximum detectability and minimal air spread.

The air was delivered as a sliding window, comparable to the phase mapping techniques using a flickering checkerboard to map the visual cortex (see Sereno, McDonald and Allman, 1994). Results showed functional voxels consistent with the tactile phase mapping for each digit stimulated. Therefore, this method of tactile stimulation appears to reliably localise areas of somatosensory cortex in a manner consistent with the safety and scanning considerations that have been discussed. However, similar to the pneumatic stimulators, there are temporal restrictions as well as restrictions concerning the frequency of delivery (that can affect the activation of SI or SII).

#### *6.2.3.4. Piezoceramic Stimulators*

Studies investigating the response to tactile stimuli that have been conducted outside the MRI environment such as Tipper *et al.* (1998, 2001) have typically used vibrotactile stimulation devices for their ease of construction, delivery and control of the stimulus as well as matching the objectives of the experiment itself. However, as has been highlighted, the same vibrotactile stimulators cannot be used within an fMRI experiment due to the electromagnetic field of the scanner within the faraday cage conflicting with the ferromagnetic construction of the tactile stimulators.

In order to overcome this difficulty, a number of recent studies (Francis *et al., 2000*; Harrington, Wright and Hunter-Downs III, 2000; McGlone *et al.,* 2002) have constructed vibrotactile stimulators using Piezoceramic materials. Piezoceramic is a non-magnetic material that, despite its absence of any internal circuitry, is able to produce internal displacement when a current is passed through it via means of non-magnetic wire that is RF shielded (such as a coaxial wire). Because they contain neither metal nor magnetic parts they are ideal for use with fMRI and operation

within both the faraday cage and the bore of the magnet itself (where the observer is located). When put under mechanical stress, piezoceramic material produces an electrical charge because of the special crystalline material within the piezoceramic device (Harrington *et al.*, 2000).

Two different types of piezoceramic stimulators have been used as vibrotactile stimuli in fMRI studies. The first of these is known as a piezoceramic wafer as used by Harrington, Wright and Hunter-Downs III (2000). The circular piezoceramic wafer is particularly delicate measuring only 5cm in diameter and 3mm deep is displaced by 150Volts. This large voltage causes a small mechanical displacement and subsequently (as in Harrington *et al.*, 2000) can only be successfully implemented in an fMRI design when the subject holds the wafer between two fingers, e.g. the thumb and forefinger, making wider application of this type of piezoceramic device limited. However, the unit price is comparatively cheaper than the second type of piezoceramic stimulator – benders.

In the paper by Harrington *et al.* (2000) they comment that although piezoceramic wafers can produce somatosensory activation, a bender may be preferable as it is driven by a lower current and results in greater displacement and detectability. Unlike wafers, piezoceramic benders are rectangular, typically measure H31.0 x W9.6 x D0.65mm and can be attached either directly to the observer (as in the present experiment) or via an additional device such as a plastic tip attached to the bender (for example see McGlone *et al.*, 2002).

Piezoceramic stimulators appear to overcome many of the problems that other types of stimulators encounter, in both temporal range, frequency of vibration and level of control they surpass the more complicated air-puff and pneumatic stimulators and are more replicable than any manual based stimulation methods. Furthermore, they do not interact with the magnetic field and therefore will not produce artefacts in the acquired MRI images. However, as has been discussed they do require a great deal of voltage relative to the degree of displacement gained, although this is less of a problem with the more expensive piezoceramic benders compared to the wafers. In

the present study we used a piezoceramic bender primarily for the ease of build and implementation within the scanner environment.

### 6.2.4. Using fMRI to investigate the representation of touch in the brain

The underlying physiology and basic homunculian arrangement of the somatosensory system has been discussed earlier in section 6.2. of this chapter. In the following, section relevant fMRI studies that have been employed to investigate the representation of touch in the cortex will be discussed to provide the reader with a comprehensive overview of the field.

#### *6.2.4.1. Using fMRI to investigate the cortical response to tactile stimulation*

fMRI studies of human somatosensory areas typically investigate both primary and secondary somatosensory regions, most likely because even unilateral tactile stimulation to a small area such as a finger tip will result in both the unilateral response of SI and the bilateral response of SII. One of the earlier studies to explore the use of fMRI for investigating tactile stimulation was conducted by McGlone *et al*. (2002) who used both piezoceramic-based vibrotactile and microstimulation (a technique whereby electrical pulses directly stimulate a nerve that a microelectrode is directly inserted into). It was reported that vibrotactile stimulation to the tips of digits two and five generated independent, significant clusters of ipsilateral activation in SI and SII as well as in additional cortical areas (BA43, pre-central gyrus, posterior insula, posterior parietal cortex-BA5 and posterior cingulate). Furthermore, they were able to subdivide SI into regions 3a, 3b, 1 and 2, in which they found activation to finger stimulation in a proportion of observers in all sub-regions. The results of the microstimulation reflected the vibrotactile results and predictably it was found that this activated smaller regions within the larger clusters identified in the vibrotactile study. This study demonstrates that fMRI can reliably localise small regions within SI and associated cortical areas and further, that simple vibrotactile stimulation results in active clusters that directly reflect the locus of activation reported from more complex microstimulation.

Digit somatotopy has also been demonstrated in a study by Overduin and Servos (2004) who used airpuff stimuli to deliver a sliding window of stimulation to the thumb, index and ring fingers. From this they were able to produce phase maps for each digit with the thumb and index finger showing the most response. These findings further demonstrate that fMRI can be used to increase the understanding of the basic somatotopic representation that was outlined by Penfield and Boldrey (1938). Furthermore, there have been a number of studies that have used fMRI to demonstrate the distributed representation of different body areas within SI. One such study was conducted by Stippich, Hofmann, Kapfer, Hempel, Heiland, Jansen and Sartor (1999) who, using a pneumatically driven tactile stimulator, were able to reliably localise postcentral lip, finger and toe representations in contralateral SI.

While the majority of tactile fMRI research has focussed on SI (i.e. 3a, 3b, 1, 2), there have been some studies that have revealed interesting insights about the secondary somatosensory area SII. Ruben *et al.* (2001) conducted a comprehensive fMRI investigation into the somatotopic organisation of the right hand second and fifth finger, and digit one of the right foot in SII. Analysis revealed a clear separation between the fingers and toe within an area corresponding to SII with the toe deeper within the lateral sulcus near the posterior pole of the insular [32 -20 6] and with the second finger more lateral within the parietal operculum [41 -27 6]. In addition, predicted, contralateral SI, activation was also reported. Furthermore, as has been demonstrated in other studies, activation was also reported in the posterior parietal lobe (both superior and inferior) as well as the insula, medial wall of the frontal lobe and cingulate sulcus. This evidence for gross somatotopic organisation of SII has also been reported by Disbrow, Roberts and Krubitzer (2000) who reported that hand, foot, shoulder, hip and face were represented separately in both SII and the adjacent subdivision PV.

Studies such as these have demonstrated that fMRI can be successfully employed to further the understanding of how tactile stimulation is represented in the human cortex. Further, it has shown that the human somatosensory system is composed of a number of regions that exist as part of a functional network and that in SII there exists a somatotopy that, at some level, reflects that of SI.

### 6.2.5. Evidence for crossmodal links between somatosensory areas and the LOC

It has been demonstrated extensively in the literature that the LOC is preferentially responsive to images of objects. However, objects are not only represented visually but also haptically (perception by touch) and therefore it is possible that the LOC may hold representations of an object in both the visual and haptic modalities. Both modes are similar in their approach to object recognition; for example the way in which they deal with extracting basic features such as contours and spatial relationships. Furthermore, it has previously been established that the LOC is responsive to object shape when it is inferred by motion, texture and luminance (Grill-Spector *et* al., 1998). In order to explore responsiveness of the LOC to somatosensory stimulation, Amedi, Malach, Hendler, Peled and Zohary (2001) scanned observers under four different conditions; (1) seeing visual objects; (2) seeing visual textures; (3) touching somatosensory objects; (4) touching somatosensory textures. Analysis revealed that there was distinct activation in both the occipito-temporal region and the post-central gyrus (SI) when one of the somatosensory conditions (condition 3 or 4) was contrasted with the rest fixation period. Furthermore, a specific functional region of the LOC was identified that was preferentially responsive to objects touched or seen. This finding suggests that the LOC is, at some level, involved in the haptic representation of objects and further implies that it is connected to somatosensory regions.

The results of this study demonstrated that consistent somatosensory activation can be found in the ventral stream in an area previously considered visual and further that the response was to tactile objects rather than simply textures. Similar results have been shown before although the locus of activation has been found in the intraparietal sulcus (for example see Roland, O'Sullivan and Kawashima, 1998). Therefore, Amedi *et al's.* (2001) findings suggest that the LOC is part of a multimodal network. It may be argued that the effect in the LOC here is one of visual imagery i.e. the object is visualised as it is being touched which hence is the cause of the LOC activation. However, even if this is the case it is still demonstrating that tactile perception is guiding visual imagery. Following on from

this, the experiments detailed within this chapter will investigate the possibility that the EBA and tactile regions (primarily SI and SII) form part of a multimodal body-touch network.

### 6.2.6. Key questions addressed and methods

In the current chapter the basis of a body-touch network will be investigated using vibrotactile and visual own/other body part stimuli. Firstly, using a hand and foot vibrotactile localiser to localise six key somatosensory areas namely unilateral hand and foot (SI) regions and bilateral (SII), which may also be divisible into hand and foot regions. Focusing upon these regions, their response to tactile stimulation will be assessed in order to validate them as being maximally sensitive to the correct stimuli. Following this, each of these ROIs will be investigated for their sensitivity to visual body part stimuli using a rapid event-related experiment containing observer's own and others' hand and foot images.

The second part of the analysis will focus upon the EBA itself. Therefore, after defining bilateral EBA, the ROIs will be explored assessing the response to both the tactile and the body part stimuli from the event-related own/other experiments. A final set of analysis in this chapter will use whole brain analysis to identify regions that are selective for own vs. other body part stimuli and explore which of these regions also respond to vibrotactile stimulation.

The intention of these three levels of analysis is that separately they will each contribute to the understanding of a body-touch network and combined they are able to build up a more comprehensive picture of how such a network may work/what regions may be involved.

## 6.3. Method

### 6.3.1 Observers

Eight observers were recruited to take part in the experiment (5 male). All observers had normal or corrected-to-normal vision. Scanning took place on the Siemens Trio 3T scanner at the CUBIC imaging facility, Royal Holloway University, UK. Observers were screened in accordance with the imaging facility's standard protocols and written consent was also obtained prior to scanning. Ethical approval was granted by the University of Surrey Ethics Committee.

### 6.3.2. Task and Procedures

The study detailed in the current chapter is composed of a number of different types of experiment each designed with the purpose of either functional localisation of a cortical region (EBA and Somatosensory regions) or exploring the functional properties of proposed regions (event related experiment). The EBA localiser experiment was used as in previous experiments (see chapter two to four) and in addition to this, a number of tactile localisers were used to locate both hand and foot SI and bilateral SII. Furthermore, an event-related task, involving own and other hand and foot images, was completed by each subject.

#### *6.3.2.1. The EBA localiser*

As has been done in previous experiments, an EBA localiser was carried out in order to successfully locate the EBA in each observer (detailed in chapter two, and also used to identify the EBA in the experiment detailed in chapter three and four of this thesis). Greyscale photographs were used (12.33° x 15.81° visual angle), a stimuli similar to those used previously to localise the EBA (Downing *et* al., 2001). However, in order to minimise total experimentation time here, unlike the localisers detailed in chapters two, three and four, only one EBA localiser run was used, as examination of previous data has shown one EBA run (as below) to be sufficient for activating both the right and left EBA.

The single localiser run lasted 340s (136 volumes; TR = 2500ms; 42 axial slices; 3mm slice thickness; 64x64 inplane resolution; 3x3x3mm matrix) and comprised four blocks of greyscale body part stimuli (B), four blocks of greyscale object stimuli (O) and five fixation blocks (+) that were organised within the run as +BO+BO+OB+OB+, an arrangement that achieved sufficient counterbalancing within the run (based upon examination of previous data). Each experimental block lasted 36s (12 volumes) and contained 45 exemplars of the category. Within blocks each stimulus was presented for 542ms, with an ISI of 125ms. Fixation blocks consisted of a fixation cross (1.42° x 1.42° visual angle) with a duration of 20s (8 volumes) and in order to control attention, observers were instructed to covertly name each stimulus in order to maintain attention during the task.

*6.3.2.2. Tactile Localisers*

Reliable delivery of tactile stimulation was achieved using a Piezoceramic bender (PL140; produced by Lambda Photometrics Ltd., UK) measuring H31.0 x W9.6 x D0.65mm and driven and controlled by a custom control unit (figure 6.3. below).

The unit allowed the experimenter to manually alter the amplitude (0-60v) and frequency (36Hz and 72Hz) of the bender displacement which was 315um at 36Hz and 158um at 73Hz. This control-unit interfaced with a PC by means of a National Instruments digital output unit (National Instruments BNC-2090) that was driven by a purpose coded Visual Basic program.

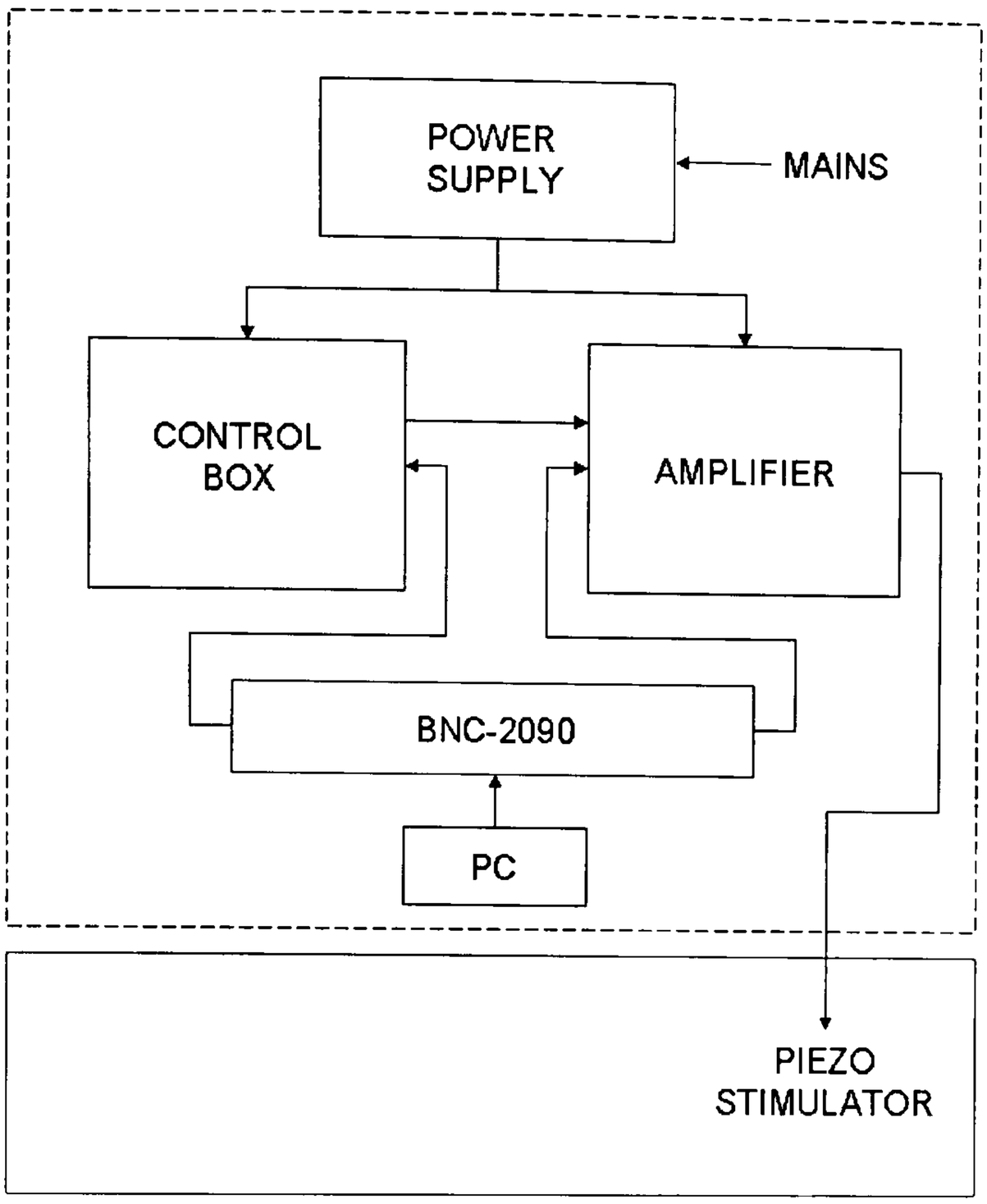



**Figure 6.3.** Vibrotactile stimulator used in localising SI and SII. The figure represents the Piezoceramic stimulator apparatus whereby a PC controlled the digital output unit BNC-2090, this in turn switched the control box on and off. At the control box frequencies of the stimulator could be manually changed. The dashed line represents the control room in which all the apparatus was housed. A stimulator was connected to the apparatus via RF-shielded coaxial wire that passed through the control room into the faraday cage where the scanner was housed.

The bender was connected to the control unit by a single 10m coaxial RF shielded wire that passed through the Faraday cage into the control room (see figure 6.3. below) so that only the bender itself was within the Faraday cage. Contact with the tactile stimulator and the skin was achieved using surgical tape to directly apply the piezoceramic bender to the skin. However, pilot testing revealed that the weight of the wire placed the bender under a great deal of stress that resulted in stress fractures in the unit. To combat this difficulty a 'splint' was attached spanning part of the connecting wire and the bender.

Each observer completed four tactile localiser runs within the experiment. In two of these runs the bender was attached to the base of the thumb on the lateral surface of

the right hand (figure 6.4.a) and in the remaining two runs it was attached to the top of the dorsal surface of the observer's right foot (figure 6.4.b).

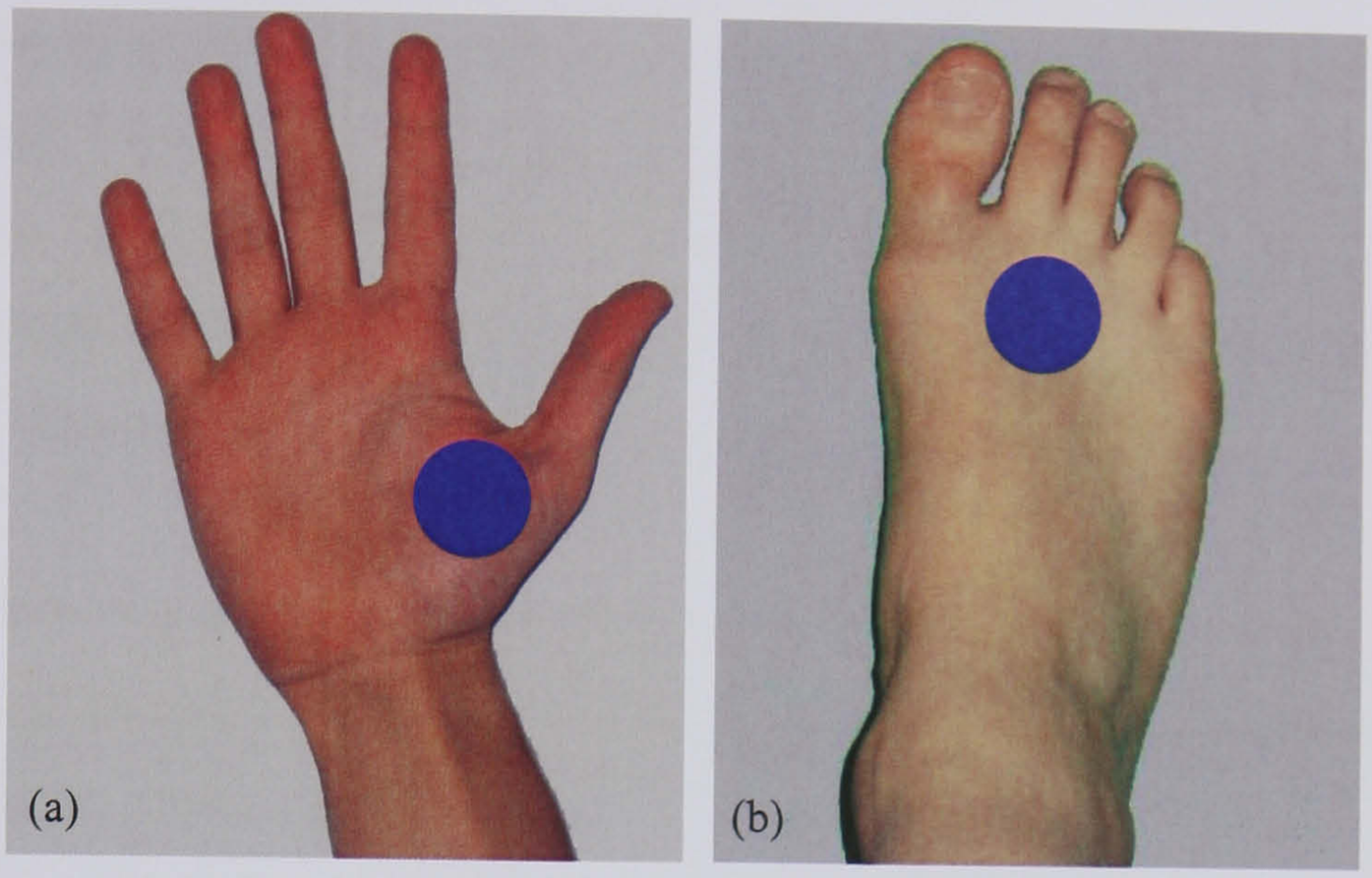



**Figure 6.4.** Location of the vibrotactile stimulators indicated by the blue mark on the hand (a) and foot (b) of each observer during the tactile localiser experimental trials.

It is important to note that by measuring responses from both locations in separate scans this may have had the effect of making the contrasts weaker. However, within-scan contrasts was restricted as the current apparatus only allowed one piezoceramic unit to be attached/run at once. In both the first hand and foot run, stimulation was delivered at 36Hz and in the second run at 72Hz; a manipulation that was intended to aid in the identification of SI and SII respectively. Each of these runs lasted 436s (172 volumes; TR = 2500ms; 42 axial slices; 3mm slice thickness; 64x64 inplane resolution; 3x3x3mm matrix) and was composed of alternating blocks of no stimulation lasting 30secs (12 volumes) followed by 10secs (4 volumes) of tactile stimulation (each run both beginning and ending with no stimulation blocks).

