# Imagining the impossible: Motor representations in anosognosia for hemiplegia*

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*This title is based on Johnson (2000a)

Abstract

Anosognosia for hemiplegia (AHP) is characterised by poor insight or underestimation of hemiplegia after brain injury. Recent explanations of AHP have used an established 'forward model', which proposes that normal motor awareness involves comparing the predicted and actual sensory consequences of movements. These accounts propose that AHP patients may be able to form representations of their intended movements (i.e., motor representations), but fail to register discrepancy between intended and actual movements. A prediction arising from this proposal is that AHP patients are able to generate motor representations involving their hemiplegic limb(s). Our study provides the first direct examination of this prediction in patients with AHP. We used an existing 'grip selection task', which investigates motor representations by comparing how patients *would* grasp an object and how they *actually* grasp the same object. Eight right hemisphere stroke patients with AHP, 10 control patients (non-AHP), and 22 age-matched healthy volunteers (HVs) completed the task. Results showed that HVs outperformed both AHP and non-AHP patients in their motor representations for the hemiplegic limb; however, the performance of AHP and non-AHP patients did not differ significantly. Motor representations for the intact limb were lower than normal in AHP patients, whereas performance in non-AHP patients was midway between the AHP and HV groups. Findings suggested that the ability to form motor representations lie on a continuum, but that impaired motor representations for the paralysed limb cannot account for AHP. Distorted motor representations, in combination with other deficits, might contribute to the pathogenesis of AHP.

Imagining the impossible: motor representations in anosognosia for hemiplegia

Anosognosia refers to a disturbance of self-awareness occurring after brain injury, in which the patient does not recognise the presence or appreciate the severity of deficits in sensory, perceptual, motor, affective or cognitive functioning (Orfei et al., 2007). The term is most frequently applied to patients with hemiplegia following right hemisphere stroke (Ellis & Small, 1997; McGlynn & Schacter, 1989), i.e., anosognosia for hemiplegia (AHP). The clinical presentation of AHP is not uniform (Ellis & Small, 1993); for example, the extent of unawareness can vary considerably. Some patients fail to recognise, appreciate the severity, or acknowledge the consequences of paralysis (Orfei et al., 2007); others deny outright any motor impairment, while some patients acknowledge the presence of a motor deficit, but explain it away (Bisiach & Geminiani, 1991). Patients with AHP may or may not also exhibit unilateral neglect (i.e. a failure to respond to stimuli presented to the contralesional side) (Berti et al., 2005; Jehkonen, Laihosalo, & Kettunen, 2006). Furthermore, AHP can occur independently at verbal and non-verbal (i.e., behavioural) levels (Jehkonen et al., 2006). That is, AHP patients may refuse to acknowledge their paralysis, but are usually content to remain in bed (Bisiach & Geminiani, 1991). In contrast, some AHP patients verbally acknowledge their paralysis, but attempt to get out of bed or perform other physical tasks that are clearly impossible (Bisiach & Geminiani, 1991). These patients are often unaware of their inability to execute bilateral tasks requiring use of the plegic limb(s) (e.g., clap hands) when asked to make self-evaluations (Berti, Làdavas, & Della Corte, 1996; Berti, Làdavas, Stracciari, Giannarelli, & Ossola, 1998; Marcel, Tegnér, & Nimmo-Smith, 2004; Nimmo-Smith, Marcel, & Tegnér, 2005).

Despite several decades of research, we are still far from a clear understanding of the cognitive processes underlying AHP. This situation may be partly attributed to limitations in the methodological and theoretical approach employed by existing studies. First, the heterogeneous presentation of AHP has resulted in a lack of consensus about how best to characterise and assess the disorder. Unfortunately, it is impossible to draw valid comparisons across studies, identify commonalities in findings, and develop a cohesive understanding of AHP from the results of studies failing to thoroughly characterise the disorder. Therefore, a comprehensive assessment of AHP, taking into account both verbal awareness and self-evaluations of ability/behaviour, is necessary (Marcel et al., 2004; Nimmo-Smith et al., 2005). For example, Berti et al. (1996) have adopted this approach in their procedure for assessing AHP. This method provides a robust method for characterising AHP, from which a better understanding of AHP may be developed.

