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Motor awareness in anosognosia for hemiplegia: Experiments at last!

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Abstract

Anosognosia for hemiplegia (AHP) is the apparent inability to acknowledge contralesional paralysis, typically following right-hemisphere lesions. Here we review studies that regard AHP as a specific deficit of motor awareness and explain its symptoms by employing an established computational model of motor control. These accounts propose that AHP arises from a breakdown in the monitoring of intended and actual movement. First, we critically examine physiological and behavioural experiments, which attempt to provide an account of AHP by verifying the presence or absence of motor intentions. We then review more recent experiments that endeavour to empirically address the hitherto unexplored role of motor intentions and internal representations of movements in AHP patients' non-veridical (illusory) awareness of movement. Finally, we consider implications of AHP research for clinical practice and the understanding of motor awareness more generally. We conclude that the false experience of movement in AHP may provide insight into what occurs when the mechanism responsible for monitoring and correcting significant discrepancies between predicted and executed actions is impaired. The system seems to continue to operate by deceiving awareness.

Understanding motor awareness in anosognosia for hemiplegia: Experiments at last!

Introduction

Anosognosia for hemiplegia (AHP) is the apparent inability to acknowledge or recognise contralesional paralysis following perisylvian lesions, typically to the right hemisphere (but see Cocchini, Beschin, Cameron, Fotopoulou, & Della Sala, 2009). Patients with AHP have a poorer prognosis than patients with similar motor deficits but without AHP (Jehkonen, Laihosalo, & Kettunen, 2006; Pedersen, Jørgensen, Nakayama, Raaschou, & Olsen, 1996); unfortunately, there is no known treatment for the condition. The presentation of AHP is not uniform, leading to the suggestion that there may be several sub-types of the disorder (Jehkonen, Ahonen, Dastidar, Laippala, & Vilkki, 2000; Marcel, Tegnér, & Nimmo-Smith, 2004). For example, some patients merely fail to appreciate the practical consequences of a recognised motor impairment, while other AHP patients do not acknowledge their disability despite obvious evidence to the contrary (Bisiach & Geminiani, 1991). Unawareness can be specific for a given deficit, such that patients may fail to acknowledge one problem (e.g., paralysis of the upper limb), but recognise another (e.g., lower limb paralysis, or some non-motor-related impairment; Berti, Làdavias, & Della Corte, 1996). Awareness can also occur independently at verbal and behavioural levels (Jehkonen et al., 2006; Marcel et al., 2004; Nimmo-Smith, Marcel, & Tegnér, 2005); for example, AHP patients may admit they have hemiplegia but attempt to walk, or deny paralysis but remain in bed.

Another notable feature of AHP is its delusional character (Turnbull, Jones, & Reed-Screen, 2002; Vuilleumier, 2004). Some patients with AHP express abnormal beliefs and attitudes towards their paretic limbs, including excessive hatred for the paretic limb (misoplegia), disownership (asomatognosia), or attribution of its ownership to someone else (somatoparaphrenia). These beliefs are often maintained despite repeated questioning, logical

arguments, and clear evidence to the contrary, warranting classification as a delusion according to the usual definitions (DSM-IV-TR; American Psychiatric, 2000). AHP patients also have fewer catastrophic reactions (i.e., episodes of tearfulness and emotional breakdown), are unduly optimistic, and/or show emotional indifference regarding their condition. However, AHP patients exhibit an apparently normal *range* of positive and negative emotions (Turnbull, Evans, & Owen, 2005; Turnbull et al., 2002), but tend to direct emotional responses towards objects other than their motor deficit, and respond more slowly to hemiplegia related words (Nardone, Ward, Fotopoulou, & Turnbull, 2007). These findings suggest an implicit awareness of motor deficit in AHP.

This remarkable condition has been the focus of considerable scientific interest over the past few decades; however, an adequate explanation of AHP has failed to emerge. Early studies of AHP were largely descriptive, and used clinical observations to propose that AHP is the result of inter-hemispheric disconnection (Geschwind, 1965), psychological defence (Weinstein & Kahn, 1950, 1955), or a combination of sensory and cognitive deficits hindering the ‘discovery’ of hemiplegia (Levine, 1990; Levine, Calvanio, & Rinn, 1991). However, each of these explanations has failed to withstand subsequent scrutiny when examined directly (see Adair et al., 1997; Berti et al., 1996; Marcel et al., 2004; Small & Ellis, 1996). AHP also shares a complicated relationship with unilateral neglect (i.e., a failure to report, respond, or orient to novel or meaningful stimuli presented to the side opposite a brain lesion; Heilman & Valenstein, 1979). Although the co-occurrence of AHP and neglect is common, AHP and neglect double dissociate (Berti et al., 2005; Bisiach, Vallar, Perani, Papagno, & Berti, 1986; Jehkonen et al., 2000; Jehkonen et al., 2006), suggesting that the two disorders are functionally independent.

