The case for the comparator model as an explanation of the sense of agency and its breakdowns ☆

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A B S T R A C T

I compare Frith and colleagues' influential comparator account of how the sense of agency is elicited to the multifactorial weighting model advocated by Synofzik and colleagues. I defend the comparator model from the common objection that the actual sensory consequences of action are not needed to elicit the sense of agency. I examine the comparator model's ability to explain the performance of healthy subjects and those suffering from delusions of alien control on various self-attribution tasks. It transpires that the comparator model needs case-by-case adjustment to deal with problematic data. In response to this, the multifactorial weighting model of Synofzik and colleagues is introduced. Although this model is incomplete, it is more naturally constrained by the cases that are problematic for the comparator model. However, this model may be untestable. I conclude that currently the comparator model approach has stronger support than the multifactorial weighting model approach.

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1. Introduction

The sense of agency over bodily actions is the *feeling* that one is the agent of one's actions. That one*self* causes an action to take place, controls it and ends it. It is a form of self consciousness in that it is an experience of oneself *qua* agent. It need not involve any experience of one's intentions, i.e. one may experience a sense of agency for an action even if the reasons one performed that action are not obvious. As such an account of the sense of agency need not necessarily involve the capacity to attribute mental states to oneself. My interest in this paper is the feeling of being the agent of action, rather than the capacity to form judgements about agents (Synofzik, Vosgerau, et al., 2008). People suffering from delusions of alien control have a deficiency in this sense of agency.

In this paper I compare Frith and colleagues' influential comparator account of how the sense of agency over one's bodily actions is elicited to the multifactorial weighting model advocated by Synofzik and colleagues, which was developed in response to some problems with this account. I defend the comparator model from the common objection that the actual sensory consequences of action are not needed to elicit the sense of agency. I examine the comparator model's ability to explain the performance of healthy subjects and those suffering from delusions of alien control on various self-attribution tasks. I argue that there are considerable case-by-case modifications that need to be made to the comparator model for it to work. There is some confirmatory evidence for the comparator model in the behaviour of normal subjects when sensory feedback is unexpectedly altered and I examine how this model may account for the findings of the 'helping hands', 'I-spy' and 'wheel of fortune' studies which some take to be problematic for the comparator model. It transpires that the comparator model

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needs case-by-case adjustment to deal with this problematic data. In the end we get several versions of the comparator model with no principled way of distinguishing between them or predicting when one will hold.

In response to this, the multifactorial weighting model of Synofzik and colleagues is introduced. Although this model is incomplete, a version can be developed which is naturally constrained by the cases that are problematic for the comparator model. However, it is not clear what, if anything, could count as evidence against this multifactorial weighting model. Despite being generated with the data in mind, it may be untestable. I conclude that currently the comparator model approach has stronger support than the multifactorial weighting model approach.

2. The comparator model of the sense of agency over bodily actions

One model of motor control which is thought to provide the resources to account for the sense of agency over bodily action is due to Frith and colleagues (2000a) and diagrammed in Fig. 1. On their model the motor control system uses a set of five types of representation, delineated by content. These are:

(a) the goal state [or the end target position for the body also called a "motor intention" or M-intention by Pacherie (2008).] This represents a target position of the body;
(b) the motor commands, of which there are two copies, produced by the so called 'inverse model'. The copy of the motor commands that remains central is often referred to as the "corollary discharge" or "efference copy" (in e.g. Feinberg, 1978; Frith et al., 2000a; Vosgerau & Newen, 2007);
(c) the predicted sensory consequences based on the copy of the motor commands that remains central and produced by the so called 'forward model';
(d) the actual sensory consequences (in any modality) of the movement (also called the 'reafference') and
(e) an estimation of the position of the body produced from the ongoing merging of information from both predicted and actual sensory feedback, see Fig. 1 (Frith et al., 2000a, p. 1773; Kawato, 1999, see Desmurget and Grafton (2000), Wolpert and Ghahramani (2000) for reviews).