*6.3.2.3. Own-Other Event-Related (ER) Runs*

In addition to completing the EBA and tactile localiser runs, each observer completed one event-related (ER) run in which images of their own right hand and foot (photographed prior to the experiment) were shown in conjunction with another (previous observers) hand and foot (all images were colour photographs measuring

12.33° x 15.81° visual angle and presented for 500ms). Each of the ER runs lasted 825s (336 volumes; TR = 2500ms; 42 axial slices; 3mm slice thickness; 64x64 inplane resolution; 3x3x3mm matrix) and was composed of 40 blocks own hand; other hand; own foot; other foot images (160 in total) and a further 160 fixation only blocks with each block only lasting one volume (2500ms). This equal number of fixation blocks acted as null-trials that were included in the counterbalancing procedure (explained subsequently) and which can be used to aid deconvolution of the timecourse during analysis, when such an analysis is necessary.

For each observer, a separate run order was generated prior to the experiment using a counterbalancing program (courtesy of David Andresen at the Grill-Spector Lab, Stanford University) that applied a one-back history counterbalancing constraint upon the pseudo-randomising of the stimuli. The one-back counterbalancing ensures that every trial type is preceded by every other type equally as often. For example, 'hypothetically' if there are three trial types (A, B and C) then using the one-back counterbalance AA, BA and CA will occur equally as often. The reason for using this is that it ensures the analysis is unbiased because all combinations happen equally. For example if A was always preceded by C then the HRF in the analysis would not reflect the response of A but in fact of CA. By having all trials precede A equally as often then when estimating A across the entire experimental run all other trial types are effectively 'cancelled out' leaving just the response of the A trial.

*6.3.2.4.* Analysis of the ER data

Including null trials helped to vary the onset of the four experimental conditions/events and the one-back procedure aided in producing effective counterbalancing. Analysis of these data were carried out using a standard GLM analysis in Brainvoyager QX, whereby the HRF is fixed rather than separately estimated for each event (a more complex analysis that may be used when there are multiple event types of differing lengths, events are exceptionally short, post-hoc sorting is required etc.), as this was sufficient for analysing this experiment. Here, for each condition/event type a model timecourse is defined and convolved with an HRF, events of the same type are subject to the linear summation of the modelled

BOLD response (i.e. that the response is increased and prolonged after multiple trials of the same type; see Dale and Buckner, 1997). This is illustrated in figure 6.5. below, where the modelled response to the 'yellow' condition is represented by the blue line (white represents the actual data). Here the linear summation can be seen when events of the same type are next to/very close to each other.

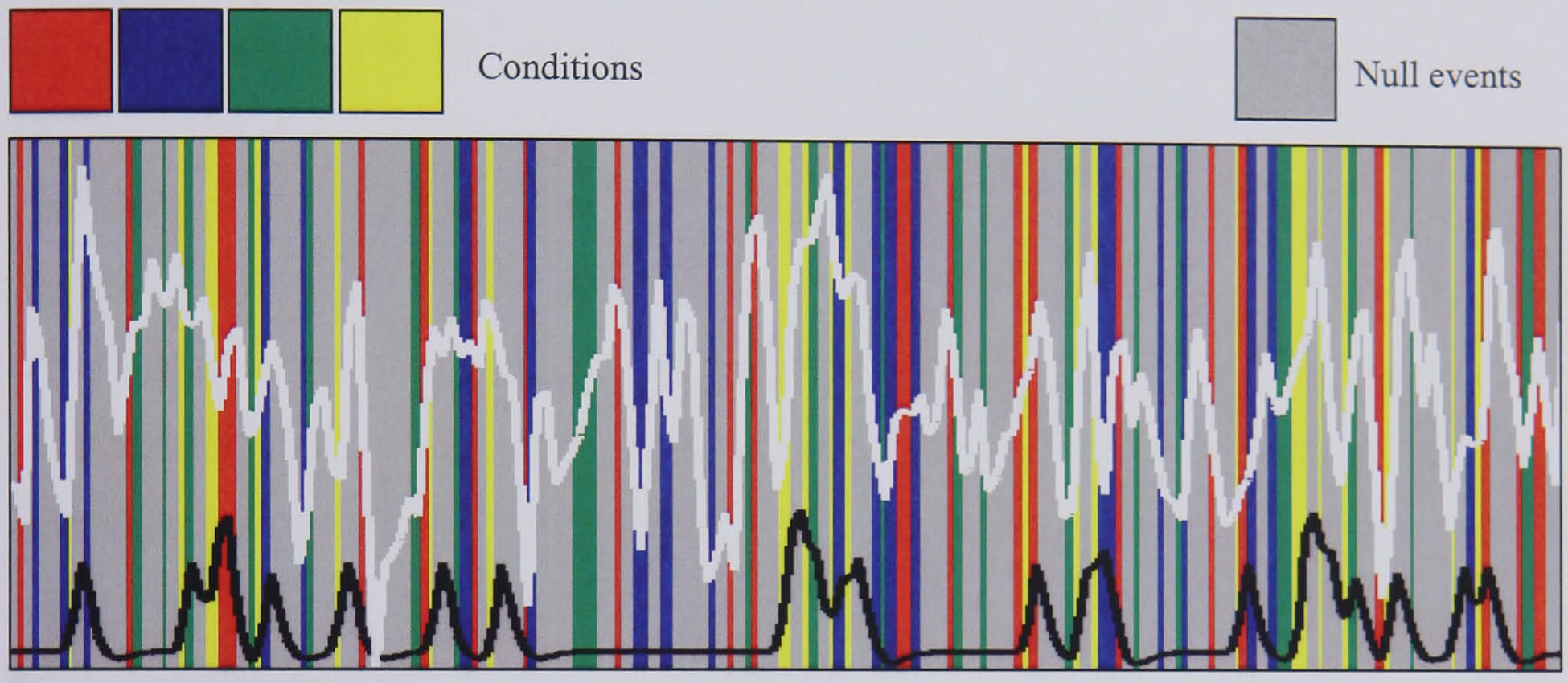



**Figure 6.5.** Example of part of a rapid-ER run. The red, blue, green and yellow bars represent an a conditions/events, grey bars represent null trials. The blue line at the base of the figure represents the modelled timecourse convolved with the HRF for the 'yellow' condition. Here the linear summation can be seen for conditions of the same type next to/close to each other. Using this method it is possible to extract the data that occurred during each condition despite the rapid presentation of events.

### *6.3.2.4.* Behavioural task

Observers were instructed prior to the study to respond to each image that was presented. If the image was either their own hand or foot the first button on the (four button) response box was to be pressed and if the image was not their own hand or foot they were instructed to press the second button on the response box. All observers' responses were recorded along with a reaction time for response to each image.

## 6.3.3. fMRI Pre-processing

Data were pre-processed (and analysed) in Brainvoyager QX using 3D motion correction with sinc interpolation and corrected for slice timing and scanning order

(ascending, interleaved). Linear trend removal and a high pass filter (with a cutoff of 0.0088 Hz) were also applied. Functional data were aligned to a high resolution anatomical scan (1x1x1 mm matrix, 256x256 inplane resolution, TR 1900, TE 5.57) taken in the same session. This was subsequently normalised to a Talairach template (Talairach and Tournoux, 1988) and the parameters applied to the co-registered functional data. Spatial smoothing, using a 6mm FWHM Gaussian spatial filter, was then carried out in the 3D domain once the data had been aligned to the observer's 3D anatomical scan. The design of the study was such that all runs across experiments contained the same scanning parameters (TR = 2500ms; 42 axial slices; 3mm slice thickness; 64x64 inplane resolution; 3x3x3mm matrix) allowing all runs to be coregistered to the first of the observer's runs, a procedure that is reported to substantially improve the effectiveness of the normalisation procedure and associated combining of runs carried out during analysis.

### 6.3.4. Behavioural data from ER experiment

Observers' responses to the own/other hand/foot stimuli were recorded during the ER experiment and from these data it was revealed that observers correctly recognised their own hand on 98% of trials (mean RT: 784.5ms) and their own foot on 97% (mean RT: 776ms) of trials. Similarly they identified another's hand and foot on 97% (mean RT: 821.6ms) and 94% (mean RT: 788.9ms) of trials respectively. From figure 6.6. below it is evident that the mean reaction times between the own and other body part stimuli were highly similar and did not differ significantly. However, the high proportion of correctly identified images confirms that observers were maintaining attention throughout the task and carrying out the task as instructed by the experimenter.

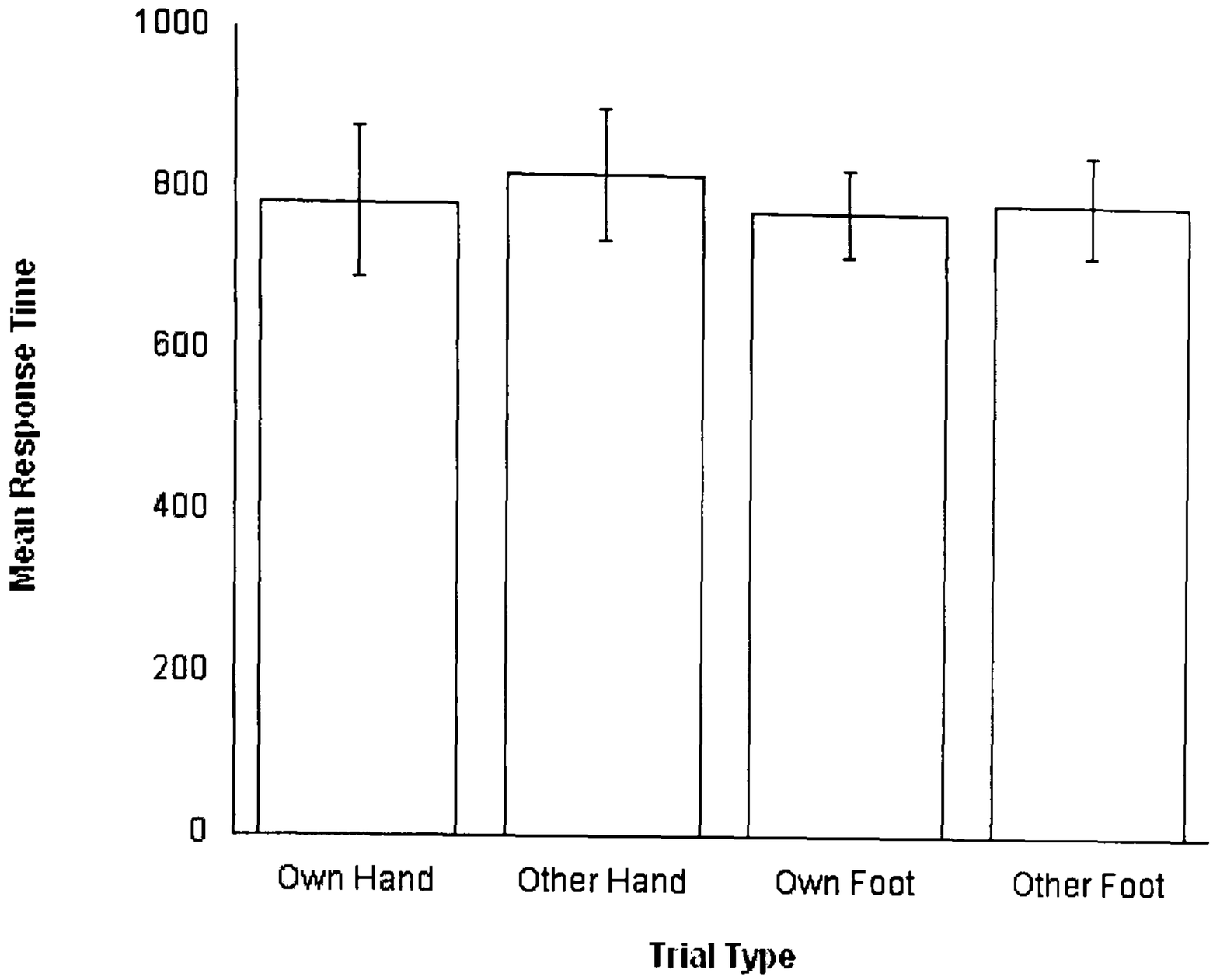



**Figure 6.6.** Behavioural data acquired during the ER runs to own and other body part stimuli. Graph shows the mean reaction time (RT) to the four different trial types present in the ER

## 6.3.5. Motor Control Task

In addition to the main experiments, a small motor control task was carried out to establish that the tactile regions identified in the localising runs were areas of the postcentral gyrus (somatosensory cortex) rather than precentral gyrus regions of the primary motor cortex. Such a validation procedure is often carried out in somatosensory fMRI experiments (such as Maldjian *et al.*, 1999) where a degree of motor cortex activation is expected as a by-product of the tactile stimulation.

### *6.3.5.1. Observers, Task and Procedure*

Two of the eight observers that participated in the study also completed an additional set of runs to those that have been detailed. In these runs observers were required to complete a self paced (right) hand and (right) foot movement task to aid the identification of the (left) primary motor cortex that would allow a comparison to the somatosensory activations to be made.

Each of the motor runs lasted 436s (172 volumes; TR = 2500ms; 42 axial slices; 3mm slice thickness; 64x64 inplane resolution; 3x3x3mm matrix) and composed of alternating blocks of no movement lasting 36secs (12 volumes) followed by 10secs (4 volumes) of self paced motor stimulation (each run both beginning and ending with no stimulation blocks). Observers were told to remain motionless when 'STOP' was presented on the screen within the scanner (i.e. the no movement blocks) and to move either the hand or the foot (observers were instructed which prior to each run) when 'MOVE' was presented on the screen. Prior to scanning observers were trained in the motor actions that were required. For the hand movement observers were instructed to repeatedly flex and un-flex their fingers of the right hand at their own pace throughout the 'MOVE' period while in the foot condition a similar flexing and un-flexing of the toes of the right foot was carried out during the 'MOVE' period.

*6.3.5.2. Motor and Tactile ROIs*

Following pre-processing, data from both observers' motor runs were grouped and two contrasts carried out. The first contrasted activation in the MOVE period for the hand with that of the foot to localise the hand motor area and the second used the inverse contrast to localise the motor foot area. Both contrasts revealed clusters of activations in the right hemisphere that matched the location of the primary motor cortex. In figure 6.7. below the location of hand (a-b) and foot (c-d) motor areas are shown (in red) alongside the identified tactile areas (in blue – localisation described in 6.4.1) for both hand and foot (for clarity both are shown alongside the tactile (e) and motor (f) homunculus).

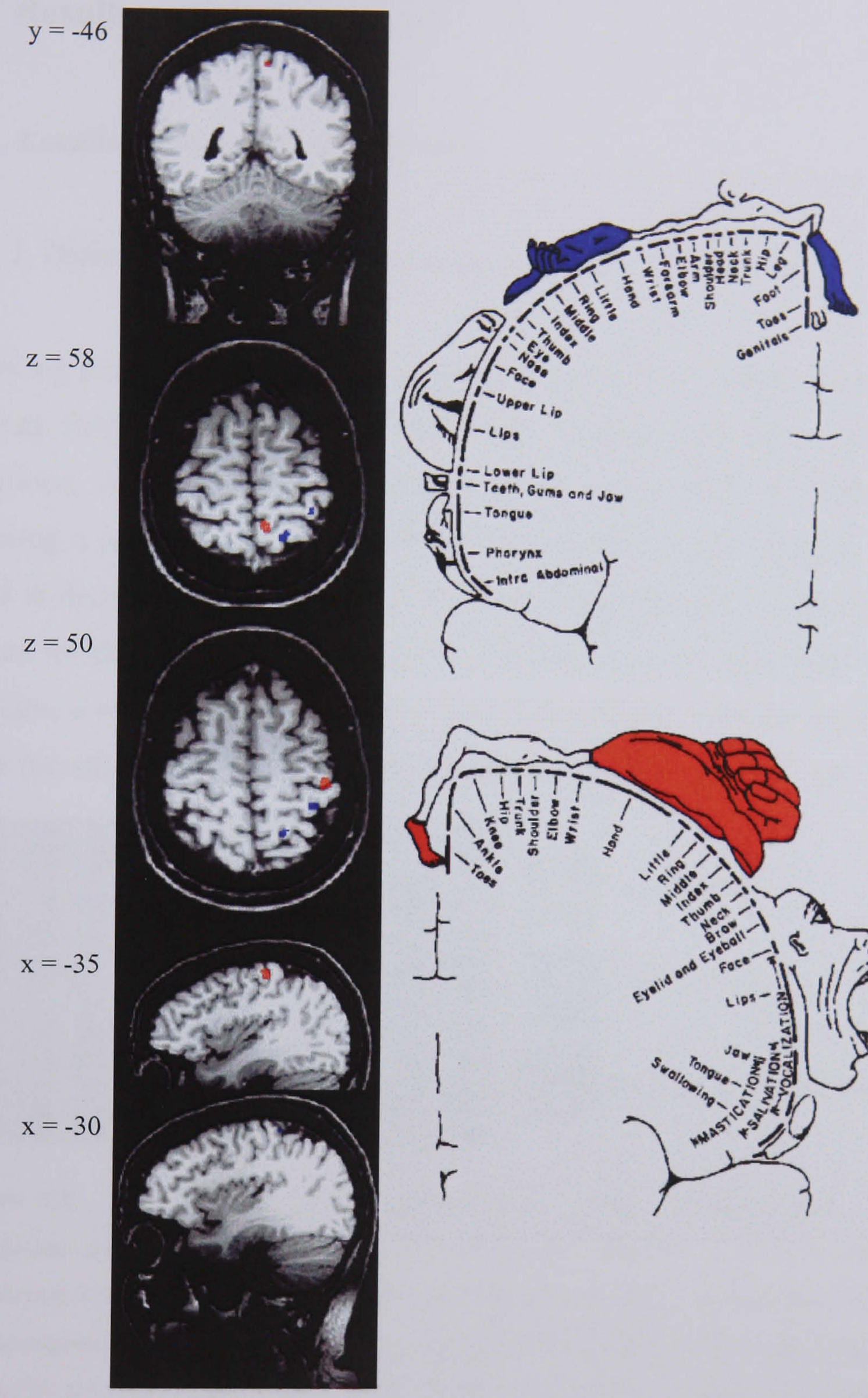



**Figure 6.7.** Motor compared to somatosensory activation in the left hemisphere. Motor (red) and tactile (blue) regions of the left hemisphere as localised in group contrasts for hand and foot stimuli. (a) to (b) (d – 2 sagital slices) represent the motor and tactile hand regions of the left hemisphere. In those images where two tactile (blue) areas can be seen the foot area is the cluster closest to the corpus-callosum. The corresponding tactile regions are highlighted in (e) on the somatosensory homunculus and likewise on the motor homunculus in red on (f).

## 6.4. Results

### 6.4.1. Localising Somatosensory Areas

#### *6.4.1.1. Defining the tactile runs for analysis*

Following pre-processing it was necessary to specify the design of each run type to facilitate further analysis. All of the tactile localiser runs were composed of two conditions; no stimulation and stimulation (at either 36Hz or 73Hz). However, following a period of tactile stimulation a refractory period exists in which a HRF signal is detected despite a cessation in actual stimulation. Therefore, in order to account for this, so that any baselines used in later analysis were 'true' no stimulation baselines, a period of 15secs (6TR's) was modelled, as shown in blue in figure 6.8. below (no stimulation is shown in grey and tactile stimulation in cyan).

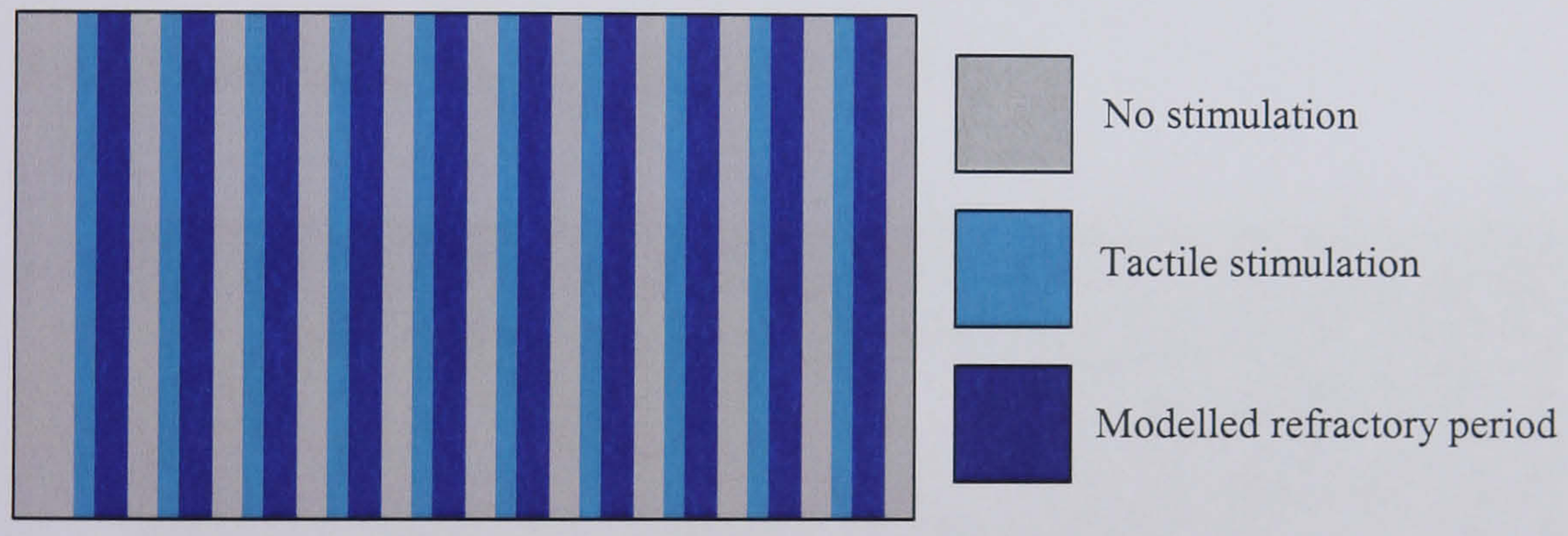



**Figure 6.8.** Experimental design representing one tactile stimulation run. Periods of no stimulation lasting 30secs (12TR's) were interspersed with 10sec (4TR's) periods of tactile stimulation at either 36Hz or 73Hz to the left hand or foot. The modelled refractory period shown in blue represents an additional 'dummy' condition added at the analysis stage to represent the time it takes for the haemodynamic response to the tactile stimulation to return to baseline.