Typically, accounts of AHP have been limited in attempting to explain the disorder as the secondary consequence of some concomitant deficit, without making explicit links to a

model of normal motor control, or conducting experimental investigations (see Berti et al., 2007 and; Vuilleumier, 2004 for critical discussions). However, a promising line of recent research proposes that AHP is a specific disorder of motor control awareness (i.e., awareness regarding the control of movement) (Berti & Pia, 2006; Berti et al., 2007; Frith, Blakemore, & Wolpert, 2000a; Pia, Neppi-Modona, Ricci, & Berti, 2004). In the remainder of this article we discuss recent experiments into AHP, in the context of a well-established framework of motor control. We begin by summarising a computational model of motor control (Wolpert, 1997), and describing recent accounts of AHP which utilise this model to provide a theoretical explanation for the disorder. We then present existing research that has focused on substantiating these accounts by verifying whether the intention to move is present or absent in AHP. Subsequently, we present novel experimental studies that examine the hitherto unexplored underlying basis of non-veridical awareness in AHP. Finally, we consider the clinical and theoretical implications of these studies, as well as the limitations of this approach.

Computational models of the motor system and AHP

Computational models of the motor system propose that the central nervous system contains a number of comparators, one of which monitors the congruence between intended and actual movement (Fig. 1). Normally, an internal predictor, or ‘forward dynamic model’, uses an efference copy of motor commands to anticipate the expected sensory consequences of an intended movement. Awareness mainly relies on these motor predictions, whereas actual sensory feedback may not be necessary to construct motor awareness, as long as the overall goal of the movement is achieved (Fournieret & Jeannerod, 1998). Thus, this model implies that whenever the motor system makes a sensory prediction about an intended movement, awareness that this movement has been performed may automatically be constructed (Berti & Pia, 2006). When intended movement is performed as planned, these

sensory predictions match actual sensory feedback, and this awareness of execution is not challenged by the system. Errors in the execution of intended movements produce a mismatch between the expected and actual sensory feedback, and an error signal at the comparator, which can be used to inform and update awareness. The results of several studies provide support for this model: for example, Blakemore and colleagues provide compelling evidence that this model is utilised to discriminate between self- and externally-produced events in healthy individuals (Blakemore, Frith, & Wolpert, 1999; Blakemore, Rees, & Frith, 1998; Blakemore, Wolpert, & Frith, 1998) and patients with abnormal motor awareness (e.g., delusion of control; Blakemore, Smith, Steel, Johnstone, & Frith, 2000; Frith, Blakemore, & Wolpert, 2000b). According to the model, self-produced sensations are normally attenuated because the forward dynamic model can predict their sensory consequences, while externally-produced sensations are accentuated because they cannot be accurately predicted. The existence of the comparator has also been convincingly demonstrated by PET experiments in which healthy volunteers detect discrepancies between intention and sensory feedback (Fink et al., 1999).

Several authors have utilised this computational model of the motor system (or a similar variant) to propose that AHP is a disorder of movement monitoring, arising from a breakdown at various possible locations in the model. Heilman and colleagues (Heilman, 1991; Heilman, Barrett, & Adair, 1998) have proposed that AHP arises from a failure to form an intention to move. According to their interpretation, if the patient is unable to generate a motor intention, then the normally functioning comparator is not primed by the forward model to expect movement. A subsequent lack of movement does not create a mismatch between intended and actual movement, hence patients never discover that they have not moved. Thus, according to Heilman, AHP occurs when the motor comparator is intact, but motor intentions are impaired.

Frith, Blakemore and Wolpert (2000a) propose an alternative account of AHP, which directly contradicts Heilman's feed-forward hypothesis by suggesting that representations of intended movements are preserved in AHP. According to Frith et al., despite an inability to move, patients with AHP are able to compute motor commands and predict the expected sensory consequences of intended movements. If, therefore, the representation of intended movements is intact in AHP and awareness of initiating a movement is based on these representations (Fournier & Jeannerod, 1998), patients with AHP would have the normal experience of having initiated a movement. Furthermore, the erroneous belief that movement has been executed successfully is maintained because of a failure to register the discrepancy between predicted and actual sensory feedback. Frith et al., speculate that this failure may be related to a lack of contrary sensory information about actual movement, since relevant brain areas are damaged or information is neglected.