A second limitation of many accounts of AHP is a failure to provide a firm theoretical framework for understanding the pathogenesis of the disorder. These accounts attempt to explain only the pathological processes involved in AHP (e.g., Bisiach, Vallar, Perani, Papagno, & Berti, 1986; Cappa, Sterzi, Vallar, & Bisiach, 1987; Cutting, 1978; Levine, Calvanio, & Rinn, 1991; McGlynn & Schacter, 1989; Weinstein & Kahn, 1950). In contrast, recent cognitive neuropsychological accounts of AHP (Berti & Pia, 2006; Frith, Blakemore, & Wolpert, 2000a) provide theoretically robust and testable explanations of the disorder, by framing their accounts within an established 'forward' model of normal motor control and awareness (Wolpert, 1997; Wolpert, Ghahramani, & Jordan, 1995), the utility of which has been demonstrated by numerous studies in normal, healthy individuals (Blakemore, 2003; Blakemore, Frith, & Wolpert, 1999; Blakemore, Frith, & Wolpert, 2001; Blakemore, Goodbody, & Wolpert, 1998; Blakemore, Rees, & Frith, 1998a; Blakemore, Wolpert, & Frith, 1998b) and patients with abnormal awareness of action (Blakemore, Smith, Steel, Johnstone, & Frith, 2000; Blakemore, Wolpert, & Frith, 2002; Frith, 2005; Frith, Blakemore, & Wolpert, 2000b).

The forward model proposes that whenever a voluntary movement is executed two sources of information are produced: (i) somatosensory feedback reflecting the *actual* consequences of the movement, and (ii) a *prediction* of the expected sensory feedback arising from the intended movement. According to the model, these sensory predictions form the basis of motor awareness, whereas actual somatosensory feedback is not sufficient or necessary to construct knowledge of motor behaviour in normal individuals (Blakemore & Frith, 2003; Blakemore et al., 2001; Blakemore et al., 1998a; Blakemore et al., 1998b; Fourneret & Jeannerod, 1998; Haggard, 2005; Haggard, Clark, & Kalogeras, 2002; Haggard & Eimer, 1999; Wolpert & Flanagan, 2001). The forward model further proposes that normal motor awareness depends on a comparator, which checks for congruence between predicted and actual sensory feedback. When movement does not occur as planned the comparator detects a mismatch between predicted and actual sensory feedback, which produces conscious awareness of an error. This is particularly evident in situations when intended movement and sensory feedback do not match, such as when visual feedback regarding intended movements are reversed by use of a mirror (Fink et al., 1999), or when distinguishing between self-generated movements and those caused by another (Blakemore, 2003; Blakemore et al., 1999; Blakemore et al., 2001; Blakemore, Oakley, & Frith, 2003; Farrer et al., 2008).

Recent cognitive neuropsychological accounts (Berti & Pia, 2006; Frith et al., 2000a) have used the forward model to predict the pattern of intact and impaired functions that produce AHP. For example, Berti and Pia (2006) draw attention to the forward model’s proposal that sensory predictions form the basis of normal motor awareness. This proposal implies that whenever a sensory prediction is created, and the comparator does not detect a mismatch with actual feedback, individuals might construct the belief that they have executed movement as intended. Accordingly, pathological awareness in AHP might occur if the ability to generate representations of intended movements (i.e., motor representations) and predict their expected sensory consequences were preserved, but patients fail to detect when these predictions are not congruent with actual sensory feedback. Under these circumstances motor awareness in AHP becomes based entirely on sensory predictions, which erroneously indicate successful execution of the intended movement. In contrast, hemiplegic patients without anosognosia (i.e., non-AHP) possess preserved awareness of their motor impairment because they are able to generate motor representations *and* detect when the predicted and actual sensory consequences of their movement do not match. This account is in direct contrast to an earlier ‘feed-forward’ hypothesis proposed by Heilman (1991), which assumed that AHP arises from a *loss* of intention to move. That is, if patients with AHP do not intend to move, the comparator is not primed to expect movement, and a subsequent lack of movement does not create a discrepancy signal or indicate an error to the AHP patient. However, this explanation is not supported by physiological studies (Berti, Spinazzola, Pia, & Rabuffetti, 2007; Hildebrandt & Zieger, 1995), which report normal muscle electrical activity (electromyography; EMG) in AHP patients instructed to move their hemiplegic limb. This activity suggests intact intention to move in AHP.

Although recent cognitive neuropsychological accounts of AHP lead to clear theoretical predictions, direct examined of these predictions is scarce. One prediction requiring examination is the ability of AHP patients to generate motor representations. Berti et al. (2005) have reported lesion analyses which suggest that AHP patients have some spared activity in premotor areas, which are known to be involved in planning movements and motor representations (Beltramello et al., 1998; Grèzes & Decety, 2001; Roland, 1993; Roland, Larsen, Lassen, & Skinhut, 1980); it is, therefore, possible that patients with AHP can form a distorted representation of intended movements (Berti et al., 2005). However, no existing behavioural study has directly examined motor representations in AHP.