#### *6.4.1.2. Establishing somatosensory ROIs*

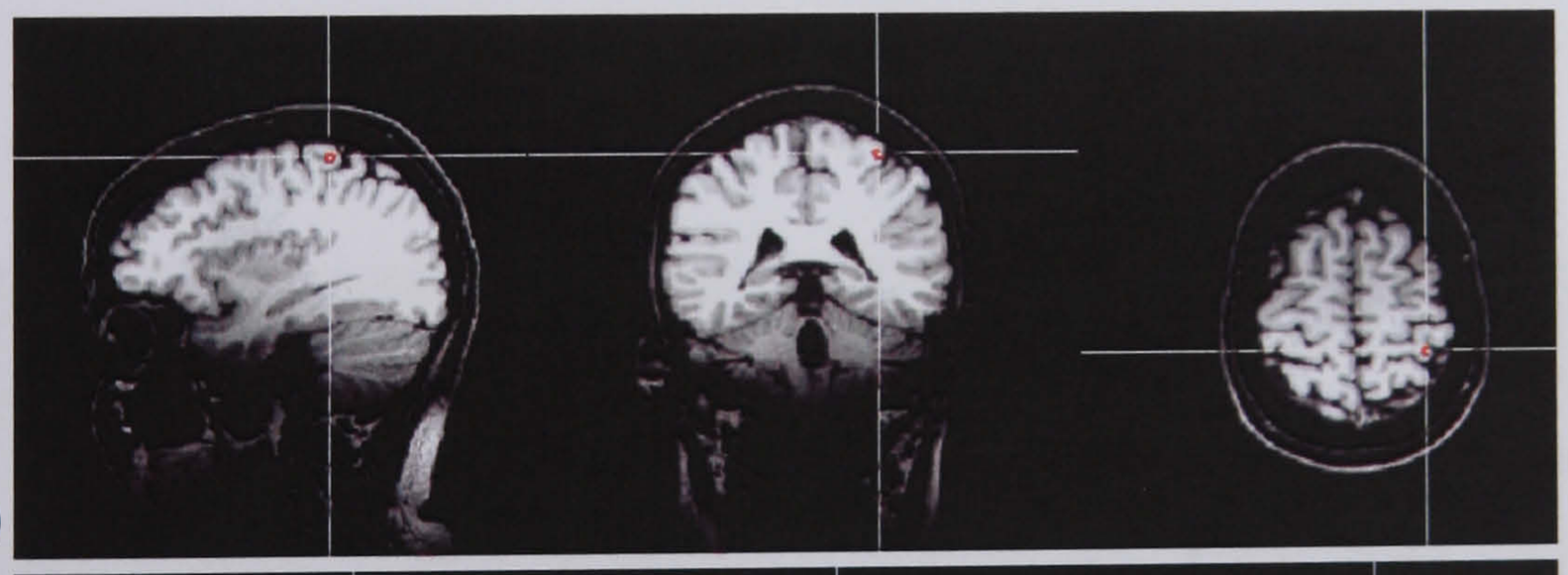
In a number of comparable studies that have used vibrotactile stimulation in fMRI somatotopy (for example see Francis *et al.*, 2000 and McGlone, 2000) the contrast of tactile stimulation condition minus no stimulation condition has been used rather than tactile stimulation condition A (e.g. hand) minus tactile stimulation condition B (e.g. foot). Here this approach was used in a group analysis combining data acquired

during the tactile runs of all eight observers and from this two contrasts were carried out: (1) tactile hand stimulation (both frequencies) minus no stimulation (in the hand condition and not including the modelled refractory period) and (2) tactile foot stimulation data from both frequencies combined minus the no stimulation periods (excluding the modelled refractory period) that occurred in the foot stimulation runs.

Activation maps produced as a consequence of these contrasts were thresholded to $p<2.1^{-9}$ revealing a number of clusters of activation. The details of these clusters including the location of the most significant voxel and anatomical location for both the hand and foot contrasts are displayed in appendix two (hand) and three (foot). From this data the six somatosensory regions that we were interested in further examining were identified: (1) hand SI and (2) foot SI of the left hemisphere, (3) hand and (4) foot SII of the right hemisphere and (5) hand and (6) foot SII of the left hemisphere.

*6.4.1.3 Hand and Foot SI of the left hemisphere*

(a)



(b)

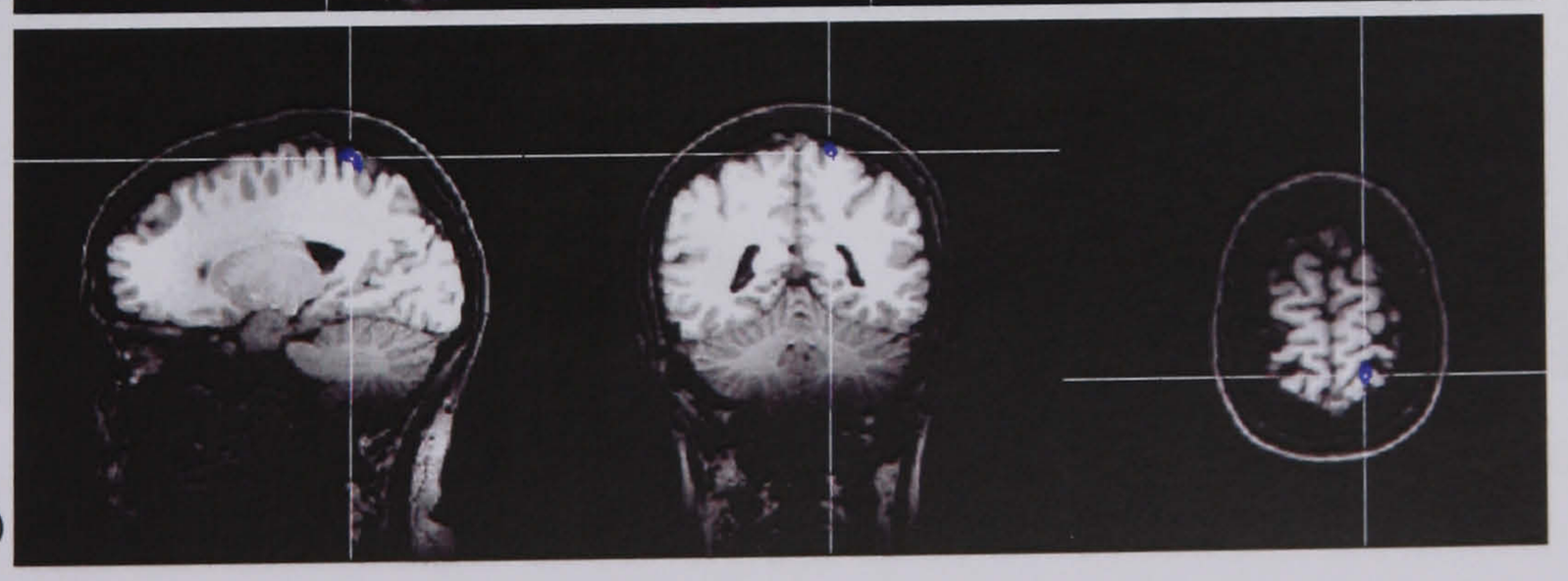


**Figure 6.9.** Localisation of SI overlaid onto a standardised Talairach brain. Average Talairach co-ordinates from all observers showing the location of a cortical region of the Postcentral gyrus – SI (primary somatosensory cortex) primarily activate by tactile stimulation to the (a) right hand [-33, -37, 58] and (b) right foot (b) [-18, -43, 64].

Figure 6.9. above shows the location of the primary somatosensory hand region (a) and foot region (b) in the postcentral gyrus. For the hand SI region, the mean location of the most significant voxel of this region was [-33, -37, 58] (Figure 6.4.a) and the corresponding foot area of SI was located at [-18, -43, 64] (Figure 6.4.b).

*6.4.1.4. Bilateral hand and foot secondary somatosensory cortex (SII)*

The nature of SII with regards to somatotopic organisation is significantly more unclear than the homunculian organisation of SI although some degree of somatotopic organisation has been reported (for example see Disbrow, Roberts and Krubitzer, 2000). Because of this, the intention was to identify areas of activation within SII sensitive to either hand or foot stimuli. However, the activation map results in appendix two and three revealed extremely large regions of activation in the area of lateral sulcus making it difficult to establish the possible different hand and foot regions. For this region the most significant voxel in each cluster was identified for both the hand and foot contrasts in each hemisphere and then from this a bounding box ($5mm^3$, thus containing 125 voxels) centred upon this voxel was used to establish the separate bilateral SII ROIs. The results of this process are shown below in figure 6.10.

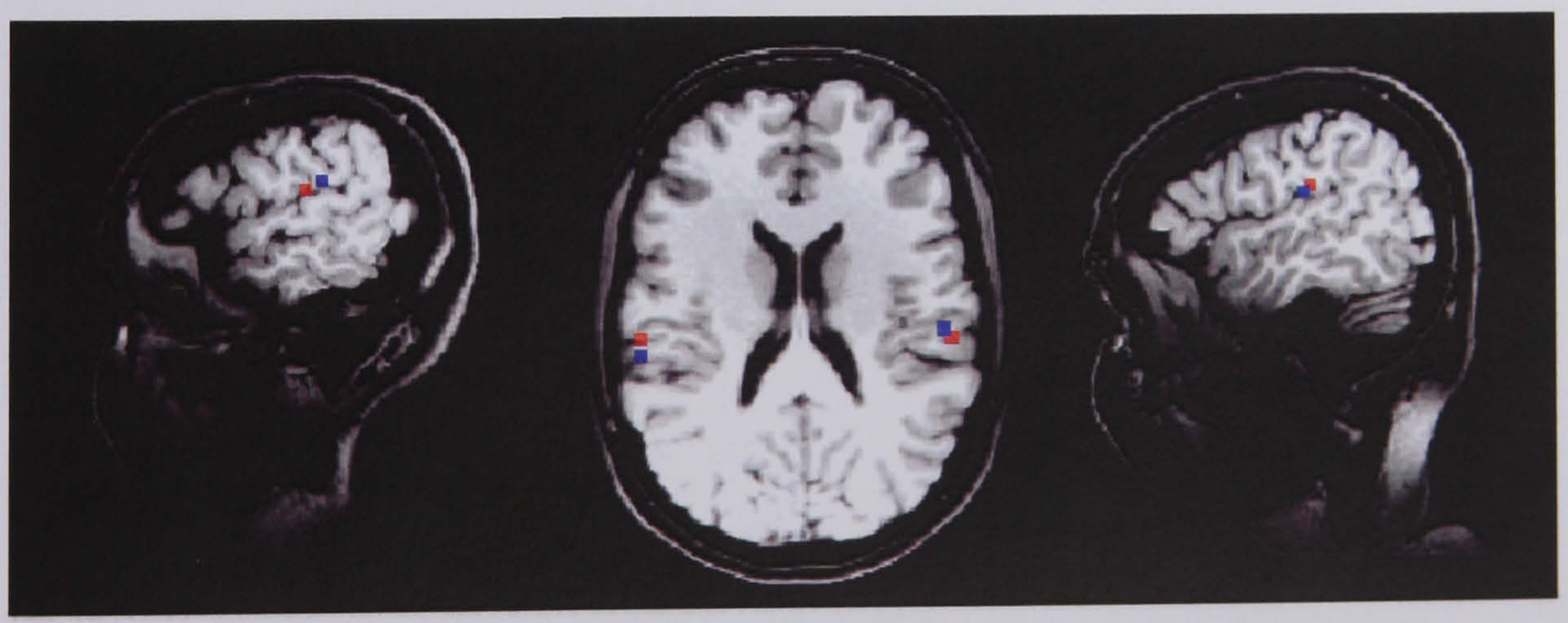


**Figure 6.10.** Localisation of SII overlaid onto a standardised Talairach brain. Hand (blue) and foot (red) regions of SII identified using the hand minus no activation and foot minus activation contrasts respectively. The most significant voxel in each location was identified and a $5mm^3$ bounding box centred upon it to establish the ROI (containing 125 voxels). In right SII (a and b) the hand region was identified at [57, -28, 22] and the foot at [57, -22, 19], likewise in the left hemisphere SII (b and c) the hand was identified at [-51, -19, 19] and the foot at [-54, -22, 22].

The location of the peak/most significant voxel of the ROIs displayed in figure 6.9. were for the left hemisphere SII: hand [-51, -19, 19] and foot[-54, -22, 22], for the right hemisphere SII: hand [57, -28, 22] and foot [57, -22, 19].

### 6.4.2. The tactile and visual responses of somatosensory ROIs

In unravelling the possible role somatosensory regions may play in a body-touch network the six main tactile areas as detailed previously were investigated; firstly, their response to the touch stimuli (to validate the areas) and then to the body part stimuli used in the own/other ER runs.

#### *6.4.2.1. Tactile response of unilateral SI: hand and foot*

From both the group unilateral hand and foot ROIs in the left hemisphere each observer's tactile data were extracted[1] which contained the fMRI response to the hand and foot vibrotactile stimulation at both 36Hz and 72Hz. Figure 6.11. (a) and (b) represent the mean timecourse for both the hand and foot respectively where (c) and (d) represent the peak PSC response[2] across the hand and foot conditions respectively.

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[1] Data was extracted from all ROIs using Brainvoyager QX's Event Related Averaging method. This method produced a mean timecourse for each condition within the data converted to PSC using the 'epoch based' method whereby the value preceding each experimental block is used to calculate the baseline value for each epoch.

[2] Peak PSC response was derived from the point in the data where the HRF peaks i.e. around 5-6 seconds as observed in the timecourse for each condition.

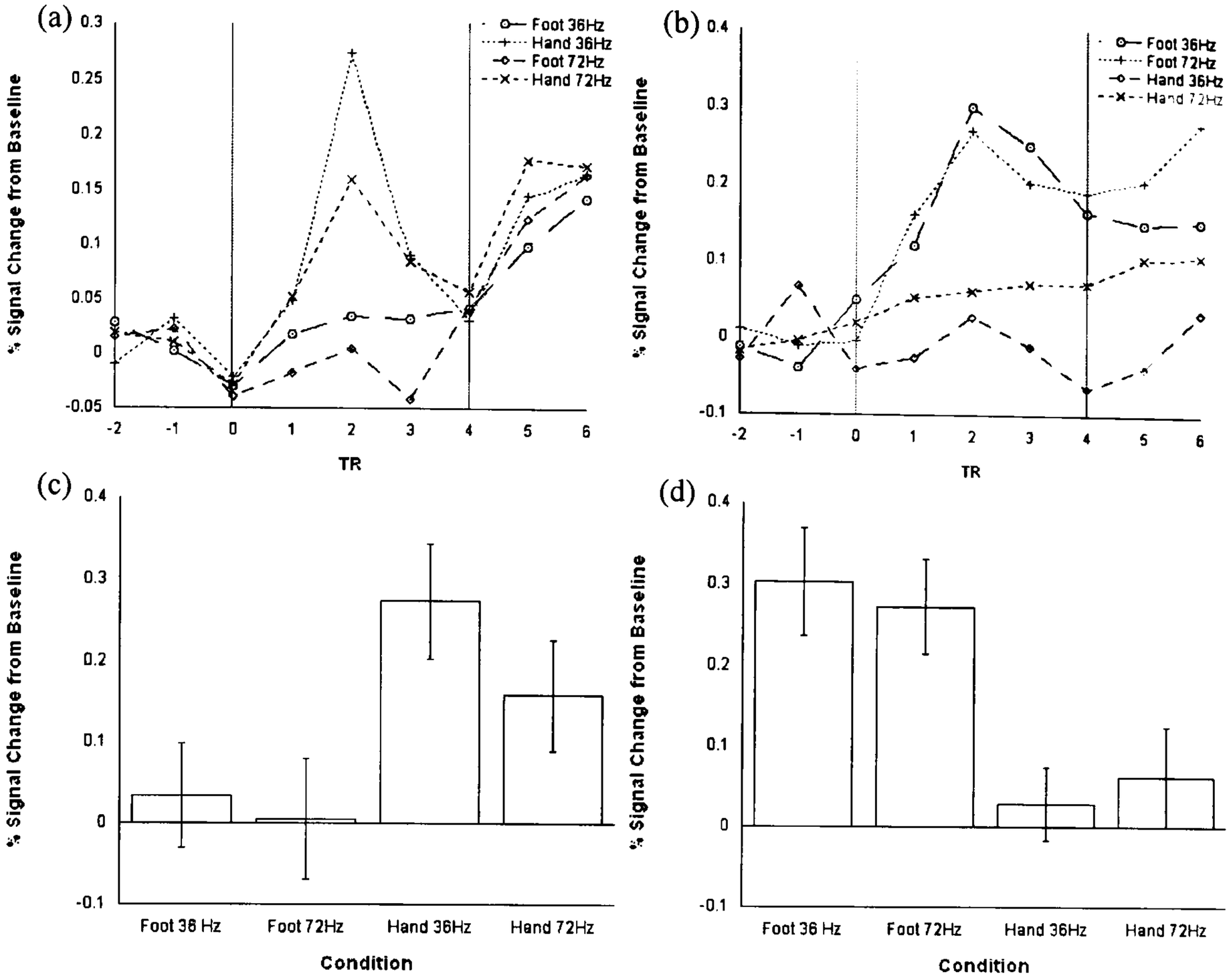
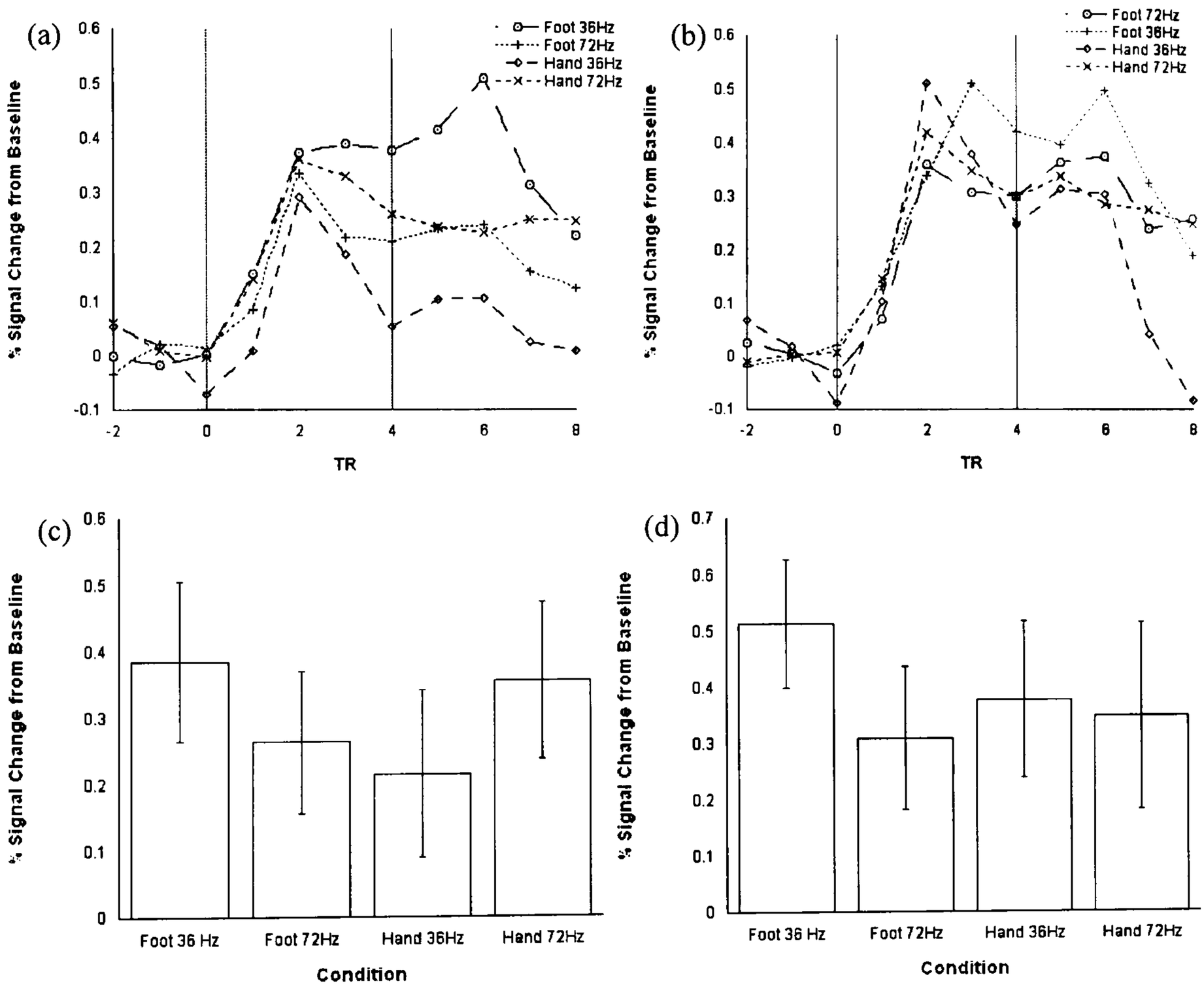



**Figure 6.11.** Tactile response of hand and foot SI. Figures (a) and (c) represent the mean response of right hand SI across all observers and (b) and (d) represent the mean response of right foot SI, error bars represent the SE of the mean and the red lines represent the tactile stimulus onset and offset. Figures (c) and (d) clearly show a greater response to both frequencies in the stimulated body region (hand or foot).

From figure 6.11, there is a difference observable between the hand and foot conditions and foot and hand conditions in hand and foot SI respectively. A 3-way ANOVA (ROI [hand and foot SI] x Location of stimulation [hand and foot] x Frequency [36Hz and 72Hz] showed a significant interaction between ROI and location of stimulation ($F(1,7,)$, 64.03, $p<0.0001$) but no effects of frequency. Furthermore, as predicted, post hoc analysis (Fishers LSD) revealed that activation to the hand stimulation was significantly greater in hand SI than to foot stimulation ($p<0.005$) and conversely that foot SI was significantly more responsive to foot than hand stimulation ($p<0.0005$). Both of which can be seen in figure 6.11(b) and (d) for the hand and foot SI locations respectively.

*6.4.2.2. Tactile response of bilateral SII: hand and foot*

As with SI observer's tactile data were extracted from each of the four SII ROIs (hand and foot SII regions of the left and right hemisphere). These are shown in Figure 6.12. with the mean timecourse of the tactile response within each of these regions in (a) and (b) for the right hemisphere, and (e) and (f) for the left hemisphere. The associated mean results for the peak response are also presented for the hand and foot SII regions in the right (c and d) and left (g and h) hemisphere.