Berti and colleagues (Berti & Pia, 2006; Berti et al., 2007) follow Frith and colleagues in proposing that patients with AHP form appropriate representations of their intended movements, but are unaware of the discrepancy between intended and actual movement. However, Berti and colleagues take a step further and specify that this failure to detect discrepancies is the result of damage directly to the comparator mechanism, and not visuospatial neglect (as originally suggested by Frith et al., 2000a). Indeed, the position taken by Berti and colleagues excludes a possible causal role of neglect in the failure to register discrepancies and pathogenesis of AHP. Instead, damage located in the comparator itself results in AHP patients constructing (non-veridical) motor awareness based entirely on their intact representations of intended movement. In contrast, hemiplegic patients without anosognosia (i.e., nonAHP) possess preserved awareness about their motor impairment, because they are able to detect when the predicted and actual sensory consequences of their movement do not match. Berti et al., (2007) support this explanation with evidence that the

brain areas involved in monitoring the correspondence between motor commands and sensory feedback (i.e., Brodmann premotor areas 6 and 44; Berti et al., 2005), are damaged in patients with AHP. Furthermore, this hypothesis can account for the transient remission of AHP that has been observed following stimulation of the vestibular system via caloric (i.e., cold water) stimulation of the ear (Cappa, Sterzi, Vallar, & Bisiach, 1987; Rode et al., 1992). According to this explanation, vestibular stimulation may cause a temporary, maximal activation of brain areas that are both afferents of the vestibular system, and also constitute the neural bases of the comparator (i.e., the insula and premotor cortex). This hyperactivation may temporarily restore the spared components of the comparator and normal motor awareness.

Taken together, the above explanations agree that normal motor awareness involves the comparison of intended and actual sensory information; however, the accounts differ regarding the pattern of intact and impaired processes giving rise to AHP. The ability to formulate an intention to move, and the functionality of the comparator, are specific points of disagreement among these accounts. Heilman's feed-forward hypothesis of AHP assumes a failure to form an intention to move in the context of a normally functioning comparator. Frith et al., (2000a), and Berti and colleagues both emphasise that the ability to form motor intentions is intact in AHP, and that a failure to register discrepancy may be due to a malfunctioning comparator (cf. Berti and colleagues) or an absence of sufficient sensory feedback (cf. Frith et al.). The last two accounts, therefore, aim to explain not only why patients are unaware of their motor failures (a negative symptom), but also why they have a non-veridical awareness of having moved, when no such movement has been produced (a positive symptom). In Heilman's account, by contrast, it is difficult to understand how the positive symptom of AHP (i.e., non-veridical awareness that movement has occurred) can arise if patients are unable to form intentions to move. Some studies conducted around the

past decade have attempted to provide clarification on these issues, principally by trying to establish the presence of motor intentions in AHP. We now turn to these studies.

Physiological studies of motor intention in AHP

Gold, Adair, Jacobs and Heilman (1994) provide support for the feed-forward hypothesis using physiological measures of pectoralis majores (pectorales) muscle activity (electromyography, EMG) in a patient with AHP. When healthy individuals move *either* their left *or* right arm, electrical activity and muscle contraction is registered in the pectorales on *both* body sides; i.e., muscle activity on one side of the body is accompanied by a simultaneous activation of the same muscle on the opposite side. This situation arises due to bilateral corticospinal innervation of the pectorales muscles. On this basis, patients with unilateral stroke and hemiplegia, but without anosognosia, should show bilateral muscle activation when asked to move their impaired (paralysed) limb if intention is intact. In contrast, according to the feed-forward hypothesis AHP patients asked to perform the same movement should not show bilateral activation, since the intention to move their impaired limb is defective. Consistent with this, Gold et al., recorded muscle activity in both the left and right pectorales of all controls asked to squeeze a dynamometer with their intact and impaired hand. The patient with AHP did not contract either pectorales muscle when asked to squeeze the dynamometer with his paretic hand, while both pectorales muscles contracted when asked to squeeze with the intact hand.