This model provides the tools for understanding how the sense of agency is elicited. On this model of the motor control system, when one performs an action without interference then the actual sensory consequences of that action match the predicted sensory consequences based on the copy of the motor commands that remain central (i.e. the efference copy/corollary discharge) (Frith, Rees, et al., 1998, p. 173; Frith et al., 2000a, p. 1784; Blakemore, Wolpert, et al., 2002, p. 240; Frith, Blakemore, et al., 2000b, p. 359). However, if the movement that actually occurs is caused by some external force then there is no or a different prediction. Thus, the actual sensory consequences do not match the predicted sensory consequences. Perhaps the sense of agency arises from the capacity to detect matches between the predicted and actual sensory consequences
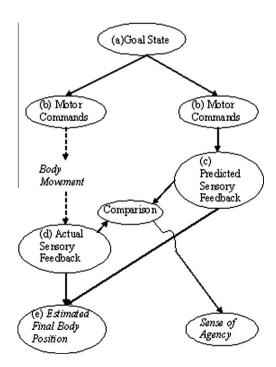

Fig. 1. The predicted sensory consequences (c) are compared to actual sensory consequences (d). When they are represented as matching the sense of agency is elicited.

of a movement. On this account, the sense of agency arises when and only when the comparator detects that the predicted sensory feedback is identical to the actual sensory feedback. By comparing these two representing vehicles the system can determine whether or not they match, i.e., whether or not they represent the same movement. If so then the sense of agency is elicited. The comparator model may explain pathological deficits in the sense of agency as being due to problems in forming or accessing representations of the actual or predicted sensory consequences of action. Below I argue that in the case of delusions of control the deficit is most likely in the formation or access of predicted sensory consequences.

There are several potential findings that could, in principle, falsify the comparator model. It will be falsified if it can be shown that there are cases of a preserved sense of agency in the absence of representation of actual sensory consequences or in the absence of predicted sensory consequences. A further potential falsification would be if the sense of agency is present along with both the actual and predicted sensory consequences of action but, they are not used in a comparison. A final potential falsification would be that the comparator is working normally but no sense of agency is elicited. In practice objections to the comparator model usually take the form of the first falsification. As such, next I consider a variety of challenges to the comparator model that claim a representation of actual sensory consequences are not necessary to experience a sense of agency over an action. However, I argue below that the majority of these arguments assume that on the comparator model the subject must be aware of the actual sensory consequences of action, even though this does not appear anywhere in the model.

For example, a common objection comes from the apparently preserved sense of agency in the case of deafferented patients. These considerations have lead some (e.g. Synofzik et al., 2008; Wegner, 2002) to disregard the comparator model in favour of an alternative account. In contrast I argue below that based on these subjects' reports and performance on action attribution tasks it is far from clear that their sense of agency is intact for actions they cannot see. A trickier argument arises from cases of the sense of agency over the actions of phantom limbs. However, as there is reason to suppose that in these cases patients form false representations of actual sensory consequences this need not be a devastating objection to the model.

3. Is representation of the actual sensory consequences of action necessary for the sense of agency to be elicited?

Gallagher (2000) offers an argument against the comparator model. According to the comparator model the actual sensory consequences of an action are used to elicit the sense of agency. As such, the model predicts that the sense of agency arises *after* the action occurs. There is some evidence that this prediction is not borne out. One classic finding of a study by Libet and colleagues is that subjects consistently report that their movements begin around 0.080 s before they actually do (Libet, Gleason, et al., 1983). This seems to pose a problem; if one is normally aware of one's actions before they occur, then one is presumably aware of oneself as the agent of one's actions before they occur. It follows that the sense of agency cannot be based on the actual sensory consequences of the action.

There is a problem with interpreting the reports of the subjects in this study. In this study subjects were asked to recall when they started to move. However, there is no way to tell at this later time if subjects have an experience of moving *initially* involving the sense of agency or the experience not initially involving a sense of agency, but having the sense added later (Dennett, 1991, chap. 5; Dennett, 1995). The second hypothesis would merely involve the sense of agency being reported as occurring earlier than it actually did. As we have no way to differentiate between these two versions of events based on the subjects reports alone, the above argument cannot establish the claim that the actual sensory consequences of an action cannot be involved in eliciting the sense of agency.