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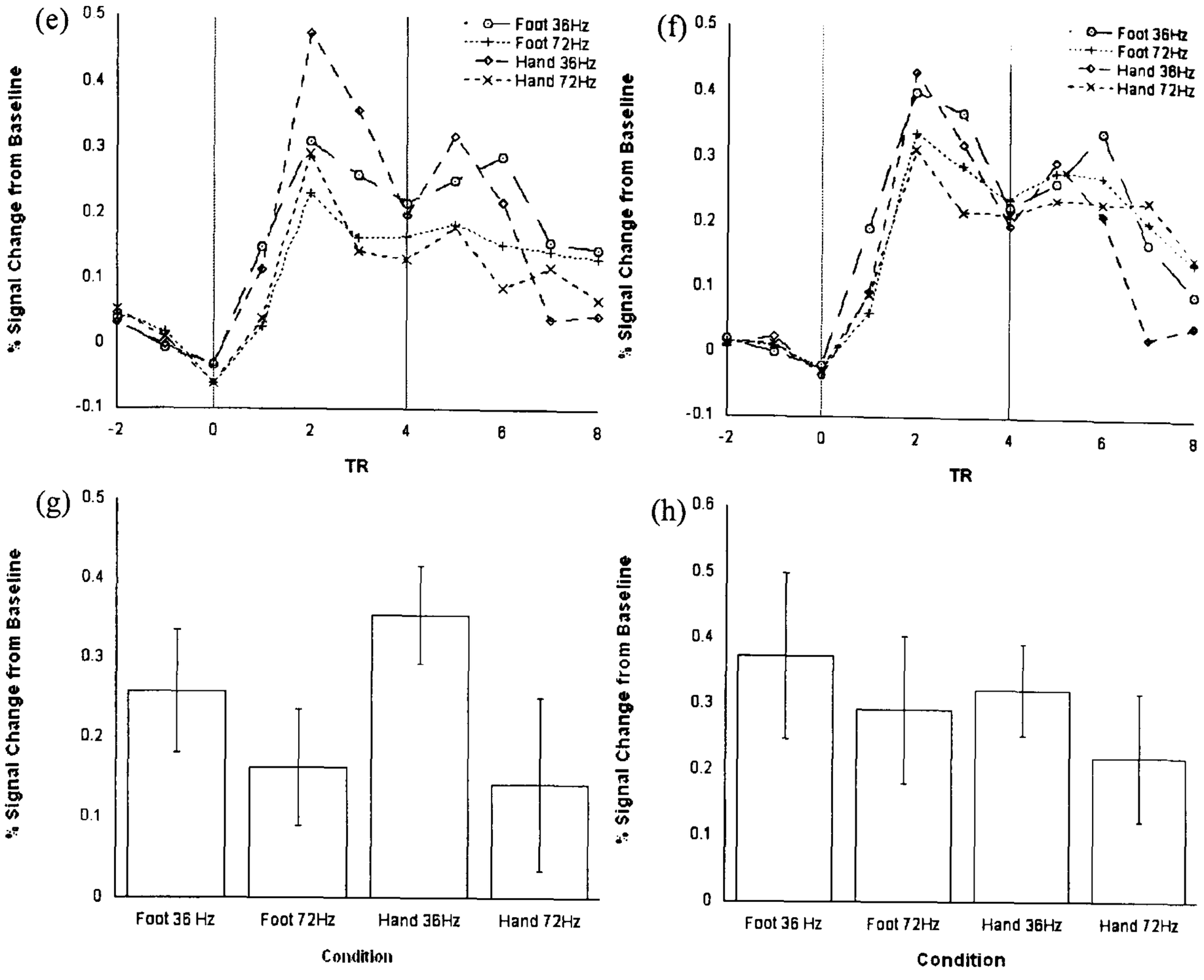



**Figure 6.12.** Tactile response of hand and foot SII. Figures (a) and (b) represent the mean timecourse of right SII hand and foot respectively across all observers and (e) and (f) represent the mean response of left SII hand and foot respectively for the tactile data. Figures (c-d) and (g-h) show the mean peak response derived from the timecourses for both right and left SII. Error bars represent the SE of the mean and red lines signal the onset and offset of tactile stimulation respectively. SII regions were found to be sensitive to the tactile stimulation in both hemispheres.

A 4-way ANOVA (Hemisphere [right and left] x ROI [SII hand or foot] x Location of stimulation [hand or foot] x Frequency [36Hz and 72Hz]) showed an almost significant main effect of ROI ($F(1,7)$, 5.393, $p=0.053$) with the mean PSC response in the foot ROI (0.34, SE = 0.08) higher than in the hand ROI (0.27, SE = 0.05) Furthermore, there was a main effect of frequency ($F(1,7)=6.808$, $p<0.05$) revealing an overall higher response in SII regions to the 36Hz (0.29, SE = 0.04) than 72Hz (0.22, SE = 0.04) frequencies contrary to our expectation that 72Hz would elicit a stronger effect. Finally, a difference from zero test showed significant differences for both right ($t(7)$, 5.211, $p<0.025$) and left ($t(7)$, 4.487, $p<0.025$) SII (Bonforroni

corrected to p = 0.025) confirming that all regions identified as SII were responsive to the tactile stimulation.

*6.4.2.3. Visual (body images) response of unilateral SI: hand and foot*

The data from the own-other ER runs of each observer were analysed as described above in section 6.3.2.3. and were extracted from both the group SI hand and foot ROI. The timecourse and mean peak responses to each of the four conditions (own-hand, other-hand, own-foot, other-foot) are shown below in figure 6.13.

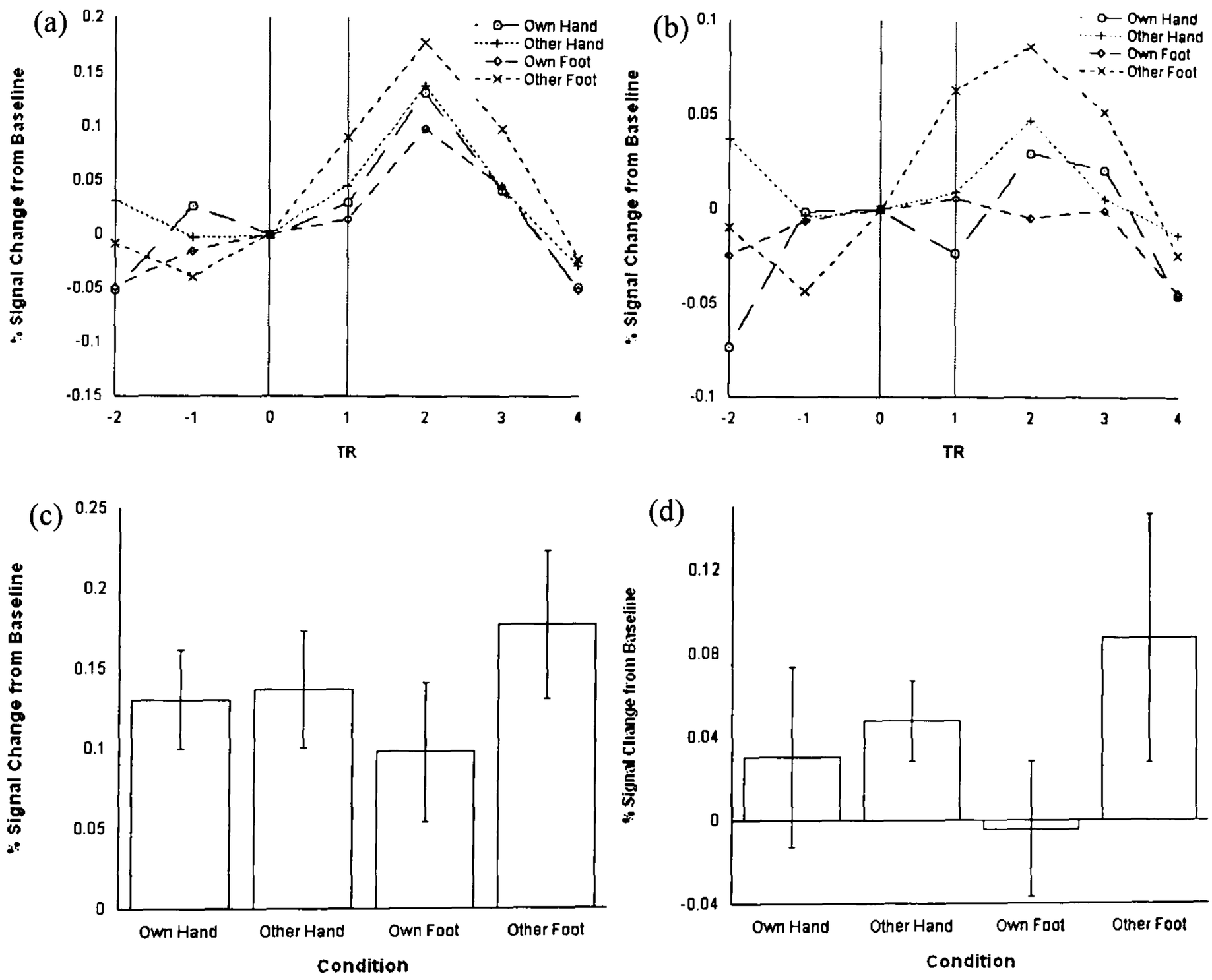


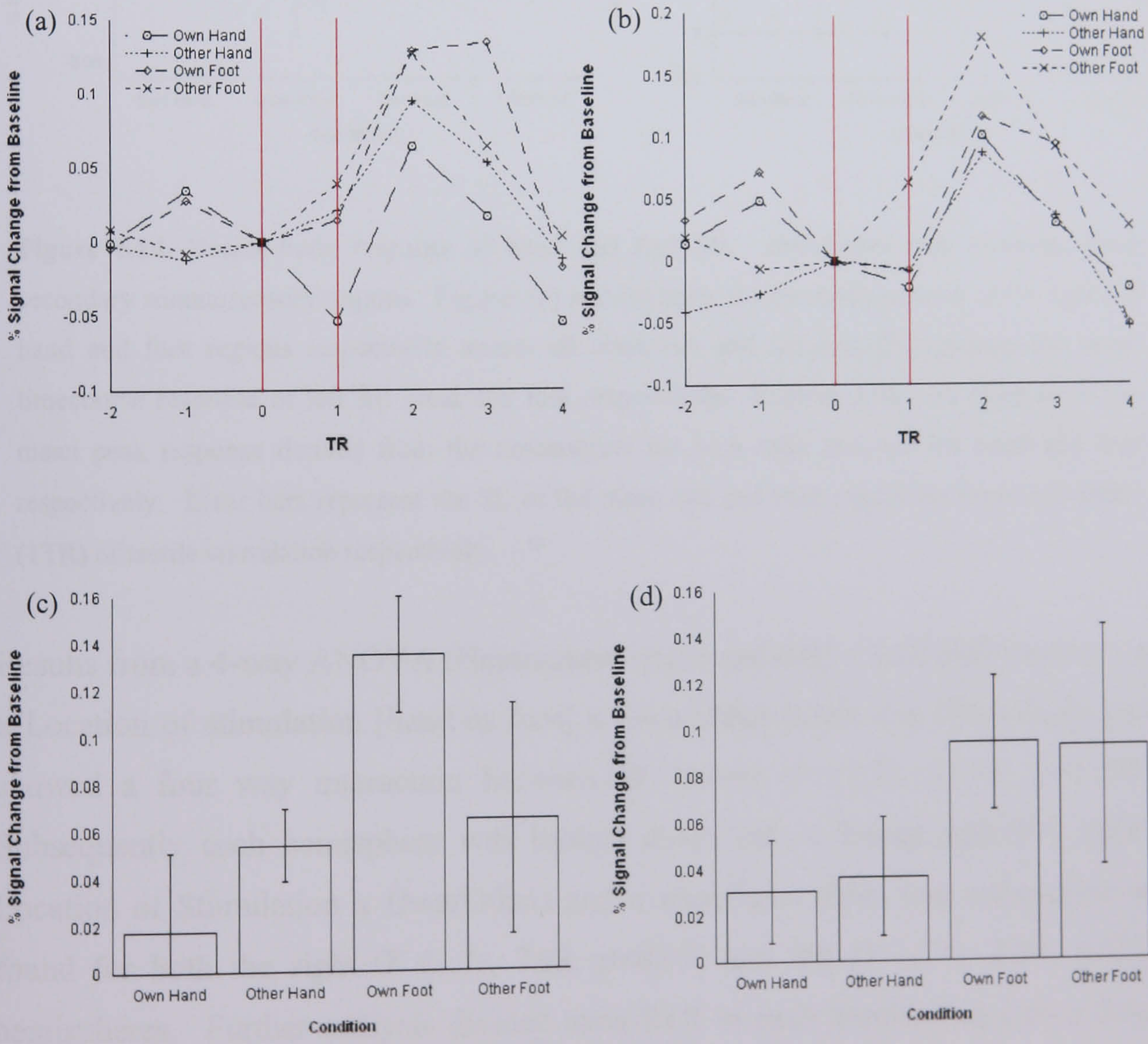

**Figure 6.13.** Visual body response of hand and foot SI. (a) and (b) show the average timecourses for the own/other hand/foot stimuli within primary somatosensory region SI of the hand and foot, (c) and (d) reflect the peak signal change in each of these conditions. Bars represent the SE of the mean and red lines indicate the onset and offset of the ER stimuli (1TR). While these regions appear not to be selective for different types of body image a significant effect was found for these conditions combined.

A 3-way ANOVA (ROI [SII hand or foot] x Location of stimulation [hand or foot] x Own/Other [Own and Other body part]) revealed only a main effect of ROI (F (1, 7). 20.78, $p<0.005$). Inspection of the means shows greater activity in the foot (0.041,

SE = 0.02/ 0.138, SE = 0.025) than hand (0.041, SE = 0.029/ 0.134, SE = 0.027) However, in an all body parts combined difference from zero t-test there is a significant difference (t (7), 4.512, $p<0.005$). This suggests that SI regions do show a significant response to the visual body part images but the ANOVA analysis suggests that they are not selective to different types or ownership (own/other) of body parts.

*6.4.2.4. Visual (body images) response of bilateral SII: hand and foot*

As in SI, the own-other ER run data were extracted from the four SII group ROIs (hand and foot SII regions of the right and left hemisphere), the results of which can be seen in the group timecourses and mean peak responses in figure 6.14. below.

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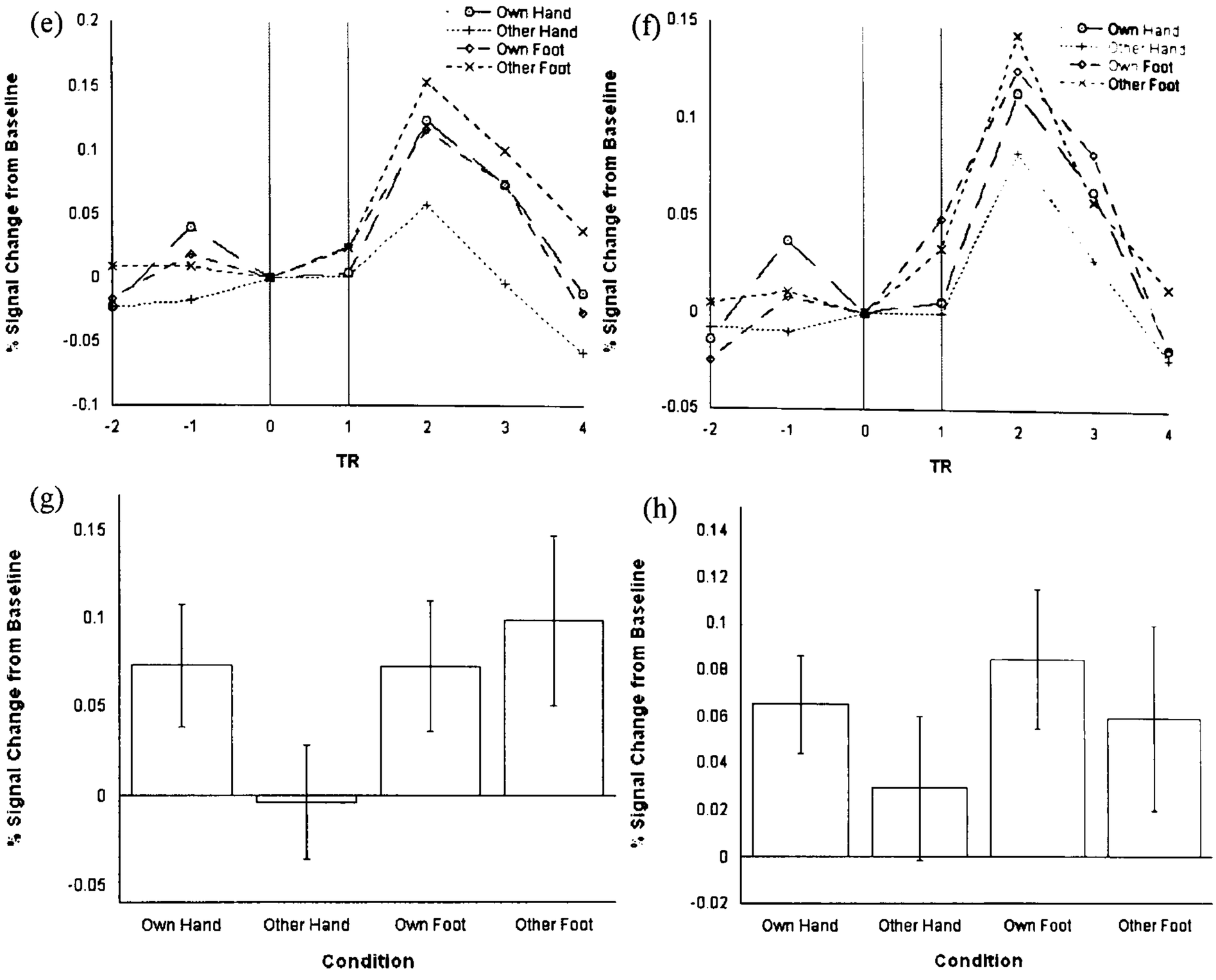



**Figure 6.14.** Visual body response of hand and foot SII. Own/Other data extracted from secondary somatosensory regions. Figures (a) and (b) show the mean timecourse of the right SII hand and foot regions respectively across all observers and (e) and (f) represent the mean timecourse response of left SII hand and foot respectively. Figures (c-d) and (g-h) show the mean peak response derived from the timecourses for both right and left SII hand and foot respectively. Error bars represent the SE of the mean and red lines signal the onset and offset (1TR) of tactile stimulation respectively.

Results from a 4-way ANOVA (Hemisphere [right and left] x ROI [SII hand or foot] x Location of stimulation [hand or foot] x Own/Other [Own and Other body part]) showed a four way interaction between all factors ($F(1,7)$, 57.76, $p<0.0005$). Subsequently each hemisphere was broken down into a 3-way ANOVA (ROI x Location of Stimulation x Own/Other) and a significant three way interaction was found for both the right ($F(1,7)$, 7.98, $p<0.05$) and left ($F(1,7)$, 8.33, $p<0.05$) hemispheres. Further analysis divided each ROI in each hemisphere into a 2-way ANOVA (Location of Stimulation x Own/Other). Here significant effects of Location of Stimulation were reported for right SII foot ($F(1,7)$, 13.15, $p<0.01$).

right SII hand (F (1, 7), 6.22, $p<0.05$) and left SII hand (F (1, 7), 10.98, $p<0.05$) but not for the left SII foot ROI (F (1, 7), 5.39, $p>0.05$). From inspecting the mean peak values in figure 6.14. it is evident that for these significant areas the foot images dominate. However, a one sample t-test reveals that the right hemisphere SII showed an overall difference from zero (t (7), 5.146, p (1-tailed)<0.0005) and this difference was also observed in the left hemisphere (t (7), 2.316, p (1-tailed)<0.05) revealing responsiveness of SII regions to body part images but differentiation specific to the regions.

### 6.4.3. The tactile response of bilateral EBA

Data from observer's EBA localiser runs were combined and a standard body minus object localiser was performed (Downing *et al.*, 2001; also see chapter two). The resulting activation map was thresholded to a highly conservative $p<1.456^{-22}$, revealing the larger right EBA region (peak voxel = 46, -61, 1; voxel count = 3055) and a smaller left hemisphere EBA (peak voxel = -48, -70, 1; voxel count 337). From these two EBA ROIs each observer's data were extracted for vibrotactile foot and hand stimulation runs.

Even if neurons are selective in the EBA to different locations of tactile stimulation it would be unlikely that any differences would be revealed between the conditions as data are extracted from a large region rather than specific regions of the EBA that may be selective for different body part stimuli (if they exist). Therefore, all tactile data for each observer were combined across location of stimulation and frequency resulting in one set of tactile data per observer. The mean timecourses and overall means of both the right and left EBA can be seen in figure 6.15. (a) and (b) below.