Gold et al., (1994) interpret their findings as supporting the feed-forward hypothesis of AHP. However, while a loss of intention is a plausible explanation in this case, Berti et al., (2007) suggest that the diagnosis of AHP is debatable in this case. The clinical description of the patient indicated that he was able to squeeze the dynamometer with the paretic hand, indicating that contralesional hemiplegia was not complete. Berti et al., (1996) have suggested that studying unawareness in cases of complete hemiplegia, where the

impossibility of moving the affected limb can be independently corroborated, generates more reliable findings than milder cases where some degree of movement remains possible. The extent to which Gold et al.'s findings contribute to our understanding of AHP, therefore, depends on the diagnostic criteria used to define the disorder. Unfortunately, it is difficult to compare across studies, identified commonalities in findings, and develop a cohesive understanding of AHP if diagnosis is uncertain.

Further physiological investigations of the feed-forward hypothesis have suggested that patients with AHP might possess intact motor intentions. Hildebrandt and Zieger (1995) report a 59-year-old woman who developed AHP for left-sided hemiplegia after a unilateral right-hemisphere haemorrhagic stroke involving the frontal, temporal and parietal lobes. Electrodermal activity (i.e., skin conductance response, SCR) and muscle responses (EMG) were recorded while the patient was asked to perform mental imagery of movement and specific tasks involving use of the impaired hand. Changes in SCR and EMG response were observed from the hemiplegic limb during these procedures, although the left arm always remained hemiplegic. These results suggest that the patient was able to formulate the intention to move and control her forearm muscle activity, despite an inability to execute overt movement and persistent AHP.

A similar EMG study by Berti et al., (2007) confirms the presence of intention for action in AHP. They instructed participants to perform a reaching action with the left or right hand, and compared muscle activity in the back of the neck (i.e., upper trapezius bilaterally) in a patient with AHP, left-hemiplegic control patient without AHP (nonAHP), and neurologically healthy control. An intention to reach with the left or right arm should be accompanied by muscle activity in the ipsilateral trapezius muscle; therefore, an absence of intention to move the hemiplegic limb in AHP would predict no activation of the muscle on the hemiplegic side when asked to reach, whereas a request to reach with the right arm should

result in muscle activity on the unaffected side. In contrast, if intention to move were preserved, the AHP patient should show muscle activation on the side that movement is requested, regardless of actual ability to move (Berti et al., 2007). Findings supported this latter prediction; in all participants, including the AHP patient, muscle activity was elicited when asked to reach with the left arm. Behavioural observations also confirmed that the AHP patient was attempting movement of the left arm requested by the experimenter, demonstrating intact intention to move.

Behavioural studies of motor intention in AHP

Whilst physiological investigation of motor intentions are useful, behavioural observation of intention to move might provide a more direct examination of this ability in AHP. Adair et al. (1997) induced AHP using intracarotid barbiturate injection in patients undergoing preoperative evaluations for intractable epilepsy surgery. After inducing AHP, the formation of an intention to move was manipulated by asking patients to move their paralysed arm, after which changes in awareness were measured. In three out of the four cases, attempted movement was associated with an improvement in awareness of hemiplegia. Awareness of hemiplegia returned in the final patient after attempted movement was combined with visual feedback regarding performance. These findings support the idea that intentions are important for motor awareness, and Adair et al. suggest that AHP may be related to a motor-intention deficit. However, the failure of one of the four patients to regain awareness following an intention to move is not in keeping with the feed-forward hypothesis. In addition, reversal of AHP in one patient only took place when the patient was offered visual feedback, thus highlighting the incongruence between intention and feedback. This finding suggests that the inability to become aware of this incongruence, rather than the lack of motor intention per se is the critical deficit in AHP.

Evidence concerning the feed-forward hypothesis is further complicated by a single case study on AHP reported by Cocchini, Beschin and Della Sala (2002). They examined patient NS, a 27-year-old, right handed man with chronic (i.e., >1 year) AHP following severe closed head injury, which resulted in cortical and subcortical lesions within the frontal lobes bilaterally. When asked to lift his hemiplegic arm and leg, NS “tried very hard to comply with the examiner’s request, resolutely contracting the muscles of his left limbs with no success” (p. 2032). These muscle contractions provide evidence of the intention to move in a patient with AHP, which is inconsistent with the proposal of a motor-intention deficit. However, attempted movements temporarily altered awareness of hemiplegia in NS. He was apparently surprised by his movement failures, making statements such as “oh, dear me, it’s not moving”. As Heilman predicted, this finding suggests that the formation of an intention to perform a specific movement can temporarily increase awareness of hemiplegia. Nevertheless, the exact role of motor intention and its interaction with sensory and visual feedback in these temporary increases of awareness is unclear. Moreover, it remains unknown why these changes in awareness are not permanent in AHP patients, as well as why some patients experience illusory (non-veridical) movements when attempting to move (Feinberg, Roane, & Ali, 2000; Fotopoulou et al., 2008). A far more controlled and systematic experimental procedure than that used by Cocchini et al. is necessary to reliably address such questions. We present a first step towards addressing these outstanding issues in the next section.

