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Brain connectivity and the self: the case of cerebral disconnection

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Abstract

Over the past several years, the study of self-related cognition has garnered increasing interest amongst psychologists and cognitive neuroscientists. Concomitantly, lesion and neuroimaging studies have demonstrated the importance of intact cortico-cortical and cortico-subcortical connections for supporting high-level cognitive functions. Commissurotomy or “split-brain” patients provide unique insights into the role of the cerebral commissures in maintaining an individual’s sense of self, as well as into the unique self-representation capabilities of each cerebral hemisphere. Here we review empirical work examining the integrity of self-related processes in patients with various disconnection syndromes, focusing on studies of self-recognition, ownership, and agency. Taken together, this body of work suggests that an intact corpus callosum enabling interhemispheric transfer is necessary for some, but not all types of self-representations.

Keywords

split-brain; commissurotomy; corpus callosum; self-recognition; self-awareness; brain network; brain connectivity; agency; alien hand; anarchic hand

1. Introduction

The self is a popular topic in psychology and neuroscience. However, the term “self” is often used to discuss multiple different cognitive phenomena, and can thus be difficult to define (Klein & Gangi, 2010). While the field has yet to agree upon a precise definition of the self, we can perhaps all concede that the self is a function of brain states and processes. One useful distinction is that between *physical* aspects of the self, and *psychological* aspects of the self (Gillihan & Farah, 2005). Physical aspects of the self are often examined in studies of self-face recognition, agency, and perspective taking, whereas psychological aspects of the self are often operationalized with studies examining autobiographical memory or other types of self-knowledge (Uddin). This conceptual distinction bears out in neuroimaging work, which has demonstrated that physical or embodied self-related

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processes and psychological or evaluative self-related processes rely on distinct large-scale brain networks (Lieberman, 2007; Uddin, Iacoboni, Lange, & Keenan, 2007). Researchers have been trying in recent years to pinpoint exactly which brain states and processes underlie which forms of self-representation, and how these different representations interact, with varying degrees of success. Like other higher cognitive functions, self-representation in the brain likely relies on the integrity of and communication between large-scale brain networks (Bressler & Menon, 2010).

Commissurotomy, or surgical sectioning of the major cerebral commissures, was at one point the most effective treatment for minimizing the spread of epileptic seizures (Bogen & Vogel, 1976; Gazzaniga, Bogen, & Sperry, 1962)(Figure 1). Commissurotomy and partial callosotomy procedures have been conducted in several cases of intractable epilepsy, though pharmacological treatments have been more widely adopted in recent years. Careful behavioral testing of the patients who have undergone “split-brain” surgery has shed light on the specialized roles of the two cerebral hemispheres, and in particular have allowed for testing theories of positive hemispheric competence (Zaidel & Clarke). Split-brain patients continue to present a unique opportunity for testing the functions of each hemisphere independent from the other, and for helping us to understand the role the corpus callosum plays in cognition (see (Gazzaniga, 2005) and (Zaidel, Iacoboni, Zaidel, & Bogen, 2003) for reviews). Callosal abnormalities can also result from congenital conditions, such as agenesis of the corpus callosum, or from acquired brain damage, tumors, or stroke. In this review we will summarize what is known with regard to self-representation and self-related cognition in split-brain patients and other patients with brain lesions affecting the cerebral commissures. We will focus primarily on studies of visual self-face recognition and agency, or the feeling of ownership of actions.

One of the most widely used methods for assessing self-awareness is the test of self-recognition. Preyer was one of the first to use mirrors to assess the development of self-concept, noting that “...the behavior of the child toward his image in the glass shows unmistakably the gradual growth of consciousness of self out of a condition in which objective and subjective changes are not yet distinguished from each other” (Preyer, 1889). Later, Amsterdam demonstrated that infants around two years of age begin to show evidence of self-recognition in front of a mirror (Amsterdam, 1972), which is the same period during which they begin to use personal pronouns. The ability to mirror-self-recognize has only been reliably demonstrated in higher primates, leading Gallup, who conducted much of the pioneering work, to suggest that the capacity is indicative of an underlying self-concept (Gallup, 1977). Self-recognition studies using functional magnetic resonance imaging have revealed that in the intact adult brain, a fronto-parietal network in the right hemisphere is involved in recognizing the self-face (Platek et al.; Sugiura et al., 2005; Uddin, Kaplan, Molnar-Szakacs, Zaidel, & Iacoboni, 2005).

Another form of self-representation is captured in the concept of the sense of agency, defined as the feeling of being the one generating an action (Farrer & Frith, 2002). This is related to the concept of ownership, or the feeling that a limb belongs to one’s body. Some split-brain patients present with an unusual condition called “alien” or “anarchic hand” syndrome, so named because the patient will display uncontrolled behavior by one extremity, intermanual conflict, or denial of limb ownership (Aboitiz et al., 2003). In this condition the sense of agency and sometimes ownership in the patient is disrupted, and the limb is perceived to be moving involuntarily or to not belong to the patient.