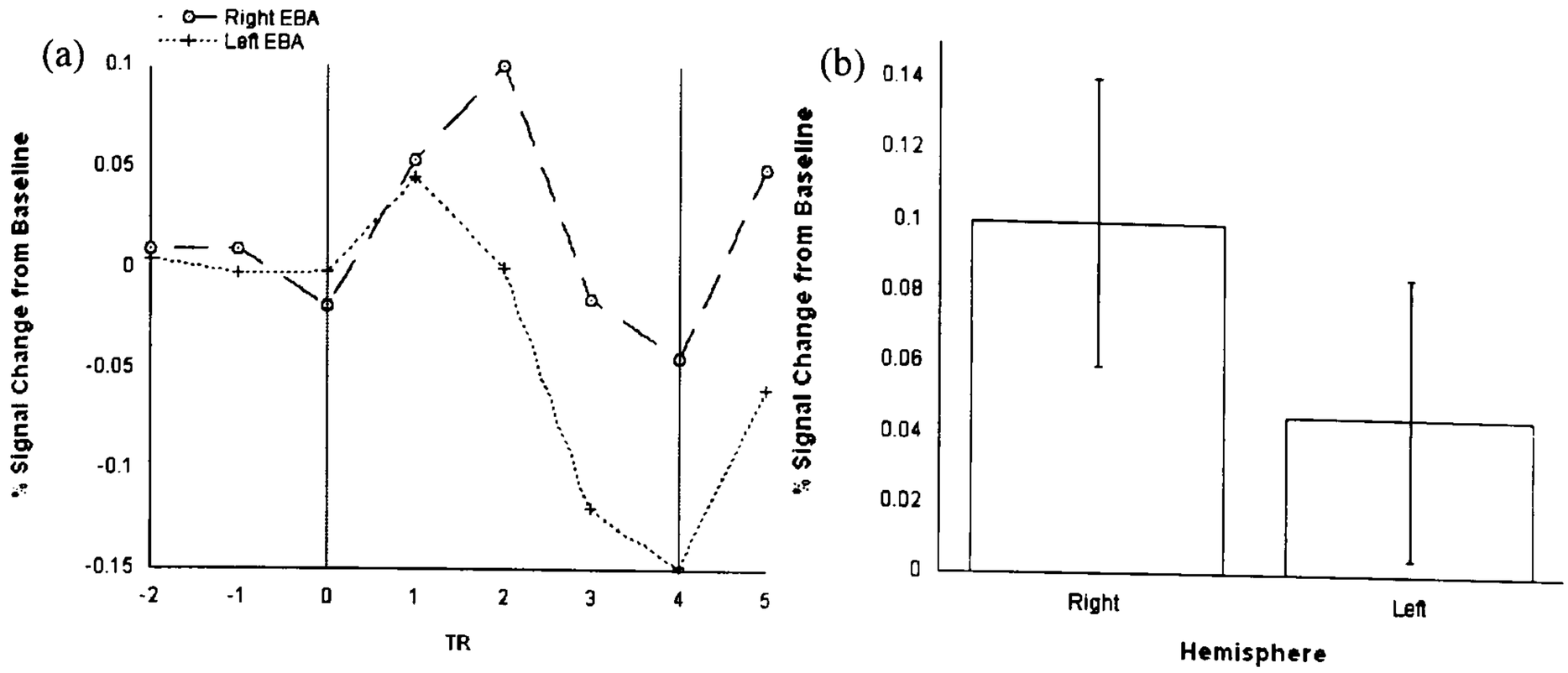



**Figure 6.15.** Response of the EBA to vibrotactile stimulation to the hand and the foot (locations of stimulation combined) for both the right and the left EBA (a). The bar graph in (b) shows the mean peak response of the timecourse with error bars representing the SE.

These resulting data were used to explore whether there was significant activation in the right and left EBA to tactile stimulation. A significant difference from zero was observed (using a Bonferroni corrected p-value of 0.025) to the tactile stimulation in the right (t (7), 2.454, $p<0.025$) but not left EBA (t (7), 1.118, $p>0.025$).

### 6.4.4. Own - Other and Other - Own: Whole brain analysis

The EBA and main somatosensory regions are not the only possible areas that may be involved in a body-touch network and, furthermore, it is probable that many other cortical regions may be sensitive to images of one's own versus another's body. Indeed it is possible that the EBA accomplishes an initial sorting of images (for example own from other) and then separately projects to regions specialised for processing own versus others' body parts. For these reasons two whole brain analyses were conducted. The first of these contrasted data from all observers in the own (hand and foot) conditions with those from the other (hand and foot) conditions and the second analysis used the inverse contrast of other minus own conditions. From all the ROIs identified from these analyses the mean data from the vibrotactile stimulation of the hand and foot was extracted to investigate if either the ROIs selective for own or other images were also responsive to tactile stimulation implicating their possible involvement in a cross-modal body-touch network.

*6.4.4.1. Own – Other whole brain analysis*

Data from all observers' ER runs were grouped and from this a subsequent own minus other contrast (collapsed across body part) produced an activation map that was thresholded to $p<0.001$ (uncorrected). This contrast revealed six clusters of activation that exceeded the $50mm^3$ cut-off, details of which can be seen in table 6.1. below.

| | | Talairach Coordinate | | | | |
|---|---|---|---|---|---|---|
| **Key** | **Region and Brodmann Area (BA)** | **X** | **Y** | **Z** | **Voxel Count** | **PSC (SE)** |
| | R.Parietal Lobe, Inferior Parietal, BA40 | 66 | -37 | 25 | 94 | 0.4 (0.09) |
| | R.Frontal Lobe, Superior F.Gyrus, BA9 | 39 | 41 | 31 | 52 | -0.004 (0.05) |
| | R. Cingulate Gyrus, BA32 | 12 | 17 | 31 | 59 | 0.01 (0.02 |
| | R.Parietal Lobe, Precuneus, BA7 | 15 | -70 | 34 | 51 | 0.1 (0.06) |
| | L.Occipital Lobe, Cuneus, BA18 | -3 | -85 | 19 | 556 | -0.04 (0.04) |
| | L.Frontal Lobe, Precentral Gyrus, BA6 | -67 | -4 | 16 | 84 | -0.02 (0.05) |

**Table.6.1.** Main clusters of activation (exceeding $50mm^3$) as identified by the own minus other contrast thresholded to $p<0.001$ uncorrected. Talairach coordinates for the peak voxel in each region are shown along with the associated brain region and voxel (3x3x3mm) count of each cluster. Mean PSC and SE for the tactile response in the region is also shown. Key corresponds to colour coded regions of figure 6.16.

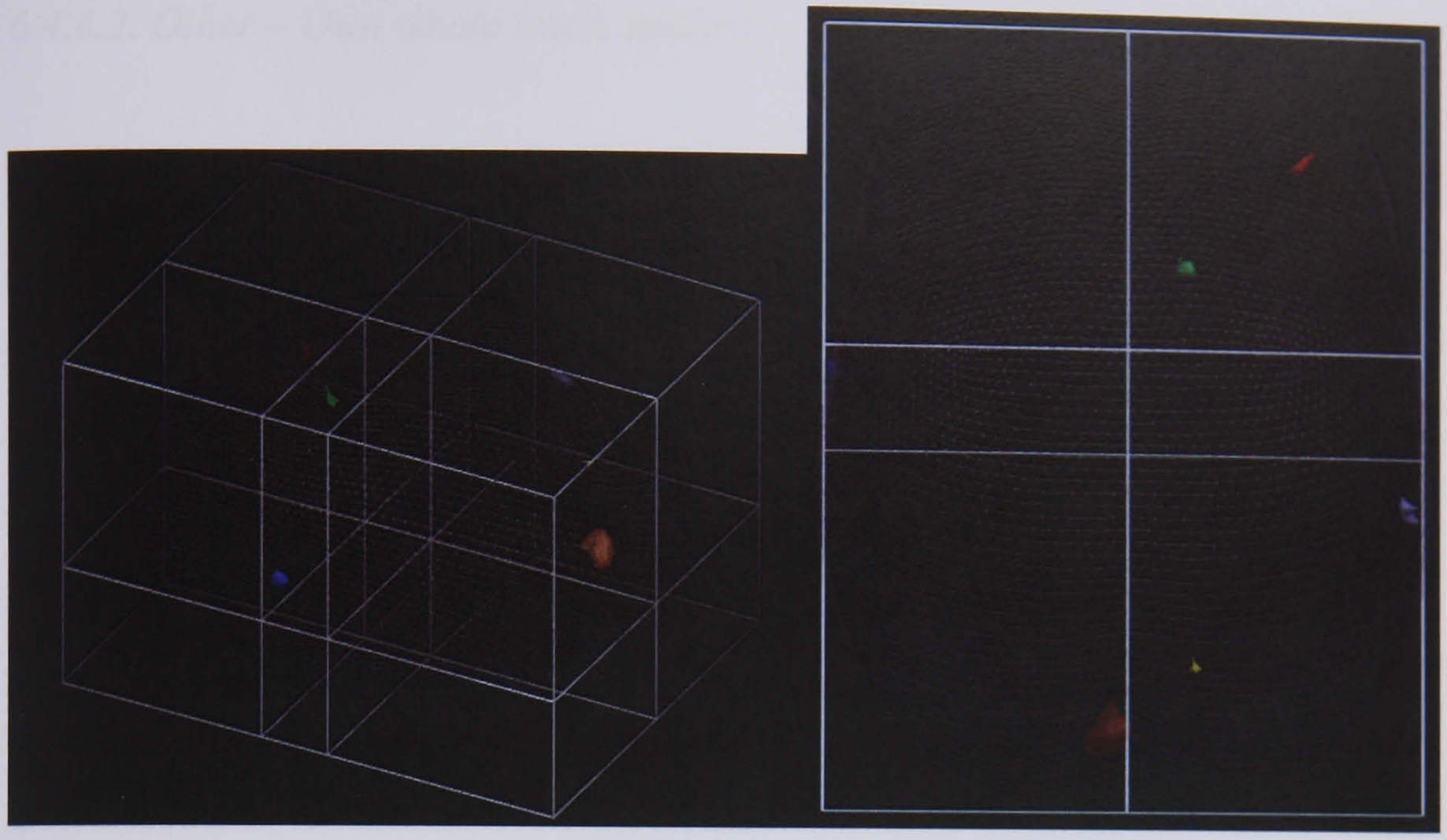


**Figure 6.16.** Results of the own-other contrast overlaid onto a Talairach brain. Left image shows the whole (glass) brain from the left hemisphere and the right image shows the activations from dorsal viewpoint revealed from a whole brain own minus other (hand and foot) images contrast. Brain areas activated at $p<0.001$ uncorrected and exceeding the $50mm^3$ cut-off for cluster size are shown. Brain areas have been overlaid onto a standardised Talairach template glass brain. Colour coded key for this figure can be found in table 6.1.

From each of these six ROIs the mean data from the vibrotactile runs were extracted and combined so that each observer had one mean tactile PSC value representing all four tactile conditions (hand and foot at 36Hz and 72Hz). A one-way ANOVA (ROI) performed upon these data revealed a main effect of ROI ($F(1,7)$, 7.411, $p<0.00005$). Post-hoc testing using Tukey's HSD showed significant greater activation in one region to tactile stimulation, inferior parietal area BA40 (marked as black in table 6.1. and figure 6.16.). This was confirmed with a one sample t-test, which showed that only this region showed activation significantly different from zero ($p<0.008$; Bonforroni corrected for multiple comparisons).

*6.4.4.2. Other – Own whole brain analysis*

An inverse contrast using the group data from the other body parts conditions against the own body part conditions resulted in thirteen clusters of activation greater than 50mm$^3$ all of which can be seen in table 6.2. and on the glass brain in figure 6.17.

| Key | Region and Brodmann Area (BA) | Talairach Coordinate X | Y | Z | Voxel Count | PSC (SE) |
|---|---|---|---|---|---|---|
| | R.Temporal Lobe, Middle Temp. Gyrus, BA21 | 69 | -31 | -8 | 99 | 0.02 (0.05) |
| | R.Limbic Lobe,Uncus,BA34 | 21 | 5 | -20 | 83 | 0.14 (0.04) |
| | R.Frontal Lobe, Medial Frontal Gyrus,BA10 | 9 | 63 | 13 | 60 | 0.1 (0.1) |
| | R.Frontal Lobe, Medial Frontal Gyrus,BA6 | 3 | -10 | 64 | 164 | 0.24 (0.07) |
| | L.Frontal Lobe, Superior Frontal Gyrus,BA6 | -5 | 23 | 52 | 320 | -0.03 (0.3) |
| | L.Sub-lobar, Caudate, Caudate Tail | -18 | -31 | 25 | 77 | -0.03 (0.2) |
| | L.Parietal Lobe, Postcentral Gyrus,BA40 | -36 | -25 | 46 | 241 | -0.01 (0.03) |
| | L.Frontal Lobe, Middle Frontal Gyrus,BA8 | -36 | 20 | 40 | 75 | -0.02 (0.02) |
| | L.Sub-lobar ,Insula, Brodmann area 13 | -42 | -10 | 16 | 79 | -0.12 (0.04) |
| | L.Temp. Lobe, Superior Temp. Gyrus,BA22 | -51 | -55 | 16 | 1763 | -0.05 (0.02) |
| | L.Parietal Lobe, Inferior Parietal Lobule,BA40 | -45 | -55 | 46 | 86 | 0.12 (0.14) |
| | L.Temporal Lobe, Middle Temp. Gyrus,BA21 | -57 | -22 | -2 | 138 | -0.04 (0.04) |
| | L.Temporal Lobe, Middle Tem. Gyrus,BA21 | -63 | -40 | -8 | 82 | 0.03 (0.08) |

**Table.6.2.** Main clusters of activation (exceeding 50mm$^3$) as identified by the other minus own contrast thresholded to $p<0.001$ uncorrected. Talairach coordinates for the peak voxel in each region are shown along with the associated brain region and voxel (3x3x3mm) count of each cluster. Mean PSC and SE for the tactile response in the region is also shown. Key corresponds to colour coded regions of figure 6.17.

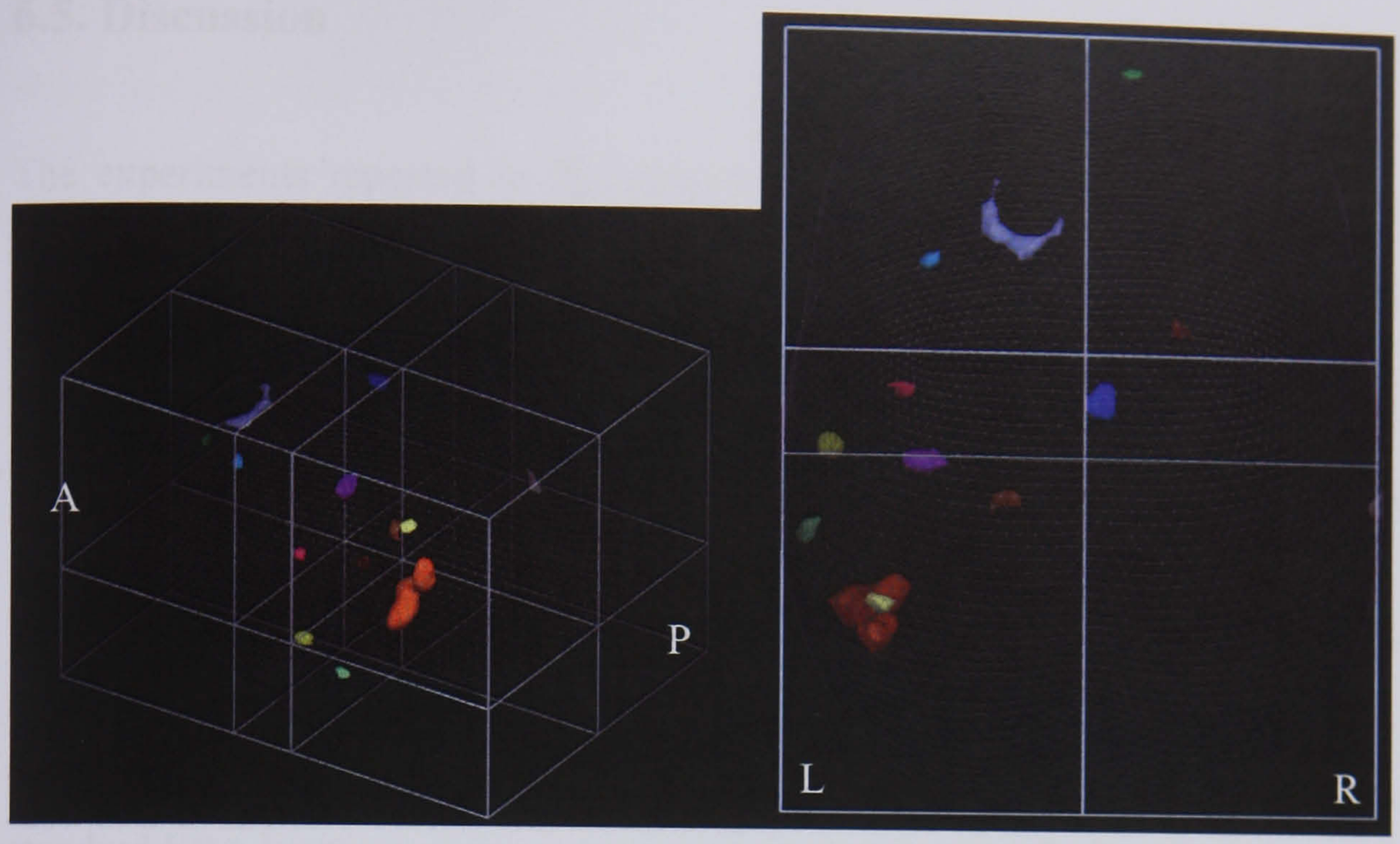



**Figure 6.17.** Results of the other-own contrast overlaid onto a Talairach brain. Left image shows the whole (glass) brain from the left hemisphere and the right image shows the activations from dorsal viewpoint revealed from a whole brain other minus own (hand and foot) images contrast. Brain areas activated at $p<0.001$ uncorrected and exceeding the $50mm^3$ cut-off for cluster size are shown. Brain areas have been overlaid onto a standardised Talairach template and the slice chosen is for illustrative purposes only i.e. all areas are not in the same sagital plane. Colour coded key for this figure can be found in table 6.2.

As in the previous contrast, the mean data from the vibrotactile runs were extracted and combined so that each observer had one mean tactile PSC value representing all four tactile conditions (hand and foot at 36Hz and 72Hz). These data were extracted from each of the thirteen ROIs and a one-way ANOVA (ROI) was performed which showed a significant effect of ROI ($F(1,7)$, 1.976), $p<0.05$). However, post-hoc (Tukey's HSD) revealed no significant differences between ROI's. Furthermore, no significant activations are revealed by the one sample t-test against zero indicating that the areas sensitive to images of other bodies are not sensitive to tactile stimulation in contrast to the region BA40 identified in the own minus other comparison.

## 6.5. Discussion

The experiments reported in this chapter set out to investigate the possible brain regions that may be involved in a body-touch multimodal network. This was achieved by addressing three key questions: (1) Are primary (SI) and secondary (SII) somatosensory regions sensitive to visual body images? (2) Is the EBA, a region preferentially selective for images of the human body also responsive to tactile stimulation? (3) What brain regions are selective to images of one's own and others' bodies and do these regions display selectivity for tactile stimulation? Each of these questions was addressed using a combination of three fMRI experiments: (1) vibrotactile stimulation to the hand and foot (at two different frequencies); (2) standard EBA localiser as has been used extensively throughout this thesis; (3) Rapid event-related study that presented images of the observer's own and another's hand and foot. In the following sections the investigation into each of these research questions will be discussed as will their contribution to the main research question of this chapter concerning the possible network between the visual representation of the body and touch.

### 6.5.1. Are somatosensory regions SI and SII selective to human body images?

Previously, in chapter two, a whole brain analysis using the final EBA localiser experiment revealed a region of the post-central gyrus that was attributed to an area of primary somatosensory cortex SI. In the current chapter we examined this possibility by localising both SI and SII for the hand and foot and then looked at the response in these regions to own/other, hand/foot stimuli (from the ER experiment). For both SI and SII regions it was apparent that although there was a significant response to body parts *per se* there was no significant difference in the response to specific own or other, hand or foot stimuli e.g. hand SI was not preferentially activated by own or other hand stimuli over the foot stimuli. Further, it was apparent that SII regions responded more to the foot than hand stimuli.

From the tactile localisation data in 6.4.4.2. it is evident that the bilateral SII regions identified as hand and foot regions (based upon the peak voxel values from the tactile

localiser) did not display significant preferential response for stimulation to the corresponding body part (i.e. hand SII – hand stimulation). Gross somatotopy of SII has been previously demonstrated (see Ruben *et al.*, 2001; Disbrown, Roberts and Krubitzer, 2000) but its organisation is much less clear than the homunclian arrangement of SI and further SII has been shown to have at least two separate regions, S2p (Burton et al., 1995) and PV (Krubitzer et al., 1995). The method of localisation used here (possible flaws discussed later) may have highlighted areas that although showed separate peaks of activation may not have been classic SII areas in accordance with established somatotopy. Therefore, our results may reflect the general response of SII to the body part stimuli rather than the specific responses of specific body part regions.

However, despite this, here it has been demonstrated that SI and SII do respond to visual stimulation of human body part images. This is in contrast with a study conducted by Amedi *et al.* (2001) where tactile responses were reported in the LOC, but no significant response was found in somatosensory regions to the visual stimuli. This concept of the somatosensory regions being sensitive to comparable visual images is consistent with the concept of vision aiding somatosensation, something that has been demonstrated psychophysically by, for example, Kennet, Taylor-Clarke and Haggard (2001) and which is also supported by the finding that visual (but not body part) cues enhance somatosensory processing (Maculso, Frith and Driver, 2000). Further evidence for a visual representation in somatosensory regions comes from an fMRI study by Keysers, Wicker, Gazzola, Anton, Fogassi and Gallese (2004) who demonstrated that viewing touch and being touched activate comparable regions of SII (but not SI).

### 6.5.2. Does the EBA show a response to tactile stimulation?

The role of the EBA and its response to modalities other than vision is not clear although, Downing *et al.* (2001) commented that the EBA may well be stimulated by other modalities. This question has been addressed previously with regards to the performance of motor actions where Astafiev *et al.* (2004) reported that EBA was responsive to this task, yet the validity of this finding has been questioned (see

Peleen and Downing, 2005). In the present study results suggest that in response to vibrotactile stimulation of the hand and foot there is a small but significant response in the right but not the left EBA. This result may be interpreted that the EBA, at some level, is involved in somatosensory processing, an effect related to the tactile stimulation experiment rather than any tactile association effects from the EBA localiser task (i.e. there were no motor/tactile tasks such as button presses in the EBA localiser) or visual images of the hand or foot during the tactile task. However, if the EBA responds to tactile stimulation why was this observed in only the right EBA region and not the left when it was the right side of the body that received tactile input? One possibility may be that the response is bilateral (like SII) and that the generally smaller EBA response in the left hemisphere just resulted in a suppressed response to the tactile stimulation, as it is evident from figure 6.15. that there is also a small peak in the HRF in the left hemisphere.

A second possibility, that may be more plausible, is the pre-established selectivity of the right EBA over the left for processing EBA selective stimuli. In the original EBA experiment Downing *et* al. (2001) had reported stronger activation in the right than left hemisphere which resulted in many researchers focussing on just this hemisphere and the results discussed in chapter four were also stronger in the right hemisphere. This is further supported by recent work from Goyal, Hansen and Blakemore (2006), which reported that when blind observers touched a dolls face there was a response to this tactile stimulation in the right FFA.

Therefore, in answer to this question of the EBA's response to tactile stimulation it appears that there is a small response of the right EBA to touch, a finding consistent with the right hemisphere's preference for differential processing of body part stimuli. Considered with the finding of visual response in somatosensory regions this points towards the possibility of a body-touch network. However, a simple mapping between the EBA and SI and SII does not seem likely given that in chapter 4 the EBA was shown to be able to discriminate own from other body part images, yet these do not lead to corresponding differential activation in SI or SII.