In sum, existing evidence regarding the role of motor intentions in AHP does not allow firm conclusions. Physiological studies of AHP rely on indirect inference about the formation of motor intentions via the presence or absence of an autonomic/muscle response, and have produced equivocal results. Likewise, studies examining motor intentions in AHP via patients’ behaviour are inconclusive, as sample sizes are typically very small, procedures

are uncontrolled, and the findings do not provide clear support for either position. Moreover, verification of the presence or absence of the intention to move is not sufficient to explain the non-veridical awareness of action in some AHP patients (see also Berti et al., 2007 for discussion).

The role of motor intention in AHP: a new study of patients' non-veridical awareness of action

Although motor intentions have been the focus of the AHP studies reviewed in the above sections, none have directly investigated the role of motor intention in the generation of illusory movements in AHP (i.e., instances of non-veridical awareness of movement). This was the aim of a recent study involving patients with lesions to the territory of the right middle cerebral artery (Fotopoulou et al., 2008); four hemiplegic patients with (AHP) and four without anosognosia (nonAHP) were provided with false visual feedback of movement in their left paralysed arm using a prosthetic rubber hand. This allowed for realistic, three-dimensional visual feedback of movement, and deceived patients in to believing the rubber-hand was their own. Crucially, in some conditions, visual feedback that was incompatible with the patient's intentions was given. For instance, in a critical condition, patients were instructed to move their left hand, but the prosthetic hand remained still. This condition essentially mirrored the classic anosognosic scenario within an experimentally controlled procedure (cf. Ramachandran, 1995). In this way the study was able to examine whether the ability to detect the presence or absence of movement, based on visual evidence, varied according to whether the patient had planned to move their limb or not. The key measure of interest was the patient's response to a movement detection question (i.e., 'Did your left hand move?'), which required a simple yes/no response. The results revealed a selective effect of motor intention in patients with AHP; they were more likely than nonAHP controls to ignore the visual feedback of a motionless hand and claim that they moved it when they had the

intention to do so (self-generated movement) than when they expected an experimenter to move their own hand (externally-generated movement), or there was no expectation of movement. In other terms, patients with AHP only believed that they had moved their hand when they had intended to move it themselves, while they were not impaired in admitting that the hand did not move when they had expected someone else to move it. By contrast, the performance of nonAHP patients was not influenced by these manipulations of intention, and they did not claim they moved their hand when the hand remained still.

To our knowledge, this is the first direct demonstration that illusory awareness of action in AHP reflects a dominance of motor intention prior to action over visual sensory information about the actual effects of movement. Finally, this experiment had the advantage of being able to simultaneously examine two alternative interpretations of AHP. First, by manipulating visual feedback of movement at a given spatial location the study has ruled out the effects of visuospatial neglect (AHP patients did perceive unexpected motor ‘failures’ in conditions of externally-generated movements). Second, because patients were able to detect such discrepancies, it is unlikely that the findings reflect a general deficit in detecting abnormalities and contradictions as Ramachandran (1995) has suggested. These findings provide further support to the view that AHP is a specific sensorimotor disorder and not the secondary result of some concomitant neurocognitive deficits.

The role of motor representations (motor imagery) in AHP

The experiment described above supports the idea that motor intentions are intact in AHP, and are crucial in patients’ non-veridical motor awareness. According to computational models of the motor system, these motor intentions reflect the planning of ‘to-be-executed’ movements, which are mistaken for actual movement in AHP. It has also been suggested that motor imagery is a form of movement planning, which involves mental representation of movements and an internal simulation of motor activity, but not motor execution (Blakemore