The ability to generate motor representations has been examined in healthy individuals (Johnson, 2000b) and neurological patients (Buxbaum, Johnson-Frey, & Bartlett-Williams, 2005; Johnson, 2000a; Johnson, Sprehn, & Saykin, 2002b) using motor imagery (i.e., "a dynamic state during which the representation of a given motor act is internally rehearsed within working memory without any overt motor output", Decety & Grèzes, 1999, p. 177).

Johnson (2000b) developed a ‘grip selection task’ to assess motor representations in healthy individuals using implicit motor imagery (i.e., tasks requiring mental simulation of planned movements to solve, rather than instructing participants to explicitly imagine making particular movements; Johnson, 2000b). The task requires participants to first make a prospective motor imagery judgement (MI condition), indicating how they *would* grasp a wooden dowel/handle presented at several orientations (i.e., choosing to use either an overhand (pronated) or underhand (supinated) power grip, as one would clench the handle of a hammer). Participants are then presented with a real dowel in the same orientations as the MI condition and asked to actually grasp them using a power grip (motor control (MC) condition). Using this method, Johnson (2000b) found a near perfect correlation between MI and MC grip selections, suggesting that MI judgements are analogous to MC judgements in healthy individuals.

Motor imagery is also an ideal method for assessing motor representations in patients with hemiplegia, because it involves movement planning in the absence of overt execution. Johnson and colleagues (Johnson, 2000a; Johnson et al., 2002b) have used a variant of the grip selection task to assess motor representations in acute and chronic hemiplegic stroke patients with preserved awareness (i.e., non-AHP), concluding that motor representations are intact in acute and chronic patients. However, a major limitation of both studies was a failure to include a healthy control group, which means it is not possible to determine whether the ability to generate motor representations is preserved at normal levels in hemiplegic stroke patients.

The ability to form motor representations may have important therapeutic implications for patients with hemiplegia. Mental rehearsal of movement has been applied as a cognitive strategy for recovery of hemiparesis (Stevens & Phillips Stoykov, 2003), based on evidence in healthy individuals that this technique can improve actual motor performance (Feltz & Landers, 1983; Smith & Holmes, 2008). Implicit in this method is the assumption that patients retain the ability to generate motor representations for movements they can no longer perform with the hemiplegic limb. Unfortunately, findings regarding the efficacy of mental rehearsal in this context are equivocal (Braun, Beurskens, Borm, Schack, & Wade, 2006). For example, Stevens and Phillips Stoykov (2003) used mental rehearsal in two case reports of patients with a chronic hemiparesis following stroke, finding improved strength and functionality of the upper limb following the interventions. However, the authors did not include a patient control condition (i.e., rehabilitation without mental rehearsal) or healthy control group against which to compare the effects of mental rehearsal; therefore, it is not possible to determine whether mental rehearsal facilitated recovery of motor function, or if motor representations are preserved following stroke.

The usefulness of motor imagery in motor rehabilitation following stroke likely depends on the lateralisation of the lesion, since side of lesion has been found to affect motor imagery in the contra- and ipsilateral side differently (Malouin, Richards, Desrosiers, & Doyon, 2004; Sabaté, González, & Rodríguez, 2004; Schaefer, Haaland, & Sainburg, 2007; Stinear, Fleming, Barber, & Byblow, 2007; Stinear, Fleming, & Byblow, 2006). While the results of these studies suggest a dominant role of the left hemisphere in movement, the role of the non-dominant (i.e., right) hemisphere in movement are less clear. Investigating motor representations in acute hemiplegic patients with right hemisphere lesions might yield important findings regarding the efficacy of motor imagery as a means of rehabilitation.

Our study aimed to clarify and extend previous research concerning motor representations in non-AHP patients, and provide the first empirical investigation of motor representations in patients with AHP. We based our study on recent accounts of AHP (Berti & Pia, 2006; Frith et al., 2000a), which utilise the forward model to provide a firm theoretical framework for investigation. From these accounts we hypothesised that AHP patients are able to generate motor representations concerning their hemiplegic and intact arms. This hypothesis predicts that motor representations for the hemiplegic and intact arms will be relatively accurate in AHP patients. If motor representations are preserved at normal levels they would not be expected to differ between AHP patients, non-AHP patients, and healthy volunteers (HVs). In contrast, if motor representations are impaired, performance will be less accurate than HVs. We tested these predictions by comparing the performance of patients with AHP, non-AHP patients, and HVs on the grip selection task (Johnson, 2000a; Johnson et al., 2002b).