We will begin by reviewing studies of self-face recognition in split-brain patients, then continue with a summary of studies of agency and ownership conducted in these and other patients with callosal disruptions. We will conclude with a discussion of what the reviewed

studies reveal with regards to these types of self-representation and how they are implemented in the brain.

2. The self in “split-brain” patients: self-face recognition

The earliest study to examine responses to self-face stimuli in the split-brain was conducted by Preilowski, who used a scleral contact lens system to allow for prolonged exposure and ocular scanning of complex visual stimuli by one hemisphere at a time (Zaidel, 1975). He found in two split-brain patients that both showed the largest skin resistance response (an index of arousal) when their own faces were presented to the right hemisphere. Amazingly, the skin resistance changes were observed even when the stimuli could not be verbally identified. This led the author to “assume the existence of conscious awareness in the ‘mute, minor’ as well as the ‘speaking, major’ cortical half” (Preilowski, 1977).

Sperry and colleagues, who have for many years espoused the view that the disconnected hemispheres are separately conscious in parallel at a moderately high and approximately equal level (Sperry, 1968) also tested self-recognition in the split-brain. They tested two commissurotomy patients’ reactions to key personal and affect-laden stimuli such as pictures of the self, relatives, pets, and belongings, as well as pictures of public, historical, and religious figures and people in the entertainment industry. The results of this work indicated that the concept of self and general social awareness were present and developed in both the right and left (language-dominant) hemispheres of these patients; responses to stimuli presented to each independent hemisphere were essentially comparable (Sperry, Zaidel, & Zaidel, 1979). Of particular interest, when the subjects were asked to identify a photo of themselves inserted among similar photos in an array of items, they had no difficulty doing so with either hemisphere. This recognition was also accompanied by appropriate emotional reactions. The authors concluded that the combination of correct identifications and appropriate cognitive associations performed by the independent hemispheres provided evidence that human subjectivity and sense of self was similar in the two hemispheres.

Several years later, self-recognition in the split-brain was again assessed, this time with a different paradigm. Morphed face images (between the patient and a familiar colleague, Figure 2) were presented in a lateralized fashion to each hemisphere, and the patient was asked to indicate by button press whether the image presented was himself. In another condition, the patient was asked to judge whether the image presented was the familiar other. The study found that the right and left hemispheres of this particular split-brain patient showed opposite biases; while the right hemisphere showed a bias for recognizing the morphed face as the familiar other, the left hemisphere was biased in favor of recognizing the self. The authors concluded that while both hemispheres were capable of self-recognition, the left hemisphere had an enhanced ability to recognize the self (Turk et al., 2002). However, another interpretation of this finding is that the left hemisphere has a more vague self-representation, and thus is biased to recognize an image as self no matter how low a percentage of the self-face is actually present in the image. The right hemisphere, on the other hand, may have stricter criteria for including an image in the category of self. Subsequent studies used alternative strategies to test behavioral hemispheric competence.

Keenan and colleagues also tested a callosotomy patient using morphed self-face stimuli. In this study, it was presumed that responses with the left hand reflected right hemisphere processing, and responses with the right hand reflected left hemisphere processing. They report that the patient made both greater true-positive and fewer false-positive responses when responding with the left hand to the question “does this image contain portions of your own face?” (Keenan, Wheeler, Platek, Lardi, & Lassonde, 2003). These findings suggest that the right hemisphere is more sensitive to self-recognition. However, it is not universally

accepted that response hand is a reliable indicator of hemispheric performance (Weems & Zaidel, 2005).

Another study published shortly after used the morphed face stimuli paradigm with lateralized presentation to test self-recognition in a complete commissurotomy patient. This study attempted to redress the methodological concerns of the previous studies in three ways, 1) by distinguishing between response bias and sensitivity, 2) by using lateralized stimuli to ensure input and processing by one hemisphere at a time, and 3) by analyzing only data from “pure hemispheric” responses, or responses where the response hand was congruent to the visual field of the stimulus. Using signal detection methods to detect sensitivity to detect a target (the self-face) independent of bias, the authors found, similar to Turk et al., that the left hemisphere had a “self” bias. However, both hemispheres were significantly above chance in their sensitivity to detection of self-faces, whereas only the right hemisphere was sensitive to detection of a familiar other. The authors concluded that the representation of the self that allows for self-face recognition is thus not restricted to a particular hemisphere, but is available to each cerebral hemisphere independently (Uddin, Rayman, & Zaidel, 2005).

One complication when comparing across different studies of split-brain patients is that the patients often have undergone varying degrees of surgical disconnection. Turk et al. tested patient JW at age 48, who underwent a two-stage callosal surgery with sparing of the anterior commissure at the age of 25 (Turk et al., 2002). Keenan and colleagues tested ML, a 26-year-old man who also underwent callosotomy, at the age of 22 (Keenan et al., 2003). Uddin and colleagues, on the other hand, tested a complete commissurotomy patient, NG, at age 70. She had undergone single stage midline section of the anterior commissure, corpus callosum, hippocampal commissure, and massa intermedia at age 29 (Uddin, Rayman et al., 2005). In addition to heterogeneity with respect to surgical histories, these patients had differing epileptic symptom severities pre- and post-operation. To complicate matters further, the experimental designs, behavioral response collection methods, and statistical analyses were not uniform across these three studies, making them difficult to compare to one another. However, all report that both cerebral hemispheres of the patients were able to complete the self-identification task, suggesting that this type of visual self-representation is available independently to each hemisphere.