& Sirigu, 2003; Buxbaum, Johnson-Frey, & Bartlett-Williams, 2005; Jeannerod, 2001; Sabaté, González, & Rodríguez, 2004). As such, motor imagery provides an ideal means of evaluating the ability to plan movements in AHP. The computational account implies that patients with AHP are able to mentally represent intended movements involving their hemiplegic limb. However, until recently, the ability to mentally represent intended movements had not been directly examined in patients with AHP. This ability to generate motor representations in AHP was investigated in a recent study by Jenkinson, Edelstyn, & Ellis (2009). The experiment utilised an established motor imagery task (Johnson, 2000a, 2000b; Johnson, Sprehn, & Saykin, 2002), which compares how participants prospectively say they *would* grasp an object and how they *actually* grasp the same object. Specifically, participants were first presented with the image of a wooden handle painted half-pink half-yellow, and prospectively asked to state where their hand *would* be (i.e., which half their thumb would mostly touch) if they were to reach and grasp the handle. This procedure was repeated with handles at various orientations in random order. Following this, participants *actually* grasped the real wooden handle at the same set of orientations. The degree of correspondence between the prospective and actual grips provides a direct measure of internal motor representation accuracy. An especially useful feature of this task is that it can be used to assess motor representations in situations where actual movement is impossible (e.g., because of hemiplegia). Because the two hands are mirror images of each other, the way an individual chooses to grasp an object with their intact (non-paralysed) hand provides a near perfect indication of how the same movement is performed with their paralysed hand (cf. Johnson, 2000a, 2000b; Johnson et al., 2002). By applying this method to AHP patients, we were able to provide a unique, behavioural assessment of motor representations for the hemiplegic arm in AHP.

Using this technique, we measured the accuracy of motor representations in eight patients with AHP, 10 nonAHP hemiplegic control patients, and 22 age-matched healthy controls. Motor representations for the left (i.e. paralysed) arm were found to be less accurate in patients than healthy controls; however, accuracy remained high in both AHP and nonAHP patients (i.e., there was around 80% correspondence between prospective and actual movement). Moreover, there was no difference in the accuracy of these motor representations between the two patient groups. In other words, AHP patients are able to represent movements involving their hemiplegic limb to a degree comparable with that of patients without anosognosia, thus negating the possibility that impaired motor representations alone can account for AHP. This crucial finding is consistent with the suggestion that patients with AHP can form representations of intended movements due to spared activity in pre-motor areas (Berti et al., 2005), which are known to be involved in planning movements and motor representations (Beltramello et al., 1998; Grèzes & Decety, 2001; Roland, 1993).

To summarise, the results of the two experiments described in this section provide support for the idea that mental representations of intended movements are present in AHP. These findings are consistent with the accounts of Frith et al., (2000a) and Berti and colleagues (Berti & Pia, 2006; Berti et al., 2007), rather than the earlier proposal of impaired motor intention made by the feed-forward hypothesis (Heilman, 1991; Heilman et al., 1998). Moreover, the two experiments described above provide the first experimental evidence in support of the claim that these representations of intended movements may actually form the basis of illusory movements experienced by some AHP patients.

Implications and limitations of motor control explanations

The aforementioned findings (Fotopoulou et al., 2008; Jenkinson et al., 2009) in AHP have important implications for the model of normal motor control. The model proposes that normal motor awareness is dominated by representations of intended movements, while

actual sensory information is not necessary, nor sufficient for awareness. Indeed, evidence from neurologically healthy people suggests that when the discrepancy between what one intended to do and what one actually did is relatively small (in both temporal and spatial terms), sensory feedback regarding one's actual body state has a remarkably limited role in awareness (e.g., Fournieret & Jeannerod, 1998). In fact, it is only when the discrepancy between predicted and actual consequences exceeds a certain threshold that we become aware of errors in motor execution (Slachevsky et al., 2003). Given that in many tasks we are able to correct and adjust our movements towards achieving a certain goal without awareness of the need for these adjustments, it has been argued that this deception of awareness (i.e., unawareness of small discrepancies) serves the important purpose of allowing flexibility (e.g., fast and efficient adjustment of movements) in the system (Knoblich & Kircher, 2004). On that view, a small degree of unawareness of motor failures is built in to the motor system, possibly as a result of the inherent noise (e.g., feedback delay) that is present in most sensorimotor loops (see Wolpert, 1997), or because the comparator mechanism may be insensitive to such minor discrepancies for the reasons outlined above. AHP can therefore be regarded as an exaggerated form of the normally functioning motor system. Specifically, AHP seems to represent an instance of pathological (i.e., lesion-induced) unawareness of *large* discrepancies between predicted and actual consequences. The counterintuitive experience of movement in anosognosic patients may provide insight into what occurs when the threshold of significant discrepancy between predicted and executed actions is reached, but the mechanism that triggers the conscious processes capable of monitoring and correcting such discrepancies is impaired. The system seems to continue to operate by deceiving awareness.