## Method

### *Participants*

18 patients with a dense left hemiplegia (12 male, 6 female, mean age = 65.28, S.D. = 10.22) participated in the study. Patients were selected on the basis of routine clinical and brain imaging evidence of a right hemisphere stroke, and were recruited from consecutive admissions to acute stroke wards at the University Hospital of North Staffordshire. Muscle power was measured using the Medical Research Council (MRC) Scale (Guarantors of Brain, 1986), which grades power on an ordinal scale from 0 (*no contraction*) to 5 (*normal power*). The extent of motor impairment varied from complete flaccidity (MRC score 0) to slight arm and/or hand movements (MRC score 1-2); however, none of the participants were able to execute controlled movements with the affected limb. Patient performance was compared with 22 age-matched HVs (10 male, 12 female; mean age = 66.50, S.D. = 7.02). Exclusion criteria comprised existing neurological or psychiatric illness (except stroke in the patient group), concurrent left hemisphere damage other than minor ischaemic changes (patients only), learning disability, or history of drug or alcohol dependency. Participation was dependent on compliance with the testing schedule, so those patients with severe cognitive impairment (screened with the Mini Mental Status Examination; Folstein, Folstein, & McHugh, 1975) or a reduced consciousness level were also excluded. An estimate of pre-morbid intelligence was also obtained (National Adult Reading Test, NART; Nelson & Willison, 1991). All participants were right hand dominant, native English speakers, with

normal or corrected-to-normal vision. Local NHS research ethics approval was granted for the study and all participants gave fully informed, written consent.

*Assessment of Anosognosia for Hemiplegia*

Assessment of AHP followed the method of Berti et al. (1996), which includes a structured interview to measure verbal awareness, and self-evaluations of the potential capacity to perform actions. Patients were classified as anosognosic if they demonstrated unawareness of their motor impairment on either measure.

*Verbal awareness of upper limb motor impairment.*

Patients were first asked to answer a few preliminary questions (Berti et al., 1996, p. 429), about their present condition: “Where are we? Why are you in the hospital/current location? How is your left arm? Can you move it?” If the patient answered “No” to the last question then he/she was asked “Why can you not move your left arm?” A second set of questions was asked if the patient verbally denied left upper limb motor impairment: “Please touch my hand with your left hand” (the experimenter put his hand in the patient’s right visual field). The patient was then asked “Have you done it?” If the patient answered “No”, then he/she was asked “Why have you not done it?” If the patient answered “Yes”, then he/she was asked “Are you sure? It is very strange because I have not seen your hand touch my hand.”

Responses were documented verbatim and later scored for anosognosic content by PMJ and SJE independently, according to the following criteria: 0 = the patient answered correctly to the first group of questions (normal), 1 = the patient acknowledged being in the hospital and/or being affected by a stroke, but denied his or her upper limb impairment; however, the patient acknowledged that the left arm did not reach the examiner’s hand (mild anosognosia), 2 = the patient claimed that he/she had reached the examiner’s hand (severe anosognosia).

*Verbal awareness of lower limb motor impairment.*

Patients were asked the following questions: "How is your left leg? Can you move it? Can you walk without any problem?", and responses scored according to the following criteria: 0 = the patient either spontaneously reported the motor impairment of the lower limb when first asked about the reasons for his/her being in the hospital (see above) or acknowledged the paralysis when specifically questioned about the left leg (normal), 1 = the patient answered "Well/fine" to the first question, but acknowledged the impossibility of walking (mild anosognosia), 2 = the patient claimed that he/she was able to walk (severe anosognosia).

*Self-evaluations of potential ability to perform actions.*

Patients were asked to rate their potential to perform several actions requiring use of the upper or lower limb. Five monomanual actions involving the left upper limb (drink from a glass, open a door, eat with a fork, lift a small object) and ten bimanual actions (clap hands, wash hands, wash face, put on gloves, open a jar, open a bottle, deal cards, tie a knot, light a cigarette with a match, put on socks) were rated on a scale from nought (*perform very badly*) to ten (*perform very well*). Five locomotor actions involving the lower limbs (walk, jump, climb stairs, drive, ride a bicycle) were also rated on the same scale as upper limb actions. Averages scores were calculated for monomanual upper limb actions, bimanual upper limb actions, and lower limb actions separately. An average score of between nought and five was considered normal (i.e. not anosognosic), and a score of six or more on any of the three measures was considered evidence of anosognosia (Berti et al., 1996).