### 6.5.3. Are there regions selective to one's own body and touch?

It has been demonstrated that SI and SII while responsive to visual body images *per se* are not selective to own over other stimuli. However, chapter four demonstrated that the EBA can distinguish such images and in this chapter the EBA has shown response to tactile stimulation. Therefore, if we are to propose a body-touch network evidence would be needed to demonstrate the integration of own body stimuli and tactile stimulation.

In order to investigate this, using the data acquired during the ER Own/Other experiment, two whole brain analyses were conducted to identify regions selective for one's own and another's body parts. The clusters of activation that were revealed by these analyses were then probed for their response to the vibrotactile stimulation. None f the regions significantly activated by the other body part stimuli showed a significant response to the tactile stimulation. However, of those regions selective to one's own body parts, one region was found to be significantly responsive to the tactile stimulation. The location of this area corresponded with the right hemisphere inferior parietal lobe (rIPL) region of Brodmann's Area 40 which is posterior to SI, superior to SII and the EBA.

The parietal lobe is an area that has been attributed to the integration of sensory feedback. However, the right inferior region of this lobe has been implicated in a number of roles connected with the sense of bodily self. For example, Chaminade. Meltzoff and Decety (2002) report that the rIPL is activated when observers imitate the observed actions of a model, a task that would require the multimodal integration of multiple modalities, not simply motor, but also visual and somatosensory. Further, Decety and Sommerville (2003) argue that the rIPL in conjunction with the right prefrontal cortex is critical in distinguishing the self from others. The argument is based upon a number of studies such as Farrer, Franck, Georgieff, Frith, Decety and Jeannerod (2003) who also have concluded that that the rIPL is a region central to the self attribution of action. Furthermore, in a more recent paper, Uddin, Molnar-Szakacs, Zaidel and Marco Iacobini (2006) comment that the rIPL has long been linked with own-body perception. In their study they created a virtual lesion in the

rIPL (and the left) which resulted in a disruption of the observer's ability to separate own from other (familiar) faces. Further, some research has reported that damage to the rIPL has also been implicated in neglect (Vallar & Perani, 1986).

### 6.5.4. Issues pertaining to tactile stimulation

The failure to find differences between the two frequency conditions may be due to firstly to the frequency used. In the study by Francis *et al.* a 30Hz and 80Hz frequency was chosen. Due to the design of the equipment used in the present study the closest frequencies to these were used i.e. 36Hz and 72Hz. It therefore may simply be that the gap between frequencies was not sufficient to gain maximally different responses from the somatosensory ROIs. However, this explanation does not appear sufficient as using the contrast of 36Hz/72Hz vs. no stimulation successfully resulted in SI and SII localisation respectively.

A further possibility is that there was a flaw in the apparatus used. The piezoceramic bender was attached directly to an observer's hand and foot using surgical tape. In some previous studies such as Francis *et al.* an intermediary device has been used between the skin and the piezoceramic device such as a static surround to limit the contact between the skin and the vibrator. By creating direct contact with the skin this may have degraded the response by altering the degree of displacement of the bender. A related possibility is that the site chosen to attach the stimulators was not optimal considering the type of stimulation (vibratory) and the frequencies chosen. Therefore, it is possible that by choosing a site with greater sensitivity, such as the finger tip and toe, a difference in frequency as reported by Francis *et al.* (who stimulated the fingers) may be found using this apparatus.

### 6.5.5. Conclusions

The aim of this chapter was to investigate the possible role the EBA may play in a body-touch network and to identify other regions that may exist in this network. It is apparent from the results that the right EBA shows a response to tactile stimulation and SI and SII to visual body part stimulation but neither of these on their own

constitute any type of network as it is unclear how the own/other selectivity of the EBA operates within this. However, the finding that rIPL is selective to images of one's own body and to tactile stimulation to one's own body suggests that this area may mediate between the EBA and somatosensory regions, although it is not clear from this study what direction this would operate. For example, does the rIPL receive input from somatosensory areas after receiving tactile stimulation, which is in turn relayed and matched to representations in the EBA or does the rIPL combine information from both areas and pass it on to a higher level region. Despite this, the present study has established the foundations of a body-touch network involving the EBA.

# Chapter Seven: General Discussion

## 7.1. Overview

The empirical work in this thesis has focused on using fMRI to explore both the selectivity of the extrastriate body area and its potential role within a putative crossmodal network of body and touch. Successful localisation of the EBA in the second chapter was followed by two chapters focusing on the use of fMR-A, both characterising repetition suppression within the EBA and demonstrating its discriminatory capabilities for body part stimuli as well as its selectivity. From here the focus of the thesis moved towards establishing the EBA in a body-touch network. The basis for this was established in the penultimate empirical chapter with regard to the use of visual body part stimuli and tactile stimulation. The final set of experiments supported the concept of a body-touch network incorporating the EBA, somatosensory areas SI and SII and the mediating region of rIPL in the crossmodal processing of the visual imagery of our own bodies and associated tactile stimulation.

## 7.2. Summary of Main Findings

### 7.2.1. Overview of Chapter Two

The central aim of the experiments detailed in chapter two was to develop a reliable and economical paradigm to localise the EBA. Three paradigms were developed and tested of which the third was the most successful and was used throughout the rest of the fMRI experiments within this thesis to locate the EBA across observers. Furthermore, a whole brain analysis revealed an area of the postcentral gyrus corresponding to a region of the primary somatosensory cortex. This finding was initially unexpected, however, from this it was inferred that the EBA may be involved in a putative crossmodal network of the body and touch a question that was then further explored in the latter part of this thesis.

### 7.2.2. Overview of Chapter Three

Chapter three began to address the issue that some selective properties of the EBA may go undetected because the standard subtraction methods of analysis used previously may not be sensitive to the selectivities of underlying groups of neurons. Therefore, we used the technique of fMR-Adaptation; a method that does enable inferences to be drawn from fMRI data about the selectivity of the underlying neuronal sub-populations while working within the spatial constraints of fMRI. Using this method, we were able to characterise the effect of repetition suppression within bilateral EBA where a clear decrease in signal was observed as the number of different body part images within a block was decreased (32, 8, 4, 2, 1). This finding revealed that the EBA was sensitive to the basic effects of repetition suppression, a critical finding that meant fMR-A could be used to explore the EBA further.

### 7.2.3. Overview of Chapter Four

By exploiting the characterised repetition suppression effect, chapter four used fMR-A to investigate whether (a) the EBA represented separate body parts and (b) if the EBA contained separate neuronal sup-populations that responded to images of one's own body and to images of another's. Analysis of the fMR-A data revealed that the EBA appeared sensitive to differences between not only body parts but different exemplars of the same body part (e.g. between two different hands). However, perhaps most strikingly it was found that the EBA showed less adaptation when images of one's own body were included in a block of trials compared to images of other's hands only. These results suggest that the EBA is not simply a region that is involved in the processing of human body images but rather is a region able to distinguish between different body part exemplars at multiple levels.

### 7.2.4. Overview of Chapter Five

Using a lab based paradigm the experiment in chapter five investigated the crossmodal links between vision and touch by manipulating trial congruency between visual hand and foot stimuli and vibrotactile stimulation to the hand and

foot. As may be predicted (Posner, 1980), reaction trials to incongruous stimuli were significantly longer than to congruous trials and reaction times to all tactile foot stimuli were significantly longer than to hand stimuli, an effect attributed to neuronal conduction length (Halliday and Mingay, 1964). The findings of this experiment reinforce the crossmodal links between vision and touch that have been previously reported (for example Macaluso, Frith and Driver, 2000; Tipper *et al.*, 1998, 2001). Furthermore, the stimuli used in this study were of the same type used to investigate the properties of the EBA and therefore suggests that the EBA may be a candidate area for facilitating crossmodal links between vision and touch.

### 7.2.5. Overview of Chapter Six

On the basis of the findings of the previous chapter, the empirical work in chapter six focused on investigating the concept of a body-touch network involving the EBA and somatosensory areas. In order to address this possibility it was broken into three questions (1) were somatosensory areas SI and SII responsive to own/other visual body part stimuli? (2) was the EBA responsive to tactile stimulation? (3) were there any additional regions that could be localised using own/other body part stimuli that may be involved in this putative body-touch network and how would they respond to tactile stimulation? The results of the series of experiments in this study suggested that the tactile areas were responsive but not differentially selective to visual body part stimuli (comparable to findings from Keysers *et* al., 2004). Further, the EBA was responsive to general tactile stimulation which was congruent with results in the FFA (Goyal, Hansen and Blakemore, 2006) and LOC (Amedi *et al.*, 2001). However, the mediating area in this network was revealed as rIPL a region of BA40 that has been implicated previously in the self-other distinction (see Decety and Sommerville, 2003). This region was found to be selective for observer's own body images and also to be responsive to tactile stimulation.

## 7.3. Core Findings of the Thesis

This thesis set out to explore how the body is represented in the brain in regard to the visual and touch related properties of the EBA. Chapter one reviewed a large body of evidence that pointed towards the existence of a cortical region selective for images of the human body/a region additional to those already implicated in the perception of bodies such as the STS. Downing *et al's.* (2001) original localisation of the EBA has now been replicated using not just fMRI (for example Bartels and Zeki, 2004) but also rTMS (Urgesi, Berlucci and Aglioti, 2004) and has further resulted in a growing number of studies that are seeking to understand the role and function of this region. Here the implications of the core findings of this thesis are discussed with relation to some of the central questions that surround this topic. Further, suggestions for future research studies are discussed with relation to extensions of the empirical findings.

### 7.3.1. Subordinate level processing within the EBA

Interestingly, the results of the first fMR-A experiment suggest that the EBA is capable of subordinate level processing, something that Tarr and Gauthier (2000) have proposed the FFA is involved in rather than in the exclusive perception of faces. This is part of their theory of domain-general object processing, arguing that there are not separate areas in the brain for processing specific types of visual stimuli but rather that this process is carried out over a distributed network of areas (hence domain-general). However, here the EBA, a region that preferentially responds to images of the human body, appears capable of this subordinate processing. That is, it has been demonstrated here, using fMR-A, that the EBA accomplishes both between and within body part category discrimination (e.g. hand/foot and hand one/hand two) as well as discrimination between own and others' body parts. It would appear from these findings that visual body part processing is highly domain-specific in a manner comparable to that proposed for faces in the FFA by Kanwisher (2000).

To further test this hypothesis a number of additional studies may be carried out. Firstly, it has not yet been shown that specific damage to the EBA impairs body part

processing or disruption of any of the other roles that have been attributed to it (such as the own-other distinction). Autotopagnosia, a neurological deficit that affects the localising, naming and describing of body parts of the self and others has been detailed in the literature (for example see Ogden, 1985; Guariglia *et al's.* 2002). However, those with this deficit have not been tested with specific reference to the EBA. It would be interesting to assess whether patients have EBA damage and/or EBA impairment in line with studies on prosopagnosia and the FFA.

However, autotopagnosia is rare and obtaining patients would be difficult. For this reason, a more manageable approach to this question of EBA impairment would be the application of TMS. Using TMS (or fMRI-TMS combined) it would be possible to create a virtual lesion of the EBA and then to assess what deficits are evident. This method may also be preferable to studying brain damage patients as patients neurological deficit are often accompanied by additional, more general disruptions to brain function due to the uncontrollable and differing natures of the lesions.

### 7.3.2. The role of the EBA in the crossmodal processing of vision and touch

At the beginning of this thesis it was discussed how vision can enhance somatosensation. A number of lab based studies demonstrated this effect such as Kennet, Taylor-Clarke and Haggard, (2002) who reported that viewing a limb just prior to stimulation could increase performance on a two-point discrimination task, and Tipper *et al.* (1999, 2001) who reported vision aided somatosensation with relation to body parts that couldn't be viewed directly. Furthermore, using fMRI Macaluso, Frith and Driver (2000) reported that visual cues (not body-part stimuli) could be used to enhance the somatosensory response and further proposed a vision-touch network, but not one that included the EBA. However, we established in chapter five that body parts, as used to stimulate the EBA, can be used to affect cross modulation and in chapter six this result was built upon where a network was proposed encompassing the EBA, somatosensory cortices and rIPL. This network might underpin findings of the previous studies of vision and touch but particularly those in which body part vision aids somatosensation. Here it can be argued that the

rIPL facilitates this process combining representations of the own body from the EBA with paired tactile stimulation received from the somatosensory cortices.

However, the exact way in which this body-touch network would operate is not entirely clear from the results of this thesis. In order to establish the precise nature and workings of this it would be useful to carry out a functional connectivity analysis. As proposed by Friston (1994), this method argues that fMRI could be used to dynamically model brain activity in order to understand the connectivity that exists between functional regions, a technique that would aid the understanding of how different functional brain regions are related to one another.

Functional connectivity has been especially successfully employed to understand crossmodal networks that by their nature imply connections between a wide variety of functional regions. For example, this has previously been done for vision and touch (Macaluso, Frith and Driver, 2000), and faces (FFA) and voices (auditory; Kriegstein, Kleinschmidt and Giraud, 2005). By using this technique a more complete picture of the present proposed body-touch network may be derived and as the present thesis points towards the basic structure of such a network, connectivity analysis would allow for accurate modelling to be realised.

Results from such work may also be further supported by blind patients. Goyal, Hansen and Blakemore (2006) demonstrated that blind patients showed FFA activation when touching a dolls face, establishing that the FFA is not a unimodal visual area but is sensitive to tactile stimulation. Interesting insights into the functioning of the EBA could be elicited if a similar study was carried out in those with both acquired blindness and those blind from birth. Such research would help to further characterise the response of the EBA to stimulation from different modalities.

## 7.4. Conclusions of the Thesis

This thesis has investigated how the body is represented in the brain and has done so with focus upon the relatively unexplored extrastriate body area. The major findings of this thesis can be summarised as follows. Firstly, the EBA is sensitive to the effects of repetition suppression as investigated with the use of fMR-A. Furthermore, the use of this technique revealed that the EBA is able to both distinguish between different body parts and different exemplars of the same body part category revealing that the EBA is capable of subordinate level visual processing. The second main finding was that the EBA can distinguish one's own body parts from those of another. This may place it a unique position to sort body part image identity and feed this information to areas that specialise in the processing of own (or other's) body images. One such area identified was the rIPL, which along with the EBA was also shown to be responsive to tactile stimulation. Thus, the EBA can be placed within a crossmodal network of vision and touch. Finally, it has been proposed that a body-touch network encompassing the EBA, somatosensory areas SI and SII and the rIPL can be used to interpret observations from the literature that have shown the enhancement of touch through vision of the body. From here, future research should focus on the precise nature of this network and, further, on the EBA's precise role in communicating with other modalities.

# References


1. Adrian, E.D. (1940). Double representation of the feet in the sensory cortex of the cat. Journal of Physiology, **98**, 16-18.

2. Allison, T., Ginter, H., McCarthy, G., Nobre, A. C., Puce, A., Luby, M. and Spencer, D. D. (1994). Face recognition in human extrastriate cortex. Journal of Neurophysiology. **71**, 821–825.

3. Amedi, A., Malach, R., Hendler, T., Peled, S. and Zohary, E. (2001). Visuo-haptic object related activation in the ventral visual pathway. Nature Neuroscience, **4**(3), 324-330.

4. Andrews, T.J. and Ewbank, M.P. (2004). Distinct representations for facial identity and changeable aspects of faces in the human temporal lobe. Neuroimage, **23**, 905-913.

5. Astafiev, S.V., Stanley, C.M., Shulman, G.L. and Corbetta, M. (2004). Extrastriate body area in human occipital cortex responds to the performance of motor actions. Nature Neuroscience, **7(5),** 542-548

6. Avidan, G., Hasson, U., Hendler, T., Zohary, E. and Malach, R. (2002). Analysis of the neuronal selectivity underlying low fMRI signals. Current Biology, **12**, 964-972.

7. Bandettini, P.A., Wong, E.D., Hinks, R.S., Tikofsky, R.S. and Hyde, J.S. (1993). Time course EPI of human brain function during task activation. Magnetic Resonance in Medicine, **25**, 390-397.

8. Bartel, A. and Zeki, S. (2004). Functional brain mapping during free viewing of natural scenes. Human Brain Mapping, **21**, 75-83.

9. Bodamer, J. (1947). Die prosopagnosia. Archiv fur psychiatrie und Nervenkrankheiten, **179**, 6-53.

10. Boyton, G.M. and Finney, E.M. (2003). Orientation-specific adaptation in human visual cortex. Journal of Neuroscience, **23**, 8781-8787.

11. Brett, M. (1999). mni2tal.m. Retrieved September 11, 2003, from Cambridge Imagers Web site: http://www.mrc-cbu.cam.ac.uk/Imaging/mnispace.html

12. Broca, P.P. (1861). Sur le principe des localisations cérébrales. Bulletin de la Société d"Anthropologie. **1861a**, tome II, 190-204.

13. Brodmann, K. (1909). Vergleichende Lokalisationslehre der Großhirnrinde in ihren Prinzipien dargestellt auf Grund des Zellenbaues. Leipzig: Barth J.A.

14. Burton, H. and Sinclair, R. (1996). Somatosensory cortex and tactile perceptions. In: Touch and pain, Kruger, L. (ed.), 105–177. London: Academic Press.

15. Burton, H., Fabri, M. and Alloway, K. (1995). Cortical areas within the lateral sulcus connected to cutaneous representation in areas 3b and 1: a revised interpretation of the second somatosensory area in macaque monkeys. Journal of Comparative Neurology, **355**, 539–562.

16. Buxbaum, L.J. and Coslett. H.B. (2001). Specialsed structural descriptions for human body parts: Evidence from autotopagnosia. Cognitive Neuropsychology, **18(4)**, 289-306.

17. Carandini, M. and Ferster, D. (1997). A tonic hyperpolarization underlying contrast adaptation in cat visual cortex. Science, **276**, 949-952.

18. Carandini, M., Movshon, J.A. and Ferster, D. (1998). Pattern adaptation and cross-orientation interactions in the primary visual cortex. Neuropharmacology. **37**, 501-511.

19. Carey, S. and Diamond, R. (1994). Are faces perceived as configurations more by adults than by children? Visual Cognition, **1**, 253-274.

20. Chaminada, T., Meltzoff, A.N. and Decety, J. (2002). Does the end justify the means? A PET exploration of the mechanisms involved in human imitation. Neuroimage, **15**, 318-328.

21. Chaminade, T., Meltzoff, A.N. and Decety, J. (2005). An fMRI study of imitation: action representation and body schema. Neuropsychologica, **43**, 115-127.

22. Chan, A.W-Y., Peelen, M.V. and Downing, P.E. (2004). The effect of viewpoint on body representation in the extrastriate body area. Cognitive Neuroscience, **15(15)**, 1-4.

23. Chaudhuri, A. (1990). Modulation of the motion aftereffect by selective attention. Nature, **344**(6261), 60-62.

24. Chubb, C., Sperling, G. and Solomon, J.A. (1989). Texture interactions determine perceived contrast. Proceedings of the National Academy of Sciences U.S.A., **86**(23), 9631-9635.

25. Clarke, T.J., Bradshaw, M.F., Field, D.T., Hampson, S.E. and Rose, D. (2005). The perception of emotion from body movement in point-light displays of interpersonal dialogue. Perception, **34**, 1171-1180.

26. Dale, A.M. and Buckner, R.L. (1997). Selective averaging of rapidly presented individual trials using fMRI. Human Brain Mapping, **5**, 329-340.

27. Dale, A.M. and Buckner, R.L. (1997). Selective averaging of rapidly presented individual trials using fMRI. Human Brain Mapping, **5**, 329-340.

28. Damasio, A. R. (1990). Category-related recognition defects as a clue to the neural substrates of knowledge. *Trends in Neuroscience*. **13**, 95–98.

29. Damasio, A.R., Tranel, D., and Damasio, H. (1990). Face agnosia and the neural substrates of memory. Annual Review of Neuroscience, **13**, 89-109.

30. Darian-Smith, I., Galea, M., Darian-Smith, C., Sugitani, M., Tan, A. and Burman, K. (1996). The anatomy of manual dexterity: the new connectivity of primary sensorimotor thalamus and cerebral cortex. In Beck, F., Kriz, W., Sano, Y. and Schiebler, T.H. (eds), Advances in Anatomy, Embryology and Cell Biology. Germany: Springer.

31. De Renzi, E. (1997). Prosopagnosia. In T.E. Feinberg and M.J. Farach (Eds.), Behavioral neurology and neuropsychology, McGraw-Hill: New York.

32. Decety, J. and Sommerville, J.A. (2003). Shared representations between self and other: a social cognitive neuroscience view. Trends in Cognitive Sciences, **17**(12), 527-533.

33. Demb, J.B., Desmond, J.E., Wagner, A.D., Vaidya, C.J., Glover, G.H. and Gabrieli, J.D. (1995). Semantic encoding ad retrieval in the left inferior prefrontal cortex: a functional MRI study of task difficulty and process specificity. Journal of Neuroscience, **15**, 5870-5878.

34. Desimone, R. (1991). Face-selective cells in the temporal cortex of monkeys. Special issue: face perception. Journal of Cognitive Neuroscience, **3**, 1-8.

35. Desimone, R. (1996). Neural mechanisms for visual memory and their role in attention. Proceedings of the National Academy of Sciences U.S.A, **93**, 13494-13499.

36. Desimone, R., Albright, T.D., Gross, C.G. and Bruce, C. (1984). Stimulus-selective properties of inferior temporal neurons in the macaque. The Journal of Neurosciece, **4**(8), 2051-2062.

37. Disbrow, E., Roberts, T. and Krubitzer, L. (2000). Somatotopic organization of cortical fields in the lateral sulcus of *Homo sapiens*: Evidence for SII and PV. The Journal of Comparative Neurology, **418**, 1-21.

38. Donaldson, D.L. and Buckner, R.L. Effective paradigm design. In Jezzard, P., Matthews, P.M., Smith, S.M. (2001). Functional MRI: an introduction to methods. Oxford: Oxford University Press.

39. Downing, P.E., Bray, D., Rogers, J. and Childs, C. (2004). Bodies capture attention when nothing is expected. Cognition, **93**. B27-B38.

40. Downing, P.E., Jiang, Y., Shuman, M. and Kanwisher, N. (2001). A cortical area selective for visual processing of the human body. Science, **293**, 2470-2473.

41. Downing, P.E., Peleen, M.V., Wiggett, A.J. and Tew, B.D. (in press). The role of the extrastriate body area in action perception. Social Neuroscience.