Further experimental data threatens the role of actual sensory feedback in eliciting the sense of agency. Some data has been interpreted as showing that a representation of the actual sensory consequences of an action is not necessary for the sense of agency to be elicited. However, we will see that much of these data show, at most, the subjects' lack of awareness of the actual sensory consequences- not that they are not represented.

Vibration of the tendon joining the biceps to the elbow causes reflex contraction of the biceps; the elbow bends. If the arm is held still by a brace whilst such vibration is administered the subject experiences the illusion that the elbow is extended (Marcel, 2003, p. 62). Correspondingly the arm feels as though it is in a position that it is not. Subjects verbally report that their arm appears to be in the illusory extended position and when asked they point to the illusory position. However, for the first 4–5 s following the peak of the illusion subjects can accurately grasp the wrist of the arm that is subject to the illusion. After that time subjects attempt to grasp the illusory location (Marcel, 2003, p. 63). In one study (Marcel, 2003) subjects had their arm held out of view underneath a table when the vibration was administered. They were able to move this arm in an arc to point at a marker. When asked to draw an estimated path that they would need to follow to do so using the hand that was not subject to the illusion, subjects made drawings appropriate to their arm starting at the illusory location. However, they were able to make the movement accurately. Following this movement subjects were asked to draw the movement they had made. Around 70% of subjects draw an arc appropriate to their movement starting from an illusory position (Marcel, 2003, p. 65–66).

These results seem to threaten the comparator model. These subjects are not aware of the exact nature of the movements they make under these conditions. As such, it appears they are not aware of the actual sensory consequences of their actions. However, none of these subjects report that they feel as though they are not the agent behind the movement. As such awareness of the actual sensory consequences of an action is not necessary for the sense of agency to be elicited. Thus, it seems that the comparator model cannot be correct.

Further evidence for this claim comes from a study by Fourneret and Jeannerod (1998) in which subjects were required to perform a simple point to point movement with a mouse. The subject's hand was obscured, such that their only visual feedback came via a computer monitor. On the screen subjects saw a line depicting the direction they were moving. On some trials a bias was introduced such that the line that appeared on the screen deviated from the direction the mouse was moved. This required subjects to change the direction they moved in order to draw a straight line. Subjects were able to do this successfully on all trials. Thus, a representation of the bias was accessible to the extent that it guided movement. However, when interviewed after the task subjects only reported that there was a bias when it was 15° or more. For biases less than this (5 or 10°) subjects could not report its presence even though they changed their hand movement in order to compensate for the bias.

Using a different method Farrer and colleagues (2003b) found that subjects performed better than chance at knowing if a bias was present if the bias was 15° or greater. Subjects were worse than chance for bias of 10° or less. This held for both passive and active movements, although subjects performed better for active movements when bias was above 30°. Similarly using a slightly different method again Farrer and colleagues (2003a) found that subjects sometimes (21.9% of trials) take it that they are looking at undistorted feedback of their own actions when what they see is distorted by 25°. What the studies by Fourneret and Jeannerod as well as Farrer and colleagues seem to show is that we are not usually aware of the exact movement we make. In other words actual sensory consequences in non-visual modes are not consciously accessed. Yet these subjects do not report experiences of alien control over these actions. They have a normal sense of agency for them. So it seems that actual sensory consequences cannot be necessary for the sense of agency to be elicited (Synofzik et al., 2008, p. 223–224).

In responding to these arguments prominently advocated by from Synofzik and colleagues (2008) and Wegner (2002, p. 37–38) it is important to note that the comparator model does not require *awareness* of the actual sensory consequences of a movement in order for the sense of agency to be elicited. On the comparator model a representation of the actual sensory consequences of an action does not need to be globally accessible. Rather it just needs to be used in the right way, namely, in the comparison to the predicted sensory consequences. In order to threaten this model we need data to show that the sense of agency can be elicited when the actual sensory consequences are not represented or when they are not used in this comparison. These data do not fulfil this requirement. The actual sensory consequences of actions must be represented and used by the motor control system during the studies by Fourneret and Jeannerod as well as Farrer and colleagues as subjects can accurately control movement of the affected arm. If the non-visual actual sensory consequences are not represented when undergoing these illusions performing the actions is exceedingly difficult (Farrer et al., 2003b, p. 615), I have more to say on this below in the case of G.L. As such, data from these studies do not contradict the comparator model.