*Grip Selection Task*

*Stimuli and apparatus.*

The grip selection task was divided into two conditions: motor imagery (MI) and motor control (MC). Stimulus for the MI condition was a life-size, photographic image of a wooden dowel, measuring 1 inch in diameter and 6 inches in length. Half of the dowel was coloured pink and half yellow (Figure 1). When viewed from a distance of 50cm the dowel subtended approximately 2.6° by 10.8° of visual angle. The digital image of the dowel was presented against a black background on a laptop computer with a 14” display.

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Figure 1 about here

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Stimulus for the MC condition was a real wooden dowel suspended in an open fronted, black wooden box measuring 60cm x 60cm x 30cm. The centre of the dowel was attached to an axel that protruded through the rear wall of the box and was attached at the other end to a pointer and 360° protractor. This enabled the experimenter to determine the orientation of the wooden dowel as viewed from the front by the participant. A black curtain attached to the front of the box at the top occluded vision of the dowel when in place. The box and dowel encompassed the majority of the participant’s visual field when viewed from a distance of approximately 50cm.

*Motor imagery procedure.*

To eliminate the possibility of participants basing their MI judgements on memories from the MC condition, the MI condition was performed first in all cases. Participants sat approximately 50cm in front of the computer with their hands palm down by their side throughout the task. They were informed that they would see the image of a wooden handle (i.e., dowel) displayed on the computer and each time the handle appeared the participant should think about using their left or right hand to grasp the centre of the handle using a power grip (i.e., the grasp applied to the handle of a hammer). No mention was made of the possibility of using motor imagery to solve this task. Either an overhand (pronated) or underhand (supinated) grip could be used, such that the thumb of the designated hand would be toward either the pink or yellow end or the handle. Emphasis was placed on there being no correct way of grasping the handle. Participants were asked “Which colour would your thumb make contact with if you were to reach out and grasp this handle?” They responded orally by saying pink or yellow, and the experimenter used a two-button response box to enter responses into the computer. No time limit was imposed on responses; however, participants were asked not to deliberate over their decision as their first instinct would be the best response. Input of a response immediately prompted the presentation of the next dowel stimulus. A practice comprising 6 trials was completed before the experiment commenced. During this practice participants were asked to point to each half of the dowel in order to establish that the stimuli were clearly visible and performance would not be influenced by the presence of unilateral neglect. If necessary, the instructions and practice were repeated until the participant was confident with the procedure.

Each participant completed six blocks of trials divided equally between their right and left hands. Over the course of each block the stimulus occurred in eight orientations, at 45° increments from 0-360°. 0° of orientation was defined as the stimulus dowel positioned vertically with the pink end pointing upward. Because the joint constraints of the left and right hands are mirror images of each other, all other orientations are expressed according to the number of degrees rotation from the neutral posture 0° moving in the direction of pronation, i.e., clockwise for the left hand and counter-clockwise for the right. This convention follows that of Johnson (2000b), and is referred to as relative hand orientation (see Figure 2). Stimulus orientation was randomised within each block. Designated hand was alternated across blocks and order of blocks was counterbalanced across participants.

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Figure 2 about here

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*Motor control procedure.*

The procedure for the MC condition closely matched that described for the MI condition; however, the task was completed using only the right hand, since hemiplegia prevented patients from using their left hand. For consistency, HVs also used only their right hand and were analysed by the same method applied to hemiplegic patients (below). Each trial began with the participant seated in front of the apparatus with their hands at their side. The dowel was occluded by the curtain while the experimenter rotated the dowel to one of the eight orientations. When the stimulus was revealed the participant grasped the dowel with their right hand choosing an overhand or underhand grip. Participants were instructed not to change their grip once they had hold of the handle. The experimenter recorded pink or yellow as a function of which end of the dowel the participant's thumb contacted and the curtain was dropped into place ready for the next trial. A practice comprising two trials was completed before the experiment commenced. If necessary the practice was repeated. Trials were blocked and randomised as in the MI condition.

*Analysis of motor imagery accuracy.*

Analysis of MI accuracy followed the method of Johnson et al. (2002b). MI judgements have no objective correct or incorrect response, as they reflect the participants' individual grip preference. Therefore, accuracy of MI performance was evaluated by direct comparison with preferences exhibited during the analogous MC task. Movement preferences on the MC task can be directly compared with judgements expressed on the MI task to obtain a measure of accuracy of MI using the formula:

$$\text{Accuracy MI } \theta ik = 100\ (1 - |\text{MI } \theta ik - \text{MC } \theta ik|)$$

where k denotes a particular hand and $\theta i$ the stimulus appearing in a given orientation. This analysis produces a measure of consistency between the individuals' mentally simulated (MI) and actual (MC) grip preferences.