42. Engel, S.A. (2005). Adaptation of orientated and unorientated color selective neurons in human visual areas. Neuron, **45**, 613-623.

43. Epstein, R., Graham, K.S. and Downing, P.E. (2003). Viewpoint-specific scene representation in human parahippocampal cortex. Neuron, **37**. 865-876.

44. Epstein, R., Harris, A., Stanley, D. and Kanwisher, N. G. (1999). The parahippocampal place area: recognition, navigation, or encoding? Neuron, **23**. 115–125.

45. Ewbank, M.P., Schluppeck, D. and Andrews, T.J. (2005). fMR-adaptation reveals a distributed representation of inanimate objects and places in human visual cortex. NeuroImage, **28**, 268-279.

46. Farrer, C., Franck, N., Georgieff, N., Frith, C.D., Decety, J. and Jeannerod, M. (2003). Modulating the experience of agency: a position emission tomography study. NeuroImage, **18**, 324-333.

47. Flourens, J.P. (1825). Experiences sur le système nerveux. Paris.

48. Forder, J.R., Nayak, K. and Pohost, G.M. (2002). Faster speed, better spatial resolution lead 3T benefits: New pulse sequences and strategies for cardiac imaging and spectroscopy must be developed. Diagnostic Imaging, **24**(13). 65-73.

49. Francis, S.T., Kelly, E.F., Bowtell, R., dunseath, W.J.R., Folger, S.E. and McGlone, F. (2000). fMRI of the responces to vibratory stimulation of digit tips. Neuroimage, **11**, 188-202.

50. Friston K. J. (1994). Functional and effective connectivity in neuroimaging: a synthesis. Human Brain Mapping, **2**, 56–78.

51. Friston, K.J., Price, C.J., Fletcher, C.J., Moore, C.J. and Frackowiak, R.S.J. and Dolan, R. (1996). The trouble with cognitive subtraction. NeuroImage, 4, 97-104.

52. Fritsch, G. and Hilzig., E. (1870). On the electrical excitability of the cerebrum. In: von Bonin, C. (ed). The cerebral cortex. Springfield (IL): Charles C. Thomas.

53. Gainotti, G., Caltagirone, C., Careechi, A. and Ibba, A. (1976). Studio sperimentale dell'autotopagnosia. Rivista di Patologia Nervosa e Mentale. **97**. 97-114.

54. Gall, F. and Spurzheim, G. (1810-1819). The Anatomy and Physiology of the Nervous System in General and the Brain in Particular (4 volumes). Paris: F.Schoell.

55. Giese, M.A. and Poggio, T. (2003). Neural mechanisms for the recognition of biological movements. Nature Reviews Neuroscience. **4**, 179-192.

56. Goyal, M.S., Hansen, P.C. and Blakemore, C.B. (2006). Tactile perception recruits functionally related visual areas in the late-blind. Neuroreport, 17(13), 1381-184.

57. Grill-Spector, K. and Malach, R. (2004). The human visual cortex. Annual Review of Neuroscience, **27**, 649-677.

58. Grill-Spector, K., and Malach, R. (2001). fMR-adaptation: a tool for studying the functional properties of human cortical neurons. Acta Psychologica. **107**. 293-321.

59. Grill-Spector, K., Henson, R. and Martin, A. (in press). Repetition and the brain: neural models of stimulus-specific effects. TRENDS in Cognitive Sciences.

60. Grill-Spector, K., Knouf, N. and Kanwisher, N. (2004). The fusiform face area subserves face perception, not generic within-category identification. Nature Neuroscience, 7(5), 555-562.

61. Grill-Spector, K., Kourtzi, Z. and Kanwisher, N. (2001). The lateral occipital complex and its role in object recognition. Vision Research, **41**,1409-1422.

62. Grill-Spector, K., Kushnir, T., Edelman, S., Avidan, G., Itzchak, Y. and Malach, R. (1999). Differential processing of objects under various viewing conditions in the human lateral occipital complex. Neuron, **24**, 187-203.

63. Grill-Spector, K., Kushnir, T., Edmond, S., Itzchak, Y. and Malach, R. (1998). Cue invariant activation in object-related areas if of the human occipital lobe. Neuron, **21**, 191-202.

64. Grill-Spector, K., Kushnir, T., Hendler, T., Edelman, S., Itzchak, Y. and Malach, Y. (1998). A sequence of object processing stages revealed by fMRI in the human occipital lobe. Human Brain Mapping, **6**, 316-328.

65. Grill-Spectore, K., Kourtzi, Z. and Kanwisher, N. (2001). The lateral occipital complex and its role in object recognition. Vision Research, **41**, 1409-1422.

66. Gross, C.G., Roche-Miranda, G.E. and Bender, D.B. (1972). Visual properties of neurons in the inferotemporal cortex of the macaque. Journal of Neurophysiology, **35**, 96-111.

67. Grossman, E.D. and Blake, R. (2002). Brain areas active during visual perception of biological motion. Neuron, **35**, 1167-1175.

68. Guariglia, C., Piccardi, l., Puglisi Allegra, M.C. and Traballesi, M. (2002). Is autotopagnosia real? EC says yes. A case study. Neuropsychologia, **40**, 1744-1749.

69. Guariglia, C., Piccardi, L., Puglisi-Allegra, M.C. and Traballesi, M. (2002). Is autotopoagnosia real? EC says yes. A case study. Neuropsychologia. **40**(10), 1744-1749.

70. Haggard, P., Taylor-Clarke, M. and Kennett, S. (2003). Tactile perception, cortical representation and the bodily self. Current Biology, **13**(5). 170-173.

71. Haggard, P., Taylor-Clarke, M. and Kennett, S. (2003). Tactile perception. cortical representation and the bodily self. Current Biology, **13**(*5*), 170-173.

72. Halliday, A.M. and Mingay, R. (1964). On the resolution of small time intervals and the effect of conduction delays on the judgment of simultaneity. Quarterly Journal of Experimental Psychology, **16**, 35–46.

73. Harrington, G.S., Wright, C.T. and Hunter-Downs III, J. (2000). A new vibrotactile stimulator for functional MRI. Human Brain Mapping, **10**, 140-145.

74. Haxby, J. V., Grady, C. L., Horwitz, B., Ungerleider, L. G., Mishkin,M., Carson, R. E., Herscovitch, P., Schapiro, M. B. and Rapoport,S. I. (1991). Dissociation of object and spatial visual processing pathways in human extrastriate cortex. Proceedings of the Natural Academy of Science USA. **88**, 1621–1625.

75. Haxby, J. V., Ungerleider, L. G., Clark, V. P., Schouten, J. L., Hoffman, E. A. and Martin, A. (1999). The effect of face inversion on activity in human neural systems for face and object perception. Neuron, **22**, 189-199.

76. Haxby, J.V., Gobbini, M.I., Furey, M.L., Ishai, A., Schouten, J.L. and Pietrini, P. (2001). Distributed and overlapping representations of faces an objects in ventral temporal cortex. Science, **293**, 2425-2430.

77. Henson, R., Shallice, T., and Dolan, R. (2000). Neuroimaging evidence for dissociable forms of repetition priming. Science, **287**, 1269-1272.

78. Henson, R.N.A. (2003). Neuroimaging studies of priming. Progress in Neurobiology, **70**, 53-81.

79. Hui, K.K.S., Liu, J., Makris, N., Gollub, R.L., Chen, A.J.W., Moore, C.I., Kennedy, B.R.R. and Kwong, K.K. (2000). Acupuncture moulates the limbic system and subcortical gray structures of the human brain: Evidence from fMRI studies in normal subjects. Human Brain Mapping, **9**, 13-25.

80. Hyvarinen, J. (1982). The Parietal Cortex of Monkey and Man. Studies of Brain Function, Volume 8. Berlin: Springer-Verlag.

81. Iacoboni, M., Koski, L.M., Brass, M., Bekkering, H., Woods, R.P., Dubeau, M-C., Mazziotta, J.C. and Rizzolatti, G. (2001). Reafferent Copies of Imitated Actions in the Right Superior Temporal Cortex. Proceedings of the National Academy of Sciences of the United States of America. **98**(24). 13995-13999.

82. Ito, M. (1989). Long-term depression. Annual Behavioural Neuroscience, **12**. 85-102.

83. Itto, M., Tamura, H., Fujita, I. and Tanaka, K. (1995). Size and position invariance of neuronal responses in monkey inferotemporal cortex. Journal of Neurophysiology, **73**, 218-226.

84. Jezzard, P., Matthews, P.M. and Smith, S.M. (2001). Functional MRI: an introduction to methods. Oxford: Oxford University Press.

85. Kaas, J.H. (1983). What, if anything, is SI? Organization of first somatosensory area of cortex. Physiological Review, **63**(1), 206-231.

86. Kaas, J.H. and Collins, C.E. (2001). The organisation of sensory cortex. Current Opinions in Neurobiology, **11**(4), 498-504.

87. Kanwisher, N. (2000). Domain specificity in face processing. *Nature* Neuroscience, **3**(8), 759-763.

88. Kanwisher, N. G., McDermott, J. and Chun, M. M. (1997). The fusiform face area: a module in human extrastriate cortex specialized for face perception. Journal of Neuroscience, **17**, 4302–4311.

89. Kapfer, D., Stippich, C., Hempel, E., Jansen, O., Heiland, S. And Sartor, K. (1999). Somatotopic fMRI Localization by Tactile Stimulation. Human Brain Mapping, Poster Number 845.

90. Kennet, S., Taylor-Clarke, M. and Haggard, P. (2001). Noninformative vision improves the spatial resolution of touch in humans. Current Biology. **11**. 1188-1191.

91. Keysers, C., Wicker, B., Gazzola,V., Anton, J-L., Fogassi, L. and Gallese, V. (2004). A touching sight: SII/PV activation during the observation and experience of touch. Neuron, **42**, 335-346.

92. Krause., F. (1908). Chirurgerie des Gehirns und Ruckenmarks nach eigenen Erfahrungen. Berlin, Urban and Schwarzenberg; 1908.

93. Krekelberg, B., Boynton, G.M. and van Wezel, R.J.A. (2006). Adaptation: from single cells to BOLD signals. TRENDS in Neuroscience, **29**(5), 250-256.

94. Kriegstein, K., Kleinschmidt, A. and Giraud, A-L. (2005). Voice Recognition and Cross-Modal Responses to Familiar Speakers' Voices in Prosopagnosia. Cerebral Cortex, **16**(9),1314-1322.

95. Krubitzer, L. (1995). The organization of neocortexin mammals: are species differences really so different? Trends in Neuroscience, **18**, 408–417.

96. Laird, A.R., Lancaster, J.L. and Fox, P.T. (2005). BrainMap: The social evolution of a functional neuroimaging database. Neuroinformatics, **3**, 65-78.

97. Lander, K. and Chuang, L. (2005). Why are moving faces easier to recognize? Visual Cognition, **12**(3), 429-442.

98. Lavie, N., Ro, T., and Russell, C. (2003). The role of perceptual load in processing distractor faces. Psychological Science, **14(5)**, 510-515.

99. Levinson, E. and Sekuler, R. (1980). A two-dimensional analysis of direction-specific adaptation. Vision Research, **20**(2), 103-107.

100. Li, L., Miller, E.K. and Desimone, R. (1993). The representation of stimulus familiarity in anterior inferior temporal cortex, Journal of Neurophysiology, **69**. 1918-1929.

101. Logothesis, N.K., Guggenberger, H., Peled, S. and Pauls, J. (1999). Functional imaging of the monkey brain. Nature Neuroscience, **2**, 555–562.

102. Macaluso, E., Frith, C., Driver, J. (2000). Selective spatial attention in vision and touch: Unimodal and multimodal mechanisms revealed by PET. Journal of Neurophysiology, **83**(5), 3062-3075.

103. Macaluso, E., Frith, C., Driver, J. (2000). Selective spatial attention in vision and touch: Unimodal and multimodal mechanisms revealed by PET. Journal of Neurophysiology, **83**(5), 3062-3075.

104. Macaluso, E., Frith, C.D. and Driver, J. (2001). Supramodal Effects of Covert Spatial Orienting Triggered by Visual or Tactile Events. Journal of Cognitive Neuroscience, **14**(3), 389 - 401.

105. Macaluso, E., Frith, C.D. and Driver, J. (2001). Supramodal Effects of Covert Spatial Orienting Triggered by Visual or Tactile Events. Journal of Cognitive Neuroscience, **14**(3), 389 - 401.

106. Maeda, K., Kakigi, R., Hoshiyama, M. and Koyama, S. (1999). Topography of the secondary somatosensory cortex in humans a magnetoencephalo-graphic study. Neuroreport, **10**, 55-62.

107. Malach, R., Reppas, J. B., Benson, R. R., Kwong, K. K., Jiang, H., Kennedy. W. A., Ledden, P. J., Brady, T. J., Rosen, B. R., & Tootell, R. B. (1995). Object-related activity revealed by functional magnetic resonance imaging in human occipital cortex. Proceedings of the Natural Academy of Science USA, **92**, 8135–8139.

108. McGlone, F., Kelly, E.F., Trulsson, M., Francis, S.T., Westling, G. and Bowtell, R. (2002). Functional neuroimaging studies of human somatosensory cortex. Behavioural Brain Research, **135**, 147-158.

109. McGonigle DJ. (2004). Somesthetic Function, in Human Brain Function, Eds: Frackowiak, Friston, Frith, Mazziota, Dolan. Elsevier.

110. Molavi, D.W. (1997). The Washington School of Science Neuroscience Tutorial. (http://thalamus.wustl.edu/course/bassens.html).

111. Moscovitch, M., Winocur, G. and Behrmann, M. (1997). What is special about face recognition? Nineteen experiments on a person with visual object agnosiaand dyslexia but normal face recognition. Journal of Cognitive Neuroscience, **9**, 555-604.

112. Mountcastle, V.B., Lynch, J.C., Georgopoulos, A., Sakata, H., and Acuna, C. (1975). Posterior parietal association cortex of the monkey: command functions for operations within extrapersonal space. Journal of Neurophysiology, **8**, 871–908.

113. Myers, A.G. and Sowden, P.T. (in prep). Seeing Yourself: The Extrastriate Body Area. *Target Journal:* Nature Neuroscience.

114. Ogawa, S., Menon, R.S., Tank, D.W., Kim, S.G., Merkle, H., Ellermann, J.M. and Ugurbil, K. (1993). Functional brain mapping by blood oxygenation level-dependent contrast magnetic resonance imaging. A comparison of signal characteristics with a biophysical model. Biophysical Journal, **64**, 803-12.

115. Ogden, J.A. (1985). Autotopagnosia: occurance in a patient without nominal aphasia and with an intact ability to point to part of animals and objects. Brain, **108**, 1009-1022.

116. Ohzawa, I., Sclar, G. and Freeman, R.D. (1985). Contrast gain control in the cat's visual system. Journal of Neurophysiology, **54**(3), 651-667.

117. Overduin, S.A. and Servos, P. (2004). Distributed digit somatotopy in primary somatosensory cortex. Neuroimage, **23**, 462-472.

118. Pavani, F., Spence, C. and Driver. (2000). Visual capture of touch: Out-of-the-body experiences with rubber gloves. Psychological Science **11**, 353-359.

119. Pavani, F., Spence, C. and Driver. (2000). Visual capture of touch: Out-of-the-body experiences with rubber gloves. Psychological Science **11**, 353-359.

120. Pavani, F., Spence, C. and Driver. (2000). Visual capture of touch: Out-of-the-body experiences with rubber gloves. Psychological Science **11**, 353-359.

121. Peleen, M.V. and Downing, P. (2005). Selectivity for the human body in the fusiform gyrus. Journal of Neurophysiology, **93**, 603-608.

122. Peleen, M.V. and Downing, P.E. (2005). Is the extrastriate body area involved in motor actions? Nature Neuroscience, **8(2)**, 125-126.

123. Peleen, M.V., Wiggett, A.J. and Downing, M.V. (2006). Patterns of fMRI activity dissociate overlapping function brain areas that respond to biological motion. Neuron, **49**, 815-822.

124. Penfield, W. and Boldrey, E. (1938). Somatic motor and sensory representation in the cerebral cortex of an as studied by electrical stimulation. Brain, **15**, 389-443.

125. Penfield, W. and Jasper, H. (1954). Epilepsy and the Functional Anatomy of the Human Brain. Boston, MA: Little, Brown & Co.

126. Pfeuffer, J., Steudel T., Merkle, H. and Logothetis, N.K. (2004). Perfusion-based high-resolution fMRI in the primate brain using a novel vertical large-bore 7 Tesla setup. 10th Annual Meeting of the Organization for Human Brain Mapping, Budapest, **TH317**.

127. Phelps, E.A. (2001). Faces and races in the brain. Nature Neuroscience, **4(8)**. 775-776.

128. Pick, A. (1922). Sorrung der orentierung am eigenen korper. Psychologische Forschhung, **2**, 303-318.

129. Pinsk, M.A., DeSimone, K., Moore, T., Gross, C.G. and Kastener, S. (2005). Representation of faces and body parts in macaque temporal cortex: A functional MRI study. Proceedings of the National Academy of Sciences, **102(19)**. 6996-7001.

130. Posner, M.I. (1980). Orienting of attention. Quarterly Journal of Experimental Psychology, **32**, 3-25.

131. Ramachandran, V.S. and Rogers-Ramachandran. D. (1996). Synaesthesia in phantom limbs induced with mirrors. Proceedings of the Royal Society of London B - Biological Sciences, **263**, 377-286.

132. Reed, C., Stone, V.E., Bozova, S. and Tanaka, J. (2003). The body-inversion effect. Psychological Science, **14(4)**, 302-308.

133. Reed, C.L., McGoldrick, J.E., Shackelford, J.R. and Fidopiastis, C.M. (2004). Are human bodies represented differently from other objects? Experience shapes object representations. Visual Cognition, **11(4)**. 523-550.

134. Reynolds, J.H., Pasternak, T. and Desimone, R. (2000). Attention increases sensitivity of V4 neurons. Neuron, **26**(3), 703-714.

135. Rezec, A., Krekelberg, B. and Dobkins, K.R. (2004). Attention enhances adaptability: evidence from motion adaptation experiments. Vision Research, **44**. 3035-3044.

136. Roland, P.E., O'Sullivan, B. and Kawashima, R. (1998). Shape and roughness activates different somatosensory areas in the human brain. Proceedings of the National Academy of Sciences USA, **95**, 3295-3300.

137. Ruben, J., Schwiemann, J., Deuchert, M., Meyer, R., Krause, T., Curio, G., Villringer, K., Kurth, R. and Villringer, A. (2001). Somatotopic organisation of human secondary somatosensory cortex. Cerebral Cortex, **11**, 463-473.

138. Sauguet, J., Benton A.L. and Hecaen (1971). Disturbances of body schema in relation to language impairment and hemispheric locus of lesion. Journal of Neurology, Neurosurgery and Psychiatry, **34**, 496-501.

139. Saxe, R., Jamal, N. and Powell, L. (2005). My body or yours? The effect of visual perspective on cortical body representations. Cerebral Cortex, **16**. 587-595.

140. Schaefer, M., Flor, H., Heinze, H-J. and Rotte, M. (2006). Dynamic modulation of the primary somatosensory cortex during seeing and feeling a touched hand. NeuroImage, **29**, 587-592.

141. Schimidt, C.F., Pruessmanni, K.P., Jaermann, T. Lamerichs. R. and Boesiger. P. (2002). High-resolution fMRI using SENSE at 3 Tesla. Proceedings of the International Societrey for Magnetic Resonance Medicine, **10.**

142. Schwindt, P.C., Spain, W.J., Crill, W.E. (1989). Long-lasting reduction of excitability by a sodium-dependent potassium current in cat neocortical neurons. Journal of Neurophysiology, **61**, 233-244.

143. Schwoebel, J. and Coslett, H.B. (2005). Evidence for multiple, distinct representations of the human body. Journal of Cognitive Neuroscience, **17**(4), 543-553.

144. Sereno, M.I., Dale, A.M., Reppas, J.B., Kwong, K.K., Belliveau, J.W., Brady, T.J., Rosen, B.R. and Tootell, R.B.H. (1995). Borders of multiple visual areas in human revealed by functional magnetic resonance imaging. Science, **268**, 889-893.

145. Sereno, M.I., McDonald, C.T. and Allman, J.M. (1994). Analysis of retinotopic maps in extrastriate cortex. Cerebral Cortex, **4**, 601-620.

146. Silva, M.M. (2005). Schema-based influences on the perception of, and memory for, real world scenes. Unpublished Doctoral Thesis, University of Surrey, Surrey, UK.

147. Slaughter, V., Heron, M., and Sim, S. (2002). Development of preferences for the human body shape in infancy. Cognition, **85(3)**, B71-B81.

148. Slaughter, V., Stone, V.E. and Reed, C. (2004). Perception of faces and bodies: Similar or different? Current Directions in Psychological Science, **13(6)**, 219-223.

149. Spence, C., Kingstone, A., Shore, D.I. and Gazzaniga, M.S. (2001). Representation of visuotactile space in the split brain. Psychological Science, **12**, 90-93.

150. Spence, C., Pavani, F. and Driver, J. (1998). What crossing the hands can reveal about visuotactile links in spatial attention. Abstract of the Psychonomic Society **3,** 13.

151. Stewart, L., Meyer, B., Frith, U., & Rothwell, J. (2001). Left posterior BA37 is involved in object recognition: a TMS study. Neuropsychologia, **39**, 1–6.

152. Stippich, C., Hofmann, R., Kapfer, D., Hempel, E., Heiland, S., Jansen, O. and Sartor, K. (1999). Somatotopic mapping of the human primary somatosensory cortex by fully automated tactile stimulation using functional magnetic resonance imaging. Neuroscience Letters, **277**, 25-28.

153. Stolle, A., Amann, M., Baudendistel, K., Hoelzl, R., Kleinboehl, D., Maucher, T., Meier, K., Meyer, H. and Schad, L. (2001). Functional mapping of the somatosensory cortex with a new pneumatically driven tactile display matrix. Human Brain Mapping, abstract.

154. Sugiura, M., Kawashima, R., Nakamura, K., Okada, K., Kato, T., Nakamura, A., Hatano, K., Itoh, K., Kojima, S. and Fukuda, H. (2000). Passive and active recognition of one's own face. NeuroImage, **11**, p36-48.

155. Sur, M. (1980). Receptive fields of neurons in areas 3b and 1 of somatosensory cortex in monkeys. Brain Research, **198**, 465–471.

