Exploration into the domain of consciousness and ‘self’ originated within the realm of philosophical thought. However, neuroscientific research facilitates the transition from conceptualization to empiricism, allowing scientists to locate the underlying neural mechanisms behind this phenomenon. Binding the multiplicity of conscious modalities, including the sense of ownership over one’s experiences, agency over actions and first-person perspective relating to memory, emotion, spatial and environmental awareness, involves a specific integrative mechanism. It is suggested that the predominant candidate for this faculty lies with synchronous firing between distal assemblies of neurons. However, each cell assembly relates to a specific cognitive capacity, the majority of which is circumstantially recruited as and when necessary, and remains transient in nature. The pervasive and underlying aspect of the conscious self comes from the sensation of ownership over phenomenal experience. This remains omnipresent during waking consciousness and can be correlated with activity within the medial prefrontal cortex. This paper reviews evidence from fMRI and PET data, along with investigations involving lesions, neurological dysfunction and meditation providing a map of cooperative neurological regions associated with the various categories of the conscious self. These regions have been located predominantly within the parietal and prefrontal cortices.

**Key words:** medial prefrontal cortex, consciousness, ownership, self.

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### Introduction

Addressing the question of consciousness and the illusive sense of ‘self’ requires the combination of a number of domains, including philosophy, psychology and neuroscience, in order to help provide a multidimensional model that offers a suitable explanation. Naturalistic philosophy dictates that conscious awareness stems from neural processes, and likewise a sense of ‘self’ must correlate with identifiable neural activity. Translated within the field of neuroscience, it should be possible to localize the neural processes relating to the capacity of the ‘self’ and discern whether this can be attributed to a specific region of neural anatomy and/or synchronicity between cooperating regions within the brain.²

The mind automatically attends to an array of phenomenal experiences, including motivation, memory, emotion and a multitude of sensory modalities, coherently representing an apparent objective reality from a subjective perspective.² Despite variance in the structures and geographical locations of the neural architecture responsible for these processes, there exists an observably integrated, singular experience. The mechanisms behind this integration have been the source of numerous investigations when trying to solve the binding problem. As described by Revonsuo¹ as ‘consciousness-related binding’, which is distinctively separate from the integration of purely sensory information, defined as ‘stimulus-related binding’, consciousness here refers specifically to the subjective perspective adopted from an egocentric frame of reference.

Proposed as a prerequisite for the capacity for integration, Vogeley and Fink¹ suggest that it is necessary to adopt a first-person perspective, with this perspective integrating the ‘world model’ with the subject, forming a ‘self-model’. Described by Gallagher⁴ as the ‘minimal’ self, this includes both a sense of ownership over an experience and a sense of agency over decisions and actions. The combination of both external (e.g. visual, auditory, olfactory, etc.) and internal (e.g. proprioception) sensory information is integrated into a unified experience, over which various aspects of an egocentric perspective have dominion.

At this point it is easy, as many psychologists and philosophers have been guilty of, to attribute this phenomenon to a mysterious ghost in the machine. An internal homunculus
within the brain, centrally oriented to receive input and orchestrate action. However, this explanation proves unsatisfactorily circular when considering the mechanisms underlying this homunculus and the origin of the control behind it. Sometimes disguised under the alias of a ‘central executive’, this explanation fails to specifically isolate the neural processes involved with generating the conscious self, and leans more towards folk psychology than empirical science.

Although both a sense of agency and ownership occur simultaneously during voluntary action, David et al. emphasize a distinction between the two. During involuntary limb movements, there is a definite lack of the sense of agency usually attributed to conscious movement, however the sense of ownership over the experience persists. This distinction is important as it highlights the transient nature of agency and, in this case, the continuity of ownership pervading throughout this conscious experience.

The purpose of this paper is to review the evidence compiled from investigations into consciousness and empirically locate the neural processes responsible for generating the egocentric perspective, as defined as a sense of ownership. Evidence will be discussed from four angles. Firstly, the sensation arises from a global synchronicity of neural activity. Secondly, there are distinct anatomical regions within the brain specifically designed to generate this self-perspective. Thirdly, diseases and lesions within specific areas of the brain can result in symptoms of self-dissociation, providing evidence for the location of the neural correlate of self. Fourthly, meditation practitioners claim an ability to dissolve a sense of self. With the aid of fMRI studies, this provides useful insight into the possible neurological mechanisms and anatomy involved with the generation of this perspective.