Because hemiplegic patients are only able to perform the MC task with their intact (ipsilesional) arm, imagery judgements for the hemiplegic limb are compared against predictions of how they would grasp stimuli if they were able to do so. These predictions arise out of the fact that both arms/hands are mirror images of each other, and therefore obey joint constraints that are 180° out of phase (Mackenzie & Iberall, 1994). For example, when the right hand is at a relative hand orientation of 90°, the equivalent left relative hand orientation is 270° (Figure 2). Therefore, inverting functions relating grip preference to stimulus orientation for the intact limb allows accurate prediction of how hemiplegic patients would prefer to engage objects if they were able to do so with their impaired limb (Johnson et al., 2002b). Any given left hand grip preference can be predicted using information from the right hand, using the formula:

$$MCleft = 1/MCright$$

where MCleft and MCright refer to the probability of selecting the overhand or underhand grip for a given orientation.

*Data analysis*

Differences between the two patient groups in the extent of hemiplegia (MRC power score) and number of days between stroke and consenting to participate in the study were analysed using Mann-Whitney *U* tests. The difference in sex distribution between groups was analysed using multiple Fisher's Exact Tests. MMSE, NART, age and MI accuracy were compared between AHP patients, non-AHP patients, and HVs using the nonparametric Kruskul-Wallis one-way analysis of variance, with post hoc analyses using multiple Mann-Whitney *U* tests applying a Bonferroni correction to obtained *p*-values[1]. All tests were two-tailed.

[1] Because an omnibus test comparing three groups indicates whether or nor the *greatest* difference between groups is significant (i.e., group with largest summed rank ≠ group with smallest summed rank), post hoc tests did not repeat this analysis and involved only the two remaining comparisons. This avoided us being too conservative in our statistical (i.e., Bonferroni) corrections, which might have obscured potentially meaningful patterns in the data by making type II errors.

## Results

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Table 1 about here

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Each group's AHP assessments, gender, age, MRC muscle power, MMSE, and NART score are summarised in Table 1. Eight patients fulfilled the criteria for AHP (4 male, 4 female) and AHP was absent in 10 control/non-AHP patients (8 male, 2 female). The proportion of males and females in each group did not differ (all *p*s > .10). The three groups were matched for age ($p = .893$), and both patient groups were matched in terms of the degree of hemiparesis ($p = .282$), length of time between stroke and participation in the study ($p = .915$), pre-morbid intelligence ($p = .432$), and current cognitive function ($p = .310$). However, compared with HVs, both AHP and non-AHP patients had significantly lower pre-morbid intelligence ($p < .001$ and .002 respective) and current cognitive functioning ($p < .001$ and .008 respective).

*Congruence between Motor Imagery and Motor Control*

Table 1 shows participants' congruence scores for the left (hemiplegic) and right (intact) arm. The omnibus test of *left* MI accuracy scores showed that AHP patients had significantly lower congruence between MI and MC conditions than HVs, $H$ (2) = 10.09, $p = .006$, and post hoc analyses showed that non-AHP patients were similarly impaired relative to HVs, $U = 55.50$, $p = .049$. There was no difference in the left MI accuracy of AHP and non-AHP patients ($p > 0.10$). Analysis of *right* MI accuracy scores revealed significantly lower congruence between MI and MC in AHP patients compared with HVs, $H$ (2) = 13.32, $p = .001$. There were no other significant differences in MI accuracy between groups (all *ps* > 0.10). Finally, because NART and MMSE scores were significantly lower in both patient groups compared with HVs, the possible influence of these factors on MI accuracy was explored post hoc using Spearman's correlations. All correlations were non-significant (all *p*s

> 0.05); however, there was a marginal correlation between MMSE score and left MI accuracy ($r_s$ = .30, $p$ = .054).

## Discussion

In this study we examined the hypothesis that it is possible for AHP patients to generate motor representations concerning their hemiplegic and intact arms. This hypothesis predicts that patients with AHP should be relatively accurate at representing movements involving their hemiplegic and intact arm. Consistent with this, we found hemiplegic stroke patients (both AHP and non-AHP) performed the grip selection task at a relatively high level of accuracy. However, we found that motor representations for the hemiplegic arm were significantly less accurate in both AHP and non-AHP patients relative to HVs. Motor representations for the intact limb were also impaired relative to normal HVs in AHP patients, but not non-AHP patients.