AHP may also provide insight into the neurocognitive correlates of our sense of agency (i.e., the sense that 'I am the one causing an action'), of which there are two dominant

views. One approach suggests that agency arises as a retrospective means of explaining behaviour (see Wegner, 2003), whilst an alternative proposes that agency could arise as a consequence of the processes associated with preparing a movement (see Haggard, 2005; 2009). Our findings are consistent with the latter stance, and the suggestion that the experience of executing a movement arises from activity in brain areas responsible for conscious intention and predicted consequences (Desmurget et al., 2009).

It should be noted, however, that several other observations in AHP cannot be accounted for by referring only to the computational model of motor control. The breakdown of a single motor comparator cannot adequately explain the reported specificity of AHP; for example, patients who are aware of one motor impairment (e.g., lower limb paralysis) but not another (e.g., upper limb paralysis) (Berti, Làdavas, Stracciari, Giannarelli, & Ossola, 1998; Marcel et al., 2004). However, one possible way to account for these dissociations is the existence of multiple comparators, each responsible for selective monitoring of a given function. A growing body of work suggests that this monitoring might even be implemented by the same neural networks responsible for controlling the function that has to be monitored (Berti et al., 2005; Spinazolla, Pia, Folegatti, Marchetti, & Berti, 2008).

Much more problematic for explanations that refer only to the motor system are the abnormal emotional attitudes (e.g., emotional indifference, or hatred of the paretic limb) and bizarre beliefs (e.g., asomatognosia, somatoparaphrenia) that are often a feature of AHP. The observation that awareness in AHP may be modified when questions are phrased in an emotionally neutral (i.e., “Are either of your arms weak?”) versus emotionally laden way (i.e., “Is it ever naughty? Does it ever not do what you want?”; Marcel et al., 2004) is also difficult to reconcile by purely motor accounts of AHP. Marcel et al., (2004) also note that the consequences of paralysis in AHP (e.g., falls occurring because of attempts to get out of bed), extend beyond simple awareness of the immediate movement failure. The model of

motor control might account for abnormal awareness about movement failures during their execution; however, additional impairments must be present in AHP for patients to be unaware of such adverse incidents, and to maintain their belief of unimpaired movement.

In a recent single case study, visual feedback from a video replay resulted in a sudden and permanent reinstatement of awareness in a severely anosognosic patient (Fotopoulou, Rudd, Holmes, & Kopelman, 2009; see below). Anosognosia was formally assessed before and after the video using measures of verbal awareness (Berti et al., 1996; Feinberg et al., 2000), and ratings of the patient's ability to perform bi-manual/pedal tasks (Marcel et al., 2004). The video was filmed with the patient's upper body clearly in view (including her hemiplegic [left] and intact [right] limbs), and showed the patient answering the awareness questions, including general questions (e.g., "Why are you here?"), specific questions about the patient's limbs ("Can you move your left arm?"), and direct confrontation ("Please try reaching my hand [extended in front of the patient] with your left hand? Have you done it?"). During the clip the patient admitted to having a stroke, but claimed she had improved since. When asked the confrontation question she incorrectly reached with her right arm then remained silent. When prompted further, the patient acknowledged she had used her right hand, but did nothing when asked if she could do the task with her left hand. Interestingly, the only observable change in the patient's cognitive and emotional profile after the reinstatement of awareness was the substantial increase in self-reported negative mood. This observation also tallied with the patient's own subjective awareness into the reasons for her anosognosia (after recovery). She stated that during the period of her unawareness she kept hoping she could move. This suggests that emotional factors may have a role in AHP. However, it remains to be empirically tested whether such emotional factors play a secondary role in maintaining the unawareness beliefs (a form of psychogenic denial superimposed on sensorimotor deficits), or whether they interact at some neurological level with the deficits

that cause motor failures and motor unawareness (see Fotopoulou, in press; Vuilleumier, 2004 for discussion on this point).

It has been suggested that the heterogeneous presentation of AHP reflects the existence of various subtypes of the disorder (Jehkonen et al., 2000; Marcel et al., 2004). Moreover, the different presentations of AHP might reflect the distinct contribution of various deficits. Therefore, a comprehensive understanding of AHP may rest in the combination of several, existing theories. For example, the delusional aspects of AHP might reflect the breakdown of more general mechanisms involved in other delusional beliefs. For instance, delusions of control in schizophrenia have been linked to deficits in source and reality monitoring (i.e., processes that enable one to discriminate between fantasy and reality) (Anselmetti et al., 2007; Brébion, Gorman, Amador, Malaspina, & Sharif, 2002; Johnson, 1991; Johnson, Hashtroudi, & Lindsay, 1993; Keefe, 1998). Consistent with this, Venneri and Shanks (2004), have speculated a link between reality monitoring and AHP, and a recent study of reality monitoring in AHP suggests a tendency to attribute information to an external source in anosognosic patients (Jenkinson, Edelstyn, Drakeford, & Ellis, in press). Further research is required to elucidate the exact nature and contribution of reality monitoring impairments in the pathogenesis of AHP.