Synchronicity

To begin with, evidence will be examined to determine how the integrated perspective is generated. It would be prudent to initially look at the mechanisms underlying stimulus-related binding and then investigate any additional features present in consciousness-related binding. Engel et al. look specifically at the integration or binding of sensory information relating to sensory awareness as an aspect of consciousness. The study highlights several important components of the ‘binding problem’. Firstly it addresses the distribution of the processes relating to a particular aspect of cognition, emphasizing that a number of components are typically involved. Secondly it states how during any given period of sensory awareness, information relating to a multitude of different objects and events is simultaneously processed, therefore requiring a specificity when distinguishing between these separate mental representations. Regarding consciousness-related binding, there is a necessity to suitably amalgamate representations when considering the whole context of a situation. They suggest binding must occur initially within specific domains (e.g. visual, temporal, working memory) prior to further integration between these domains. The primary candidate mechanism suggested for the phenomenon of binding is the transient and specific synchronization of neuronal activity, as originally proposed by Crick and Koch, utilizing the temporal facet of activity throughout different groups of functionally specific neurones (assemblies).

Engel et al. cited evidence for both interhemispheric synchronization between assemblies of neurones across the hemispheres and intrahemispheric synchronization of assemblies at different regions within the same hemisphere, along with temporally significant synchronicity between cells within the frontal cortex, all with a temporal accuracy within milliseconds. It was also demonstrated that synchronization of neuronal firing within visual binding ceases if incoherent images are viewed by opposing eyes. Shown nicely in an experiment involving interocular rivalry, in which images are presented dichoptically, i.e. images to both eyes cannot be matched and unified into a single percept, a shift in ocular dominance was discovered with signals from only one eye considered for further processing, ultimately resulting in a corresponding oculomotor response. This study found an increase in synchronicity between neurones involved with the dominant eye, and a decrease in those neurones involved with the suppressed eye. It was concluded that synchronicity of neuronal firing in early levels of processing determined whether a signal enters into conscious perception to then undergo further processing, eventually resulting in an oculomotor response.

The problem faced when trying to apply this model to the unified self-perspective stems from a necessary lack of synchronization between cell assemblies relating to different representations. The conclusions drawn rest on the premise that synchronization integrates neuronal activity within an assembly of spatially separate neurones, and helps only to segment related sensory information within awareness. This does not, however, equate to unifying all modalities globally into the entity of consciousness. The compartmentalization of structured representations from sensory information within temporal binding does not fully account for the macrocosmic integration associated with consciousness. However, introduced within this study comes the notion of frequency-specific synchronicity within the gamma-band frequencies (40–80 Hz), as evidenced during electroencephalogram (EEG)/magnetoencephalogram (MEG) experiments. A correlation is suggested between gamma-band frequencies exhibited within waking human brains and conscious awareness. The citation of evidence for gamma-band synchronization between ventral occipital and prefrontal areas, and prefrontal and posterior regions during visuospatial working memory tasks, supports claims that perhaps gamma-band synchronization plays a role in the integration of
geographically distant regions, and specifically, assemblies relating to different modalities. The thalamus has been identified as particularly important in this respect as evidenced by intralaminar neurones firing within the gamma-band frequency to an array of projections throughout the cortex. Here it has been shown that increased attention to auditory stimulation brings about greater synchronicity within this frequency.

Conceding that a unified, coherent consciousness does not equate to homogeneous synchrony, which presents during the unconscious period of sleep, Engel and Singer speculate synchronicity as the mechanism which binds specific subsets of neuronal assemblies, all of which could be mediated by a hierarchy of binding responsible for the cross-modal synchronisation. It has also been suggested that propagation of cross-modal synchronisation can be attributed to ‘coincidence detectors’. These are cortical neurones that relay synchronisation from dominant input assemblies by adjusting the timing and rhythm of their output. The precise mechanism responsible for generating the hierarchy is yet to be fully understood, however comparisons are made between externally generated sensations and internal influences on neural assemblies by coincidence detectors within the thalamus, which propagates synchronized output signals throughout its cortical network.