Whilst these data do not directly contradict the comparator model, they do suggest that some modifications are needed. In particular it seems that there are some conditions in which those non-visual actual sensory consequences that the subject is conscious of do not play a role in eliciting the sense of agency. We will see below that the fact that some actual sensory consequences may not be used in some conditions is not predicted by the initial presentation of the comparator model is motivation for taking up the multifactorial weighting model.

3.1. Deafferented patients

Potentially more problematic for the comparator model are the cases of I.W. and G.L (Cole & Paillard, 1995). Both of these subjects lost the senses of proprioception and touch (at or below the mouth) following a viral infection. Both retained the vestibular sense, thermal sense and pain. These subjects need to watch their movements to ensure they are accurate. Unsurprisingly their movements appear to lack certain kinds of control. Their movements appear distinctly unnatural to observers and they have difficulty in accurately judging how much force to apply with their fingers. Both of these subjects lost these senses due to demyelization of components of the peripheral nervous system. This results in an inability to transmit information about touch or limb position from the periphery (Cole & Paillard, 1995, p. 245–248). They cannot form a representation of the actual sensory consequences of actions in these modalities due to this lack of input.

I.W. and G.L. seem to have a sense of agency. That is, both seem to feel that they control their bodily actions. For example, G.L. occasionally states that she feels that she imposes commands on her body like a machine. This is admittedly unusual, but it is still clear that she feels that *she* is the one controlling her body, even if it is in an abnormal way. I.W. recalls that when he first lost these senses that his "relationship" to his body changed; in part, because he could no longer control it as he once had (Cole & Paillard, 1995, p. 261). These reports suggest that the change in their ability to control their actions is accurately reflected in these subjects phenomenology. Furthermore, they still possess a sense of agency over their bodily actions.

These data have been used to argue that the sense of agency is not dependent on the actual sensory consequences of action in either the touch or proprioception modes (Wegner, 2002, p. 37–38). However, it is not obvious that these cases establish that the sense of agency does not depend on the actual sensory consequences of action. Although both I.W. and G.L. lack touch and proprioception, they need to visually observe their actions in order to control them. As such, they do have the resources to form representations of the actual sensory consequences of their actions, at least visually. As such, these data do not undermine any model that suggests the sense of agency is dependent on a representation of the actual sensory consequences of an action. This being said, it would undermine such models if I.W. and G.L. feel a sense of agency over actions they do not see. However, it seems these patients do not experience a sense of agency over actions they do not see, at least for the case of conversational gestures. Both of these patients gesture when talking. G.L. was shown a video of her doing so.

On seeing this she reported that she did not feel that she controlled the movements at the time they occurred (Cole & Paillard, 1995, p. 260). To be conclusive this would have to be investigated more systematically. For example the nature of these subjects' experience of agency in conversational gestures would need to be compared to the nature of healthy control subjects' experience of agency over those actions. It would be more straightforward to investigate these subjects' experiences of agency over obscured actions, such as reaching for something behind a mask.

When performing experiments such as these we need to carefully choose the actions. Reaching actions behind a mask are unlikely to provide us with insight into the comparator model, as these subjects cannot perform the act without being able to see the target (Cole, Gallagher, et al., 2002, p. 59). As such there is always visual feedback available for part of the action and the accomplishment of the goal. However, I.W.'s gestures are normal even with the complete lack of visual feedback.