3. The self in “split-brain” patients: ownership and agency

Some patients with lesions affecting the corpus callosum present with a curious behavior that has come to be termed “alien hand syndrome” (AHS), translated from the French ‘le signe de la main étrangère’ (Brion & Jedynak, 1972). First noted in a discussion of apraxias by Goldstein in 1908 (Goldstein, 1908), the term was used to describe patients who denied ownership of one of their hands, or whose one hand involuntarily performed a movement, often in opposition to the other hand (Akelaitis, 1945). In 1992, Feinberg proposed a distinction between a *frontal* AHS, associated with reflexive grasping and compulsive manipulation of tools, and a *callosal* AHS characterized mainly by intermanual conflict. He reviewed evidence that frontal AHS results from damage to supplementary motor area, anterior cingulate gyrus, and medial prefrontal cortex, whereas callosal AHS results from anterior corpus callosal lesions (Feinberg, Schindler, Flanagan, & Haber, 1992). Aboitiz and colleagues further refined the subtypes of AHS into four categories, 1) diagnostic dyspraxia and intermanual conflict, in which one hand performs actions contrary or opposite to the actions executed by the other hand, 2) alien hand sign, in which the patient reports a subjective feeling that the hand does not belong to him/her, 3) anarchic or wayward hand, in which the affected hand performs goal-directed movements that the patient does not perceive as controlled by his/her own will, and 4) supernumerary hands, in which the patient

reports the subjective feeling of having an extra extremity (Aboitiz et al., 2003). Of these syndromes, a subset can result from callosal damage only while the others result from cortical damage in addition to callosal damage. Intermanual conflict is typically seen with posterior or mid-body corpus callosum lesions, or complete commissurotomy patients in the early post-operative period, and rarely persists in the long term. Alien hand sign can be caused by posterior callosal lesions, but typically also involves damage to parietal cortical areas. Anarchic hand typically results from frontal lobe or anterior corpus callosum lesions, and is distinct from alien hand in that the patient does not lose the feeling that the unwilling hand is his/her own (Aboitiz et al., 2003). There has been one reported case of hemispatial neglect as a result of subacute infarction of the entire corpus callosum, though this is rare (Muangpaisan, Srisajjakul, & Chiewvit, 2005).

The cases of AHS resulting from corpus callosum lesions illustrate the role of the corpus callosum in maintaining an integrated sense of self with regards to body awareness and planning of actions. It appears that communication between the two hemispheres enabled by the anterior corpus callosum is necessary for awareness of initiation of goal-directed movements. Posterior corpus callosum integrity seems necessary for maintaining a sense of limb ownership, as this region interconnects parietal areas involved in self-body representation. Thus, unlike with self-face recognition, interhemispheric communication and coordination appears to be necessary for feeling ownership of one's own actions and body parts.

4. Summary and Conclusions

Studies of individuals with complete or partial corpus callosum lesions have revealed a complex story of representations of the self in the brain. Self-face recognition, on the one hand, appears to be available to both hemispheres in isolation, and does not rely on interhemispheric communication. Subjective feelings of limb ownership and agency, on the other hand, appear to require the posterior and anterior corpus callosum, respectively, **in addition to intact fronto-parietal cortical functioning.**

It is worth noting that in his first studies of individuals who had undergone a split-brain procedure, Bogen observed that his patients “show a remarkable absence of functional impairment in nearly all ordinary behavior” (Bogen, Fisher, & Vogel, 1965). But what accounts for this remarkable adaptation? It has been assumed that some information can be transferred between the hemispheres through subcortical pathways when cortical commissures are no longer available (Funnell, Corballis, & Gazzaniga, 2000). It has recently been shown in a complete commissurotomy patient that residual functional connectivity can be detected between the disconnected hemispheres by examination of low-frequency BOLD MRI signal. The authors suggested that this evidence of continued interhemispheric interaction in the absence of cortical commissures is evidence for subcortical coordination of cortical networks (Uddin et al., 2008).

Directions for future work include examination of other types of self-related cognition in the disconnected hemispheres. While physical aspects of the self, including self-face recognition and agency have been the focus of quite a few studies, less attention has been directed at investigating psychological aspects of the self in split-brain patients and individuals with lesions affecting the corpus callosum. Studies of autobiographical memory and self-knowledge would in particular shed light on the role of the corpus callosum in the maintenance of the psychological self. Split-brain patients continue to challenge the notion of a unified self, as envisioned by Sherrington (Sherrington, 1941), and suggest instead that different aspects of the multifaceted entity we call the self are subserved by distributed neural systems.

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Figure 1.
Structural MRI scan of a commissurotomy patient showing absence of the major cerebral commissures.

Figure 2.

Example of stimuli used in self-recognition studies. Studies of self-face recognition have used morphed face stimuli, wherein a photograph of an individual is combined to varying degrees with a photograph of another individual (adapted from Uddin 2005).