Synchronisation of distant cell assemblies is an attractive proposition for integrating a multitude of cognitive processes into a single, coherent perspective, and is one which is supported by a plethora of experimental evidence. However, in the search for the ‘subject’ of the perspective, the sensation of ownership, synchronisation cannot represent the only substrate for consciousness. Rather it serves as an instrument for communicating between distant regions of the brain and integrating multiple processes into a unified experience. As with all studies investigating synchronisation, cell assemblies and specific neural anatomy serve as the vital components. It should therefore be considered that the sensation of ownership might originate from the involvement of a particular region or regions of the brain, which can be integrated via specific synchronisation to generate the global conscious experience.

Neural anatomy

The pervasive sensation of a first-person perspective, as described by Gallagher as the ‘minimal self’, has been inextricably linked to the cognitive capacity for adopting a third-person perspective, as initially described by Premack and Woodruff as a ‘theory of mind’ (TOM). This involves the ability to model another person’s mental states with an understanding that the beliefs held by others are internalized and interpretive, as opposed to exact representations of an objective reality. The discovery of mirror neurons, which become active in both observation of an action and the subsequent implementation of that action, has lead to debate over the existence of a single neurological module responsible for adopting a first-person perspective, and subsequently transposing that into a third-person perspective. This requires a close relationship and proximal neurocircuitry between the two. This opinion reflects the ‘simulation theory’ of the self, which conflicts with the ‘Theory’ stating that each capacity relates to distinctly separate processes.

Vogeley et al. designed a semantic experiment to address this dispute and determine whether the assignment of a ‘TOM’ perspective recruited separate neural architecture to that involved with the assignment of a ‘SELF’ perspective. They employed a number of conditions, each presenting a story followed with a question to monitor the correct assignment of perspective. This was assessed by asking the subject to either infer a behaviour of a third party or participate as one of the characters: (i) a baseline was determined presenting unlinked sentences and asking a question relating to one of the sentences; (ii) a coherent story was presented and a question posed requiring a description of an event, with no particular assignment of perspective; (iii) an isolated ‘TOM’ condition was achieved by presenting a story in which the subject had to correctly assign a third-person perspective without including themselves as a character; (iv) a combined ‘TOM’ and ‘SELF’ condition was achieved by presenting a scenario which required an answer demonstrating the assignment of both a third-person and a first-person perspective and (v) an isolated ‘SELF’ condition was achieved by presenting the subject with a story in which they participated as the only character. Functional magnetic resonance imaging (fMRI) provided maps upon which corresponding neurological activity could be illustrated.

Results indicated some differentiated patterns of neural activity for each condition, suggesting variance in the neural architecture needed for generating the two perspectives. The third-person perspective related to activity principally in the anterior cingulate cortex (Fig. 1a), previously attributed to processing emotional experience as part of the limbic system and more specifically the Papez Circuit. The ‘SELF’ condition generated activity predominantly in the right temporoparietal junction and the medial superior parietal lobes (Fig. 1b).

It has been proposed that the sensation of ownership, as separate from agency, is a pervasive and constant aspect of normal consciousness, and therefore cannot be switched off during waking consciousness. According to this postulate, the ‘TOM’ condition, despite not explicitly pertaining to a first-person perspective, should already prescribe implicitly to this perspective (e.g. the ‘TOM’ condition asks Person A to adopt a third-person perspective resulting in the statement: ‘I think Person B believes…’ however this automatically includes a sense of ownership over the opinion expressed). A parallel can be drawn between the
sensation of agency and third-person perspective, as both faculties are transient and employed circumstantially, whilst the sensation of ownership persists. Therefore, rather than utilizing this study to isolate the neural correlate of the ‘self’, it is important to consider the interaction between the conditions and locate parallel neurological activity, prevalent throughout both. A common region of significant activity, present during both the ‘TOM’ and the ‘SELF’ conditions, lies within the right prefrontal cortex (Fig. 1c).