This is not to say that the study of blind gestures will answer all of the worries about the comparator model raised in this section. Studies with I.W. suggest a dissociation between systems used for communicative/gestural actions on the one hand and instrumental actions (such as reaching) on the other. In particular, whilst his ability to perform instrumental actions is severely impaired by the lack of feedback, his gestures are indistinguishable from those of healthy individuals (Cole et al., 2002, p. 50). After sometime spent deliberately learning to gesture after the initial deafferentation, I.W. has largely regained the ability to perform communicative actions (Cole et al., 2002, p. 55) without needing to watch himself, whereas he can only perform instrumental actions with considerable conscious attention. For I.W., at least, successful performance of communicative actions depends much less on sensory feedback than instrumental acts do. This suggests that the capacities to produce these actions are at least partially dissociable. As such insight into the status of the comparator model as an account of the sense of agency for communicative actions may not generalise to instrumental actions, and *vice versa*. We may wonder if this is a peculiarity of I.W.'s situation. Has he perhaps learned a new way to produce gestures? We might think so, recalling the considerable effort he spent to learn to gesture after deafferentation. This interpretation seems improbable, as I.W.'s speech was never affected, suggesting that at least some communicative actions were never affected by the loss of feedback. But, why would it be that some communicative actions (gesture) were initially impaired and others (speech) not? The answer, suggested by Cole and colleagues, is that to successfully perform gesture one needs more than the mental competence to produce them. In particular they suggest that I.W. needed to learn to overcome postural instabilities and from new way of knowing where his hands were located to start to gesture (Cole et al., 2002, p. 58). This would take considerable effort even if basic competence were left intact. Due to this dissociation any findings regarding the sense of agency for communicative actions may not generalise to instrumental actions.

As such, the lessons from blind gestures recounted below have limited scope and as such may not speak to the truth of the comparator model more generally. However, they do tell us something about I.W.'s sense of agency over blind gestures and so are worth considering here. It seems that I.W. does not experience a sense of agency over gestures he cannot see. In one study I.W. was asked to recount a story from a cartoon he was shown whilst his hands were held out of sight, behind a screen. Once he was confident of his safety he gestured during his narrative in a manner considered normal (Cole et al., 2002, p. 55). However, he was unaware of his doing so. After performing 14 identifiable gestures in 20 s, he announced "...and I'm starting to use my hands now..." (Cole et al., 2002, p. 56), suggesting he had not known that he was gesturing beforehand. As such he could not have had a sense of agency for those actions. As such it seems, at least for communicative acts, that I.W. does not have a sense of agency for actions he does not see.

This is not the only plausible interpretation of I.W.'s report here. We may ask if his claim that he is beginning to act (*I'm starting to use my hands*) arises from a sense of agency. Did his sense of agency 'kick in' 20 s after he began his action? It is unlikely. I.W. could not be reporting a feeling that his hands are starting to move, as he has no way to experience that. More likely this report comes from knowledge of his intention to begin moving. In other words this report is a result of I.W.'s theory of mind and not his sense of agency. As such it seems most plausible that I.W. does not experience a sense of agency for these actions. What about G.L.?

G.L. reports feeling that she does not control her actions when visual feedback is distorted by inducing an angular bias in an image of her movement (Farrer et al., 2003b, p. 616). In fact G.L. cannot perform actions when she watches distorted visual feedback of them. This suggests that non-visual actual sensory consequences of action are needed to control movement when visual feedback is distorted. This is consistent with the fact that she makes far more errors of action attribution than controls when a bias is introduced to the visual feedback of the final position of a movement. She only performs above chance for the attribution of action if the distortion is above 60° (Farrer et al., 2003b, p. 616). Note that because patient G.L. cannot control movements if she sees biased visual feedback, she performed the actions with her eyes closed, with her only visual feedback being the final position of the body (Farrer et al., 2003b, p. 615). Controls do perform this task worse than when they observe the whole action, however, they are still significantly better than G.L. G.L. has problems with attributing a movement to herself. This may be due to a deficit in her sense of agency. This is consistent with her reports of a lack of a sense of agency when visual feedback is distorted. This suggests that deafferented patients may not have a sense of agency over actions they do not see.

3.2. Phantom limbs

People who have phantom limbs feel that their amputated limb is still present. Some such patients feel that the phantom limb is voluntarily moveable. Ramachandran and Blakeslee describe a patient Tom who, after losing his left arm from just above his elbow, experienced a vivid phantom arm that he felt he was able to move. He was able to wiggle each phantom

finger, reach out and grab things and perform a variety of more automatic actions, such as bracing for a fall (Ramachandran & Blakeslee, 1998, p. 21–22). He seems to have an intact sense of agency for these phantom actions. He never seems to report that someone else does the action or that the phantom arm does the action on its own.