156. Suzuki, K., Yamadori, A. and Fujii, T. (1997). Category-specific comprehension deficit restricted to body parts. Neurocase, **3**, 193-200.

157. Tabachnick, B.G. and Fidell, L.S. (1996). Using Multivariate Statistics 3E, HarperCollins College Publishers: New York. p. 73.

158. Talairach, J., and Tournoux, P. (1988). *Co-planar stereotaxic atlas of the human brain*. Thieme: New York

159. Tarr, M.J. and Gauthier, I. (2000). FFA: a flexible fusiform area for subordinate-level visual processing automized by expertise. Nature Neuroscience, **3**(8), 764-769.

160. Taylor-Clarke, M., Kennet, S. and Haggard, P. (2002). Vision modulates somatosensory cortical processing. Current Biology, **12**. 233-236.

161. Taylor-Clarke, M., Kennett, S. and Haggard, P. (2002). Vision modulates somatosensory cortical processing. Current Biology, **12**, 233-236.

162. Thomas, R., Press, C. and Haggard, P. (2006). Shared representations in body perception. Acta Psychologica, **121**, 317-330.

163. Tipper, S.P., Lloyd, D., Shorland, B., Dancer, C., Howard, L.A. and McGlone, F. (1998). Vision influences tactile perception without proprioceptive orienting. NeuroReport, **9**, 1741-1744.

164. Tipper, S.P., Lloyd, D., Shorland, B., Dancer, C., Howard, L.A. and McGlone, F. (1998). Vision influences tactile perception without proprioceptive orienting. Neuroreport, **9**, 1741-1744.

165. Tipper, S.P., Phillips, N., Dancer, C., Lloyd, D., Howard, L.A. ad McGlone, F. (2001). Vision influences tactile perception at body sites that cannot be viewed directly. Experimental Brain Research, **139**, 160-167.

166. Tipper, S.P., Phillips, N., Dancer, C., Lloyd, D., Howard, L.A. and McGlone, F. (2001). Vision influences tactile perception at body sites that cannot be viewed directly. Experimental Brain Research, **139**, 160-167.

167. Tootell, R.B., Hadjikhani, N.K., Vanduffel, W., Liu, A.K., Mendola, J.D., Sereno, M.I. and Dale, A.M. (1998). Functional analysis of primary visual cortex (V1) in humans. Proceedings of the National Academy of Sciences U.S.A., **95**, 811-817.

168. Turk, M. and Pentaland, A. (1991). Eigenfaces for recognition. Special issue: face perception. Journal of Cognitive Neuroscience, **3**, 71-86.

169. Tyler, L.K., Stamatakis, E.A., Acres, K., Abdallah, S. and Moss, H. (2004). Processing objects at different levels of specificity. *Journal of Cognitive Neuroscience*, **16**(3), p351-362.

170. Uddin, L.Q., Molnar-Szakacs, I., Zaidel, E. and Iacoboni, M. (2006). rTMS to the right inferior parietal lobule disrupts self-other discrimination. SCAN, **1**, 65-71.

171. Urgesi, C., Berlucchi, G. and Aglioti, S.M. (2004). Magnetic stimulation of extrastriate body area impairs visual processing of nonfacial body parts. Current Biology, **14**, 2130-2134.

172. Vallar, G. & Perani, D. (1986). The anatomy of unilateral neglect after right hemisphere stroke lesions. A clinical/CT-scan correlation study in man. Neuropsychologia, **24**, 609-622.

173. Vuilleumier, P. Henson, R. N., Driver, J. and Dolan, R. J. (2002). Multiple levels of visual object constancy revealed by event-related fMRI of repetition priming. Nature Neuroscience, **5**(5), 491-591.

174. Wachsmuth, E., Oram, M.W. and Perrett, D.L. (1994). Recognition of objects and their component parts: responses of single units in the temporal cortex of the macaque. Cereberal Cortex, **4**:509–522.

175. Wall, J.T. (1988). Variable organization in cortical maps of the skin as an indication of the lifelong adaptive capacities of circuits in the mammalian brain. Trends Neuroscience, **11**, 549–557.

176. Wernicke, K., Breslau, Crohn, M. and Weigert (1874). Der aphasische Symptomencomplex. Eine psychologische Studie auf anatomischer Basis.

177. Wilson, M. (2002). Six views of embodied cognition. Psychonomic Bulletin and Review, **9**, 625-636.

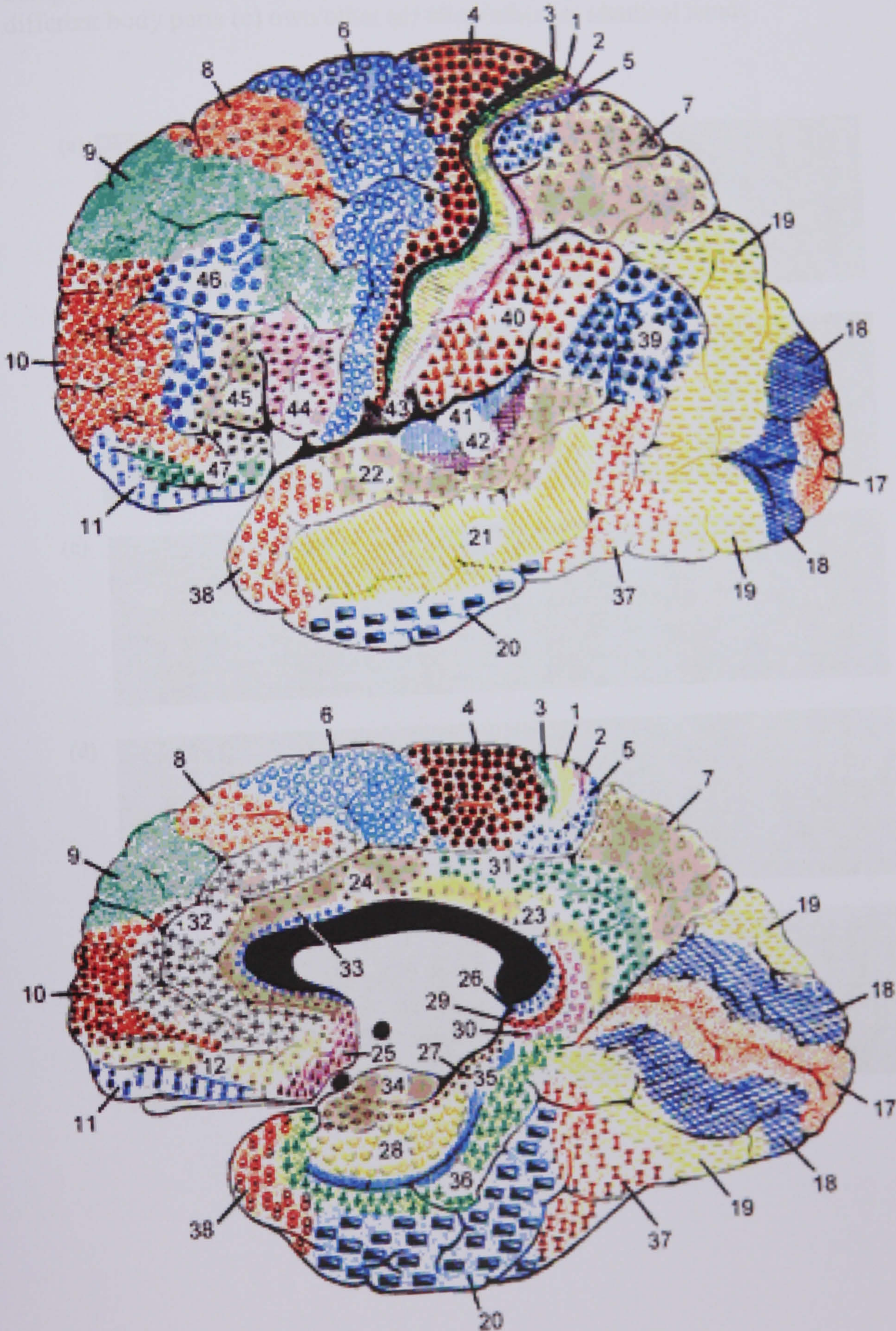
178. Wolbers, T., Weiller, C. and Buchel, C. (2003). Contralateral coding of imagined body parts in the superior parietal lobe. Cerebral Cortex, **13**, 392-399.

179. Yin, R.K. (1969). Looking at upside-down faces. Journal of Experimental Psychology, **81**, 141-145.

180. Yovel, G. and Kanwisher, N. (2004). Face perception: domain specific, not process specific. Neuron, **44**, 747-748.

181. Zappe, A-C., Maucher, T., Meier, K. and Scheiber, C. (2004). Evaluation of a pneumatically driven tactile stimulator device for vision substitution during fMRI studies. Magnetic Resonance in Medicine, **51**, 828-834.

# Brodmann Cytoarchitechtonic Areas*

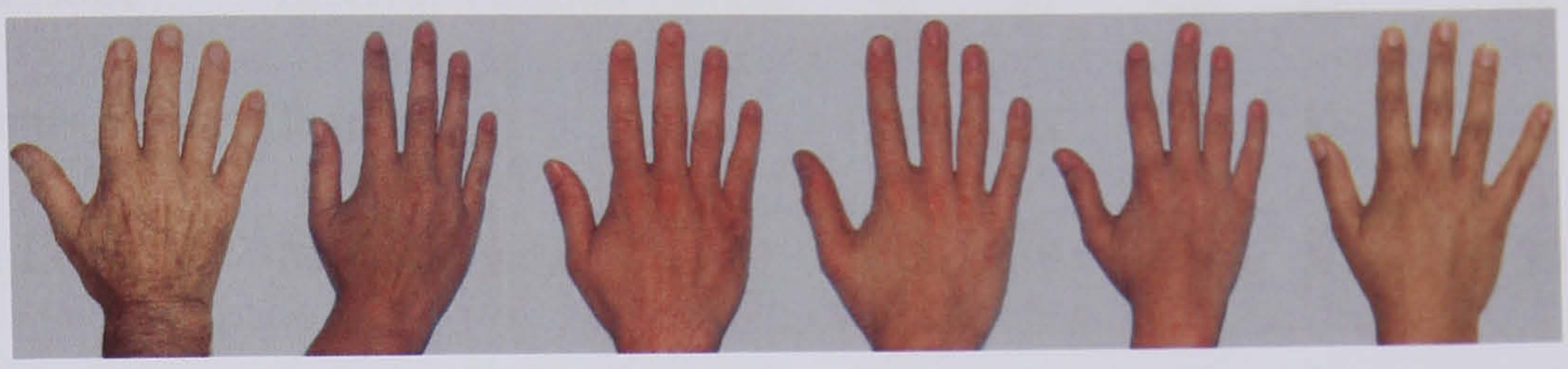



* Brodmann (1909)

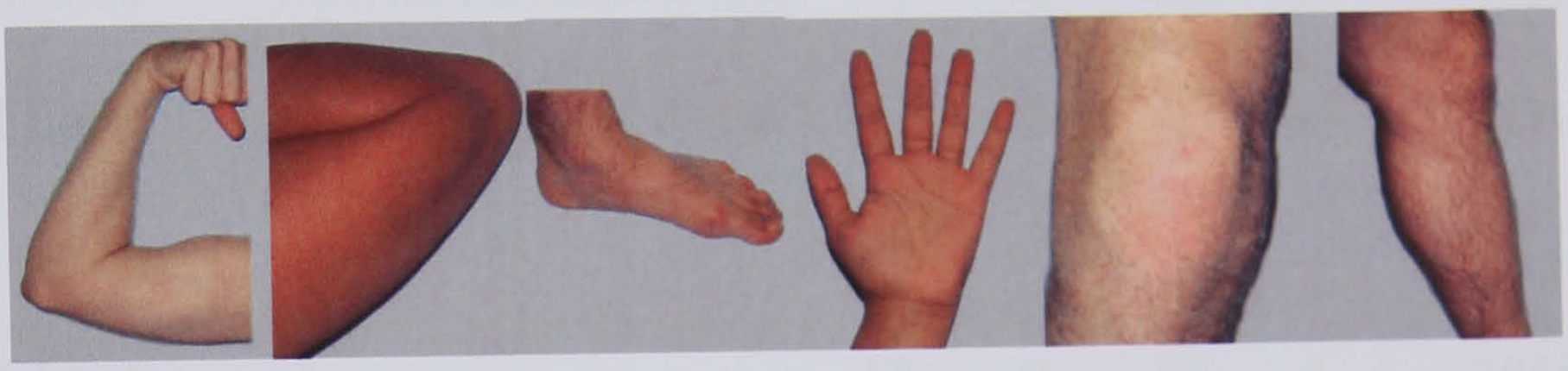
Sample Stimuli from experiment detailed in Chapter Four

Sample stimuli from the experiments detailed in chapter four: (a) different hands (b) different body parts (c) own/other (d) other/other (e) identical hands

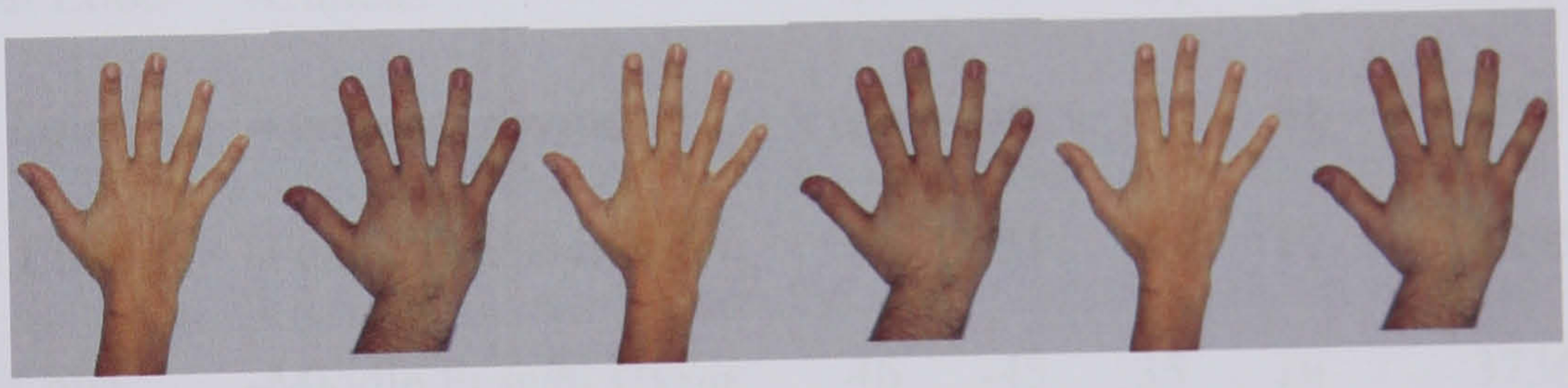
(a)



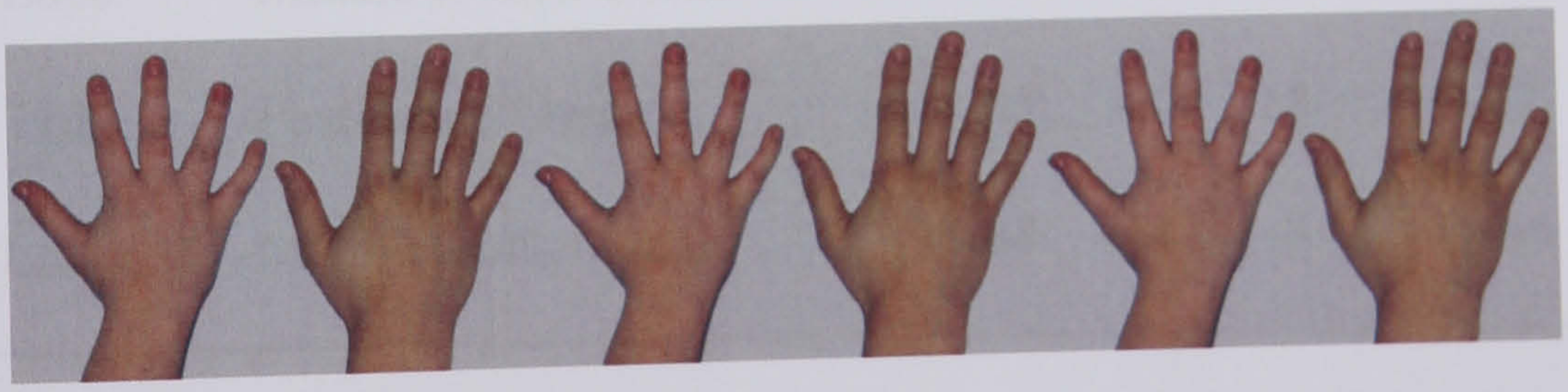
(b)



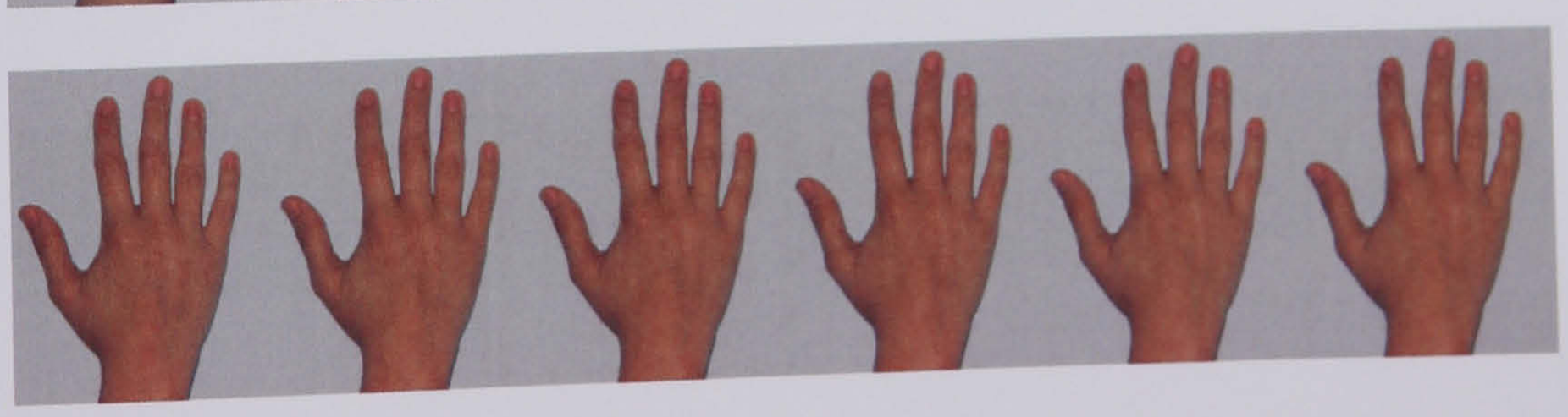
(c)



(d)



(e)



Activation maps produced from a hand minus no stimulation contrast $p<2.1^{-9}$

| | | | Talairach Coordinate | | | |
|---|---|---|---|---|---|---|
| **Region** | | **BA** | **X** | **Y** | **Z** | **Voxel Count** |
| R.Parietal Lobe | -Inferior Parietal Lobule | 40 | 57 | -28 | 22 | 6831 |
| R.Sub-lobar | -Insula | 13 | 45 | 8 | 16 | 13373 |
| R.Frontal Lobe | -Middle Frontal Gyrus | 10 | 39 | 41 | 10 | 395 |
| R.Parietal Lobe | -Inferior Parietal Lobule | 40 | 40 | -52 | 52 | 338 |
| R.Frontal Lobe | -Superior Frontal Gyrus | 6 | 12 | -1 | 61 | 170 |
| L.Occipital Lobe | -Cuneus | 17 | -9 | -91 | 4 | 38550 |
| L.Limbic Lobe | -Cingulate Gyrus | 23 | -9 | -22 | 31 | 718 |
| L.Parietal Lobe | -Postcentral Gyrus | 43 | -51 | -19 | 19 | 8295 |
| L.Frontal Lobe | -Middle Frontal Gyrus | 46 | -45 | 35 | 16 | 3736 |
| L.Parietal Lobe | -Postcentral Gyrus | 2 | -33 | -37 | 58 | 87 |
| L.Frontal Lobe | -Middle Frontal Gyrus | 47 | -48 | 44 | -8 | 166 |

Activation maps produced from a foot minus no stimulation contrast $p<2.1^{-9}$

| | | Talairach Coordinate | | | | |
|---|---|---|---|---|---|---|
| | **Region** | **BA** | **X** | **Y** | **Z** | **Voxel Count** |
| R.Parietal Lobe | -Postcentral Gyrus | 40 | 57 | -22 | 19 | 8654 |
| R,Frontal Lobe | -Inferior Frontal Gyrus | 44 | 51 | 17 | 10 | 2493 |
| R.Frontal Lobe | -Middle Frontal Gyrus | 46 | 45 | 32 | 19 | 1201 |
| R.Parietal Lobe | -Inferior Parietal Lobule | 40 | 39 | -46 | 43 | 5i |
| R.Sub-lobar | -Claustrum | - | 36 | -1 | 7 | 80 |
| R.Sub-lobar | -Claustrum | - | 30 | 17 | 10 | 1153 |
| R.Occipital Lobe | -Inferior Occipital Gyrus | 18 | 33 | -85 | -8 | 408 |
| R.Occipital Lobe | -Lingual Gyrus | 18 | 6 | -79 | -8 | 31955 |
| R.Frontal Lobe | -Superior Frontal Gyrus | 6 | 3 | 8 | 52 | 54 |
| L.Occipital Lobe | -Cuneus | 7 | -9 | -67 | 31 | 914 |
| L.Parietal Lobe | -Postcentral Gyrus | 5 | -18 | -43 | 64 | 2545 |
| L.Frontal Lobe | -Inferior Frontal Gyrus | 47 | -24 | 29 | -2 | 328 |
| L.Sub-lobar | -Insula | 13 | -30 | 14 | 13 | 1540 |
| L.Parietal Lobe | -Postcentral Gyrus | 40 | -54 | -22 | 22 | 3870 |
| L.Frontal Lobe | -Middle Frontal Gyrus | 6 | -36 | -4 | 52 | 319 |
| L.Frontal Lobe | -Precentral Gyrus | 6 | -36 | -7 | 34 | 136 |
| L.Frontal Lobe | -Inferior Frontal Gyrus | 9 | -45 | 8 | 22 | 1821 |
| L.Frontal Lobe | -Precentral Gyrus | 44 | -48 | 2 | 7 | 1487 |
| L.Frontal Lobe | -Middle Frontal Gyrus | 10 | -39 | 41 | 16 | 133 |