Vogeley and Fink categorize the self-model into specific contexts and examine fMRI data relating to activity when stimulated by context-specific experiments. These categories include: (i) first-person perspective in space, referring to the centred subjective perspective of one’s own body in space; (ii) first-person perspective in action, referring to a sense of agency over movements and actions; (iii) first-person perspective in social interaction, which replicates and lends support to prior TOM/SELF-based studies; (iv) first-person perspective and body representation, including one’s internal model of one’s body and sensation of bodily movements (e.g.}

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**Figure 1.** The fMRI images displaying the anatomical locations active during various conditions of the experiment. (a) During the isolated (‘TOM’) condition, activity was localized to the anterior cingulate cortex and medial aspect of the superior frontal cortex. (b) During the isolated ‘SELF’ condition, activity was found predominantly in the right temporoparietal junction. (c) Significant activity common to both the ‘TOM’ and ‘SELF’ conditions was found in the right prefrontal cortex. Reprinted from ref. 28, with permission from Elsevier.
proptoception) and (v) a view of the self-conceptualized in relation to an environmental context. The resulting fMRI data shows minimal deviation from a collective of anatomical features exhibiting activity throughout these categories. Table 1 summarizes the results from this study, detailing the categories of self and the corresponding regions of activity, based on fMRI and lesion data.

Although the above-mentioned categories are valid and important characteristics for generating a normal functioning, holistic sense of self, they are not omnipresent during wakeful consciousness. It is important to distinguish which aspects are transient so as to negate them from consideration and isolate which that is pervasive. Some aspects of the ‘self’, for example, are not present until the early stages of human development. Carpendale and Chandler’s aforementioned claim that conscious awareness is discontinuous.28 This study proposes that conscious awareness, despite appearing to be continuous, actually relies upon changes in cognition in which awareness updates in distinct cycles. Based on research by Libet29, discovering a time lag of $\sim 350$ ms between instigating an effect and it actually entering into awareness, it is suggested that this delay allows for comprehensive neural feedback and supports his claim that conscious awareness is discontinuous.28

The brain, however, generates a seemingly continuous stream of consciousness. It is proposed that conscious vectors within the dorsolateral prefrontal cortex add the sensation of continuity to detecting changes in stimuli,28 in much the same way as motion vectors connect an ever-changing stream of still images to produce the impression of motion. Evidence suggesting this region of the brain is important for awareness of change comes from repetitive transcranial magnetic stimulation studies, in which awareness of changes within the visual field was impaired when applied to the right dorsolateral prefrontal cortex.30 This region has also been linked to conscious identification of changes within auditory stimuli31 and working memory.32 Supporting evidence suggests that this region is particularly important within the study of consciousness. Activity within the dorsolateral prefrontal cortex ceases during REM sleep.28 Interestingly, as confirmed by Vogeley and Fink,1 during this period of unconsciousness, activity ceases in orbital and inferior parietal cortices,28 suggesting the global sensation of conscious awareness stems from both parietal and dorsal aspects of the prefrontal regions of the brain.

Carpendale and Chandler’s aforementioned claim that children remain fixed within a self-centred perspective,
prior to the development of the theory of mind, further supports the importance of this region. It was discovered that children also displayed greater activity within the medial prefrontal cortex and the anterior cingulate cortex during ‘self’ conditions. However Vanderwal et al., illustrated that the dorsomedial prefrontal cortex is not exclusively dedicated to the ‘self’, as the SRE links both ‘self’ and ‘other’ conditions to this region. It seems that despite an obvious correlation with the self-perspective, this region is not unique to this faculty.