Some rather different reports come from a patient who suffered from a congenital lack of limbs; she was missing both arms from above the elbow. She seems to experience her phantom arms as moving on their own when she says:

> ... as I'm talking to you, they are gesticulating. They point to objects when I point to things, just like your arms and hands (Ramachandran & Blakeslee, 1998, p. 41).

> When I walk, doctor, my phantom arms don't swing like normal arms, like your arms. They stay frozen on the side... But when I talk...my phantoms gesticulate. In fact, they're moving now as I speak (Ramachandran & Blakeslee, 1998, p. 41).

Here the subject seems to be describing the gestures her phantom arms perform as automatic. Perhaps she is going as far as to deny that she is the agent of these actions, but this is not necessarily the case. However, despite these reports this patient also experiences her phantoms as voluntarily controllable (Ramachandran & Blakeslee, 1998, p. 42).

These reports are problematic for the comparator model. There is no actual sensory feedback from the phantom arm, either visual or non-visual, that could be compared to predicted sensory consequences of the action. Yet these patients do not seem to deny that they are the agents of their phantom actions. The reports of phantom arms moving on their own when gesticulating seem more consistent with the comparator model. However, these reports seem to be the exception, with even the patients who have these experiences at other times reporting that they voluntarily control their phantom movements.

In addition to this Synofzik and colleagues (2008) raise a problem from cases of paralysed phantoms. Those patients who experience their phantom limbs as paralysed can come to experience it as moveable using a simple visual illusion. To experience this illusion the patient is asked to place their real arm and their phantom arm into a box on either side of a mirror. They are then asked to look at the reflected image of their real arm and move it until it seems to be superimposed on their phantom arm. They are then asked to attempt to move both arms. On seeing the reflected image move they can feel as though their phantom arm is now moving (Ramachandran & Blakeslee, 1998, p. 48, 52–53). As with the patients described above, these patients seem to feel that they are the agents of these actions. They do not attribute the action to someone else, nor do they claim that the phantom moves on its own. There is a possible comparator explanation here of the sense of agency over these actions in terms of the visual feedback from the mirror. However, as Synofzik and colleagues point out this requires that visual feedback from the limb is still being predicted long after the amputation (Synofzik et al., 2008 p. 225). It seems that the motor control system should be able to learn not to predict visual feedback when such feedback is permanently lost. Indeed one proposed role of the comparison between actual and predicted sensory feedback is to teach the motor control system to generate more accurate predictions (Frith et al., 2000a, p. 225; Synofzik et al., 2008). As such this potential explanation just raises a further problem of why the motor system is no longer updating its ability to predict sensory consequences. Furthermore, such an explanation is not applicable to those cases where phantoms are felt to be voluntarily moveable without using the mirror.

However, there is data from these reports that offers a way out of the problem. The feelings of position, touch, pain and kinaesthetics that these patients experience all seem to the patient to be real feedback. The touch seems to be touch; the pain seems to be pain. All of the current perceptual representations of the phantom are misrepresentations, their false content is that they are real feedback from a real limb (this is even the case for visual feedback, at least in the case of Ramachandran's box). If these representations have this false content when accessed, then perhaps they have this false content when they are not accessed. That is current perceptual representations of the phantom limb that are part of the body image have the false content that they are real feedback from a real limb and entered into the comparator as such. Given, this the sense of agency could still be elicited in the case of phantom limbs. Furthermore, as the comparator is consistently receiving representations mistaken for actual sensory consequences it would continue to generate a learning signal for the formation of predictions consistent with there being real feedback. As such the motor control system ought to continue to predict the formation of actual sensory feedback.

Ramachandran's spreading activity hypothesis offers a way to explain this for the modality of touch. When various parts of the body are touched, patients with phantoms undergo strange 'double' sensations (Ramachandran, 2003, p. 11; Ramachandran & Blakeslee, 1998, p. 24). These experiences are elicited in very simple yet profound experiments. First, the patient is blindfolded then touched on various body surfaces using a cotton tip. The following is a report taken from one such experiment; the examiner (Ramachandran) first swabs the patient's (Tom's) cheek:

Examiner: What do you feel?
Patient: You are touching my cheek.
E: Anything else?
P: Hey, you know it's funny; you're touching my missing thumb, my phantom thumb.
Examiner moves cotton tip to the patient's upper lip:
E: How about here?
P: You're touching my index finger. And my upper lip.
E: Really? Are you sure?