Johnson (Johnson, 2000a; Johnson et al., 2002b) previously reported investigations of motor representations in acute and chronic hemiplegic stroke patients with preserved awareness (i.e., non-AHP) using the grip selection task. These studies reported the performance of the hemiplegic and intact limbs to be comparable. From this, Johnson and colleagues conclude that motor representations are intact in (non-AHP) hemiplegic stroke patients, despite their inability to execute planned movements. However, a major limitation of these studies was a failure to determine if motor representations were at normal levels following stroke, as comparisons were not made with a healthy control group. Our study extended these studies by employing the same grip selection task, while including a healthy control group. Consistent with Johnson, we found hemiplegic stroke patients (both AHP and non-AHP) performed the task at a relatively high level of accuracy for their hemiplegic and intact limbs. However, performance was not at normal levels when compared with HVs: both AHP and non-AHP patients demonstrated impaired motor representations for their hemiplegic limb. Overall, the pattern of results suggested that motor representations might exist on a continuum in the three groups, with AHP and non-AHP patients generally more deficient than HVs.

Despite several attempts to explain AHP in the past, none have fully accounted for the phenomenon in all its complexity. A major shortcoming has been a failure to provide a firm theoretical framework for interpreting the disorder. In contrast, recent accounts use a 'forward model' to propose that AHP arises because patients may be able to generate representations of their intended movements and form predictions of their consequences, but fail to detect a mismatch between predicted and actual movement (Berti & Pia, 2006; Frith et al., 2000a). Non-AHP patients are similarly expected to be able to generate motor representations, but have preserved awareness because they register a mismatch between their predicted and actual movement. A major strength of the present study was the use of this theoretically robust model to make and test predictions in patients with AHP. Our findings indicate that motor representations are not normal in AHP and non-AHP patients, although the relatively high level of accuracy suggests that patients with hemiplegia might be able to generate distorted motor representations. This is consistent with the proposal that some spared activity in pre-motor areas allows AHP patients to form distorted motor representations (Berti et al., 2005). Our findings are also contrary to the proposal that AHP stems from a loss of intention to move (Heilman, 1991), instead supporting findings of EMG studies that suggest intention to move is intact in AHP (Berti et al., 2007; Hildebrandt & Zieger, 1995). Furthermore, our findings are consistent with the idea that the *predicted* sensory consequences of movement form the basis of motor awareness. That is, the forward model proposes that sensory feedback is not sufficient or necessary to construct knowledge of motor behaviour (Blakemore & Frith, 2003), but rather that sensory predictions arising from motor representations govern awareness. The fact that patients with AHP believe they can execute intended movements is consistent with awareness being based on motor predictions derived from an ability to generate (distorted) motor representations.

The comparable levels of performance in AHP and non-AHP patients would suggest that impaired motor representations for the hemiplegic limb cannot, on their own, account for the pathogenesis of AHP. It is possible that impaired representations for movements involving the paralysed limb, in combination with other deficits, contribute to the pathogenesis of AHP. For example, both AHP and non-AHP patients might still be able to use their distorted motor representations to predict the sensory consequences of intended movements, and base motor awareness on these predictions; however, while non-AHP patients detect a mismatch, further deficits, such as an inability to determine the origin of information (i.e., source monitoring; Johnson, Hashtroudi, & Lindsay, 1993), result in AHP patients failing to notice that actual movement did not match the intended one. Further research is necessary to characterise these additional deficits in AHP.

The present study also has implications regarding the role of the right (i.e., non-dominant) hemisphere in motor representations, and relationship between motor planning and motor representations. Although previous research has demonstrated a dominance of the left hemisphere in movement (Sabaté et al., 2004; Stinear et al., 2006), the role of the right (non-dominant) hemisphere is less clear (Malouin et al., 2004; Schaefer et al., 2007; Stinear et al., 2007). We found impaired motor representations for both the left and right arm in AHP patients with an intact left hemisphere and damage to the right (i.e., non-dominant) hemisphere. This suggests a contribution of the right hemisphere to motor representations regarding both the contralateral (left) and ipsilateral (right) limb.

There is also some debate in the literature regarding the relationship between motor planning and motor representations. One viewpoint is that motor representations signify the mental simulation of a fully formed premotor plan, when execution of the plan is inhibited (Jeannerod, 1994; Jeannerod, 1995). An alternative position suggests that motor representations denote a problem-solving approach to the construction of the premotor plan, by internally simulating the body and selecting appropriate parameters to achieve the intended movement (Johnson, 2000b; Johnson et al., 2002a; Johnson, Corballis, & Gazzaniga, 2001). Consistent with previous work by Johnson and colleagues, our study suggested that participants used motor representations to solve the problem of which movement (i.e., underhand or overhand grip) to select. However, further work is needed to fully understand the role of the right hemisphere in motor representations and exact nature of the relationship between motor planning and motor representations.