Disease and lesion data

A particularly useful area when locating functional brain regions comes from examining diseased or damaged brains. Not limited by the low temporal resolution of imaging techniques such as fMRI, or the low spatial resolution of EEG/MEG, brain dissection can relate deficits in cognitive performance to specific regions within the brain. Lesions found within the right posterior parietal cortex are symptomatic of ‘egocentric disorientation’. This inhibits the subject’s ability to orient themselves in relation to the external environment without visual cues. It involves a deficit in communication between one’s self in relation to one’s body, and subsequently one’s conceptual worldview. Vogeley and Fink link the disability anosognosia with damage to the right parietal cortex. This condition prevents sufferers from being aware of other disabilities such as blindness, limiting their first-person perspective in relation to their body representation. These examples show damage resulting in loss or impairment of aspects of the self-model previously described as transient. This evidence cannot entirely rule out these regions as contributors to the pervasive sense of ownership, as the remaining, undamaged parts may be sufficient to maintain this capacity. Nor can we deduce that the prefrontal cortex is exclusively responsible for this omnipres- en-t level of consciousness, as lesions found here do not entirely eradicate ‘higher conscious experience’. In cases where the lateral prefrontal cortex has been completely destroyed, however, patients present with no indication of any levels of consciousness and remain in a persistent vegetative state, suggesting a strong link for its involvement in generating a conscious self.

Consciousness, however, remains an illusive subject to measure and many studies require a linguistic capacity in order to express conscious awareness. Sevush describes a form of non-verbally expressible consciousness correlated with anatomy separate from the left lateral prefrontal cortex. It is suggested that due to direct links with the language centres of the brain, specifically Broca’s area, the left lateral prefrontal cortex relates to an ‘extended consciousness’, whereas bilaterally the medial prefrontal cortex correlates with a ‘core consciousness’. This ‘core consciousness’ appears to correspond with the pervasive sensation of ownership over experiences and is best exemplified by a condition known as intermanual conflict. Having undergone a corpus callosotomy, in which the hemispheres of the brain have been surgically disconnected, patients often exhibit conflicting actions between the two hands, and the sense of ownership over one of their hands disappears. In right-handed people, with dominant left hemispheres, their sense of ownership remains within their dominant hand. This lends great support for the localization of ownership residing within the dominant medial prefrontal cortex.

The disease schizophrenia has been described as a clinical disorder disrupting the self-model. Depersonalization, as a clinical syndrome of schizophrenia, includes disruption of the sensation of ownership and involves the sensation that thoughts have been inserted along with a loss of agency over actions. This has been explained in terms of decreased metabolic activity within the prefrontal cortices and even total loss of activity within the dorsolateral prefrontal cortex. Although this evidence does not differentiate between ownership and agency, it does lend support to previous studies suggesting the involvement of the prefrontal cortex.

Effects of meditation

Finally, the intended outcome of many meditative practices involves the dissolution of a sense of agency and volition. The meditator’s aim is to relinquish conscious control and remain an objective observer of phenomena. PET was used to measure cerebral blood flow in meditation practitioners during various stages of meditation, with the aim to highlight changes within neurological activity during various states of consciousness. Whilst in the meditative state, subjects showed a reduction in blood flow to the dorsolateral prefrontal, anterior cingulate and orbital frontal cortices, striatum, thalamus and cerebellum. Citing evidence of re-entrant loops within these areas, upon which post-synaptic potentials are regulated by dopamine, the study suggested that this inhibition of volition could be related to the dopaminergic system. C-raclopride was used to measure dopamine binding. Results indicated a 7.9% decrease in the C-raclopride binding potential of dopamine within the striatum, correlating approximately with a 65% increase in extracellular dopamine. This study, although not specifically linked with a sense of ownership, highlights the reduced activity within cortical pathways associated with the various aspects of the sense of self. The study described two circuits involved with both the striatum and frontal cortex (Fig. 2).

Reduced function within circuit (i) results in ‘orbitofrontal syndrome’ characterized by poor decision-making and behavioural disinhibition such as impulsiveness. Reduced function within circuit (ii) results in ‘anterior cingulate syndrome’ characterized by symptoms of apathy and
Both sets of symptoms have striking similarities with aspects of the meditative state in which the sensation of agency diminishes. However, a prevalent aspect of this meditative state includes the sensation of ownership over one’s experiences described as an impartial observational perspective. This, therefore, helps partially disregard the regions inactivated during meditation, allowing the focus to reside on the medial prefrontal cortex, as already associated with the sensation of ownership.

**Conclusion**

The subjective nature of this research creates a major limitation in terms of interpretation of mental states. The experimental validity relies upon accurate descriptions from the meditation practitioners concerning their subjective experiences, however the evidence does empirically show systematic change within the neural chemistry during these states.