Marcel et al., (2004) also make the interesting observation that AHP patients who fail to recognise paralysis when questioned about their own abilities (e.g., “in your present state how well, compared with your normal ability, can you walk?”), are able to recognise the same paralysis attributed to another person (e.g., asked “if I was in your present state how well would I be able to walk compared with my usual ability?”). Notably, both questions require explicit knowledge of the patient’s *own* motor ability; therefore, in terms of the computational model of motor control, the same comparison processes should be engaged to give both answers. However, the greater awareness of paralysis demonstrated when AHP

patients respond to questions attributing impairment to *another* person, suggests a dissociation within awareness according to the manner or viewpoint of the question (i.e., 1st vs. 3rd person perspective). This dissociation has been examined more recently by the aforementioned study, in which an AHP patient regained normal awareness of hemiplegia following observation of her paralysis in a video replay (Fotopoulou et al., 2009). The video allowed the patient to observe her motor impairment ‘from the outside’ (i.e., from a 3rd person perspective) and ‘offline’ (i.e., at a time later than the actual attempt to execute movement). The authors suggest that these conditions may have allowed the patient to update her body representation when the ability to do so in the first-person is impaired by brain damage. In terms of the computational model of motor control, judgements of ability made offline might facilitate awareness because the intention to move, which usually produces non-veridical awareness (as described above), is no longer present. A direct comparison between the effects of 1st and 3rd person perspective as viewed ‘online’ could not be determined, since awareness recovered completely and permanently following observation of the video. Thus, further studies are needed to explore the role of 1st and 3rd person viewpoints, both online and offline, in AHP.

Implications for rehabilitation

The above findings might be used to inform clinical practice in a number of ways. A growing body of research suggests that visual feedback (mirror therapy) and mental rehearsal of movement (i.e., repetition and practice of movements with the impaired limb(s) using imagination), are effective means of motor rehabilitation after stroke (de Vries & Mulder, 2007; Dunskey, Dickstein, Marcovitz, Levy, & Deutsch, 2008; Stevens & Phillips Stoykov, 2003; Yue & Cole, 1992). Likewise, these strategies might be a useful means of rehabilitating motor function in AHP. Third-person perspective on one’s deficits (feedback from mirrors and video replays) may turn out to be important in facilitating motor awareness, as the

previously described single case study suggests (Fotopoulou et al., 2009). In addition, the study of motor representations in AHP (Jenkinson et al., 2009), demonstrated that despite an inability to execute movements with the hemiplegic limb, the ability to generate an internal representation of a specific action is relatively preserved. Therefore, it may be possible for patients with AHP to use mental rehearsal as a rehabilitation strategy, since the underlying functional mechanisms are relatively preserved. This suggestion is tentative, and future research might profitably assess the effectiveness of mental rehearsal in the rehabilitation of motor function in AHP. Applying mental rehearsal to patients with AHP would have several advantages: awareness of actual ability to perform the imagined movement is not necessary; therefore, the technique can be implemented acutely post-stroke, when awareness is impaired and physical practice is hindered by weakness and fatigability. Additionally, mental rehearsal training is low-cost, low-risk, and less labour-intensive than physical practice.

Conclusions

In this paper we reviewed experiments that examine AHP in the context of an established computation model of the motor system. We argued that previous research, which aimed to establish the presence or absence of an intention to move in AHP, does not account for the positive symptom of non-veridical awareness of movement. We therefore reviewed novel experiments, which suggest that AHP patients are still able to mentally represent movements of their plegic arm, and that their non-veridical awareness of movement seems to stem from the dominance of such representations about the intention to move over sensory information about the actual effects of movement. Findings of these experiments are consistent with an established computational model of motor control. However, sensorimotor accounts of AHP cannot fully account for all aspects of the disorder, such as the observed specificity, emotional and delusional features. Future studies in AHP patients are needed to specify how motor awareness (as described by the model of motor

control) interfaces with other cognitive processes, such as source/reality monitoring, emotional processing and body representations. These ongoing studies into AHP are crucial, as they can inform our knowledge of normal self-awareness, and may generate new rehabilitation strategies for AHP patients.

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Figure Caption

Figure 1. A simple computational model of the normal motor system (from Blakemore, Frith, & Wolpert, 2001).