Our study also has important therapeutic implications, and may provide some explanation for equivocal results regarding the use of mental rehearsal in the rehabilitation of hemiplegia following stoke (Braun et al., 2006). Ipsilesional motor deficits have been linked to significant functional impairments and problems in performing activities of daily living (Wetter, Poole, & Haaland, 2005). This may occur because patients with hemiplegia affecting the contralesional side rely heavily on ipsilesional limb function. Our finding of impaired motor representations concerning the ipsilesional limb in AHP patients suggest that functional recovery may be more problematic for these patients. Furthermore, the use of motor imagery/mental rehearsal training in the rehabilitation of hemiplegic stroke patients assumes that motor representations are possible in this group. The present findings suggest that motor representations for a hemiplegic limb are possible, but impaired, following a stroke. Thus, poor efficacy in mental rehearsal studies might be a consequence of patients' difficulties in generating motor representations of their planned movement. We speculate that success in using mental rehearsal for rehabilitation might depend on motor representations being preserved at a particular level, the extent to which is currently unknown. Hence, a clinical implication of our findings is that the grip selection task, or similar, might provide a potentially useful means of screening patients, in order to decide whether or not they are likely to benefit from mental rehearsal training.

A major methodological weakness of existing research into AHP has been a failure to adequately characterise the disorder, which makes comparisons between studies difficult to analyse and commonalities in findings hard to identify. A thorough characterisation of the disorder is necessary to establish consistency across studies and a detailed understanding of AHP. For example, AHP can occur independently at verbal and non-verbal levels of behaviour, such that patients remain unaware of the consequences of their illness despite being aware of their stroke and/or paralysis (Jehkonen et al., 2006). As such, AHP should be assessed using instruments that measure (un)awareness manifest both verbally and via estimates of the patients' ability to execute tasks requiring use of the hemiplegic limb (Nimmo-Smith et al., 2005). A strength of the present study is our thorough characterisation of AHP using an existing instrument that measures both types of awareness (i.e., Berti et al., 1996). The methodological robustness of our approach offers greater certainty in our conclusions, and a firm basis for links with other research.

Some possible limitations of the study should be taken into consideration. First, significantly lower levels of pre-morbid and current intellectual function were found in our patients; however, the use of nonparametric statistics means it was impossible to include these as a covariate in analyses, and determine their possible influence on motor representations. A series of correlations did not identify any significant relationships between these factors; however, a marginal correlation between MMSE score and left MI accuracy suggested a tendency for poorer performance on the grip selection task in patients with greater cognitive impairment. Unfortunately, this effect cannot be stated with certainty.

Second, it might be argued that our relatively small sample size may have influenced the statistical power of our analyses. This might have resulted in a failure to detect some significant differences between AHP and non-AHP patients. Nevertheless, similar numbers have been used in other studies employing the grip selection task. For example, Johnson (2000a) examined motor representations using the grip selection task in a group of 11 acute stroke hemiplegic stroke patients, Johnson et al. (2002b) compared performance on the task in 4 chronic hemiplegic stroke patients and 4 control patients having fully recovered from an initially dense hemiplegia, and Buxbaum et al. (2005) employed the grip selection task in comparing 8 stroke patients with ideomotor apraxia (i.e., a deficiency in producing complex movements) and 6 healthy matched controls. These studies have reported meaningful findings despite relatively small sample sizes.

Finally, it is possible that different results might have been obtained on the task by explicitly instructing participants to imagine grasping the handle (i.e., employing explicit motor imagery). The advantage of using *implicit* motor imagery, such as employed in this study, is the avoidance of possible demand characteristics. For example, accuracy of motor imagery on the grip selection task is verified objectively by comparing performance on an analogous task involving actual movement, rather than relying entirely on introspection. It would be of interest in future investigations to see if the use of explicit motor imagery during the task has any effect on performance.

In conclusion, the present study provides the first direct examination of motor representations in patients with AHP, employing a robust theoretical and methodological approach. Representations for the hemiplegic limb were found to be impaired relative to normal levels, but comparable to those of non-AHP patients with preserved awareness for their motor deficit. Findings are consistent with the idea that patients with AHP are able to form a distorted representation of intended movements and use this to predict their sensory consequences. However, further research is needed to determine if AHP patients fail to notice a mismatch between predictions derived from motor representations, and the actual sensory feedback arising from movement, as proposed by recent accounts of AHP utilising the forward model.

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Figure Captions

Figure 1. Stimulus for the MI condition of the grip selection task.

Figure 2. Relative hand orientations of the grip selection task.