Further research into anaesthetic awareness would contribute greatly to this ongoing debate. This would allow for the inactivation of much of the transient aspects of consciousness, and help isolate the neural correlate of the ‘core self’. Locating this ‘core self’ has serious implications regarding brain death, and subsequent decisions for organ transplantation. If activity relating to the ‘core self’ resides definitively within a particular subset of neurones found in the medial prefrontal cortex, physicians can use this information to search for neurological activity in patients presenting with little or no consciousness. Currently, two medical opinions are required to assess the level of brain activity within patients prior to brain death being established, and organs made available for transplantation. Detection of activity within this specific region can indicate the presence of conscious awareness, raising a number of ethical considerations and a possible need to re-evaluate the criteria before confirming death or diagnosing coma.

Lesions to the pons or malformation of the basilar artery can result in a condition known as cerebromedullospinal disconnection or locked-in syndrome, in which patients present with no indication of consciousness, however, upon recovery, later describe being fully aware but unable to express themselves. Advances in brain–computer interface technology allow patients to use focused attention to control the movement of a cursor on a screen. This can help improve quality of life by facilitating communication in patients that are ‘locked-in’ or suffer from poor muscular control. Both areas of study could greatly help expand our understanding of the neural mechanisms involved with generating consciousness.

This paper has systematically narrowed down regions within the brain associated with the various aspects of consciousness. Due to the ambiguity surrounding the definition of ‘consciousness’, it has been necessary to explore a multitude of facets suggested within this field. The ‘self-model’ has incorporated internal and external sensory information and sensations of a first-person perspective relating to ownership, agency, working memory and various bodily frames of reference. It has been assumed throughout that the sensation of ownership is an omnipresent phenomenon during waking consciousness and that the different ‘transient’ conscious states occur circumstantially, recruiting specific neurological assemblies dedicated to their specific domains. These have included distinct regions of the parietal lobe and prefrontal cortex. It is proposed that these contingent conscious states arise, flavouring global consciousness with perspectives of agency, TOM, spatial and visual awareness, etc., all resting on a foundation of ownership as the ‘core self’.

Consistent with fMRI, PET and lesion data, the pervading sense of ownership over one’s perspective and experience has
corresponded consistently with neural assemblies within the medial prefrontal cortex, although it cannot be concluded that this region exclusively accommodates this faculty. The integration of a unified consciousness, including the multiplicity of conscious modalities is currently best attributed to synchronicity within cell-assembly firing. From the evidence reviewed here, it is hypothesized that the ‘core self’, that which is pervasive and relates specifically to the sensation of ownership over phenomenal experience, can be attributed to the following processes: sensations pertaining to external stimulation and internal bodily monitoring relate to distal regions of the brain. Regions associated with the transient aspects of the self lie within the parietal and prefrontal cortices. These have been shown to relate to these recruited portions of the ‘self-model’ and are not a prerequisite for the maintenance of a continued ‘core’ self. Neurological activity relating to phenomenon presented within consciousness synchronously fires with the prevalent ‘core’ self, expected to reside within the specific anatomical regions of the medial prefrontal cortex, although it is suggested that this network may extend to both parietal and dorsal aspects of the prefrontal cortex. Synchronicity, as a mechanism, acts as a communicative tool amalgamating different levels of awareness into a global model of consciousness.

It has also been suggested that conscious vectors within this region update cyclically and unify the changing internal environment into an apparent continual stream of experiences. What is important, however, is that neuroscientific exploration has provided new means to investigate the illusive sense of ‘self’, debated and deliberated for thousands of years, reducing the entirety of our conscious selves to a network of neural architecture.

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Author biography

Having finished a 3 year undergraduate course studying Neuroscience and Psychology at Keele University, S.W. has since moved back to his home town of Bournemouth, recently being awarded the directorship of a charity, housing and supporting vulnerable adults across the southwest.

Keele invited S.W. to develop his love for questions and a thirst for answers, particularly relating to the way thought and behaviour can be translated anatomically. This allowed him to explore the questions conjured by philosophers and mystics concerning the nature of the ‘self’ within the credible foundation of science.

S.W.’s passion continues to lie within the exploration of consciousness and mind, allowing him to fuse his love for philosophy within the realm of empiricism.

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