P: Yes. I can feel it both places.
Examiner touches the patient's lower jaw:
E: How about here?
P: That's my missing pinkie. (Ramachandran & Blakeslee, 1998 p. 29)

For this patient there was a systematic mapping from various parts of his face to his phantom hand (he also had a second map on his shoulder) (Ramachandran, 2003; Ramachandran & Blakeslee, 1998).

How can current experiences alter the experience of a limb that is not there? Ramachandran offers an explanation in terms of body surface representations and neuroanatomy. He suggests that this occurs due to cross wiring in the 'Penfield Homunculus' (Ramachandran, 2003, p. 11–14). The Penfield Homunculus is an area of the somatosensory cortex, which is responsible for representations of body surface. Different regions of the cortex are responsible for representations of different parts of the body surface. The regions of the cortex that generate representations of the face and the hands are anatomically adjacent. Perhaps when one region (say the hand region) loses input (due to amputation), signals from adjacent regions (e.g. the face region) spread into the now inactive area (Ramachandran, 2003, p. 14). Since this region is still responsible for representations of the hand, the signals from the face are misrepresented as coming from the hand. As such the patient experiences the sensation as arising from their amputated hand. Furthermore, as the region that generates representations of the patients face is still working normally, the patient *also* experiences the sensation as arising from their face.

This hypothesis offers one possible way to understand how patients with phantoms may generate false actual sensory consequences, at least in the modality of touch. To complete this hypothesis future work will need to examine how false representations of feedback from an arm that is no longer there in the modalities of pain, proprioception and kinaesthetics are formed.

In this section I have examined a variety of arguments to the claim that the sense of agency does not depend on a representation of the actual sensory consequences of an action. None of these arguments have been able to establish this claim. At most they establish that awareness of the non-visual actual sensory consequences of action is not needed to elicit the sense of agency provided visual representations are present. This does not contradict the comparator model. Yet the comparator model must be altered to deal with the data. One may be concerned that there is no way to predict from the standard presentation of the comparator model that such an alteration will be necessary, or even possible. Why is it, for example, that non-visual feedback seems to matter so little in cases such as Fourneret and Jeannerod's point to point drawing? Why is it that conscious visual consequences matter so little in the studies from Farrer? I consider a way out of this issue in the final section when I discuss Synofzik and colleagues "multifactorial weighting process" as a way to deal with these issues; however, I argue in the final section that this solution is itself problematic as it is unfalsifiable. Before getting there, however, I consider how the comparator model can account for the data which has been taken to test models of the sense of agency. Again some modifications of the comparator model are needed to account for all these results.

4. Testing the models against action monitoring/attribution problems

In this section I will argue that the comparator model receives some support from its ability to explain the deficit in the sense of agency seen in delusions of alien control. On this model this is due to a deficit in the representation of predicted sensory consequences. I defend this view from a possible objection and discussion how the comparator model can explain changes in the sense of agency in healthy individuals.

4.1. Self monitoring problems

A classic study by Frith and Done (1989) suggests that those with delusions of control have degraded awareness of their own actions. In particular these patients have difficulty in identifying their own actions in the absence of visual feedback. In this study subjects were required to move a joystick left or right to fire a virtual gun at a target. In order to produce movement errors the relationship between the joystick movement and the target fired at was altered throughout the experiment. In one case the flight of the bullet was obscured for 2 s, leaving it visible for 0.8 s. Those suffering from alien control made no more errors or corrections than those with schizophrenia or affective psychosis but without alien control or healthy control subjects. However, those with alien control were significantly less likely to correct errors in the first 2 s of the bullet's flight. That is they were less able to correct errors in the absence of visual feedback.

In order to correct any errors, subjects must (i) keep track of the relationship between direction of movement and target fired at (ii) know which movement they have made. Condition (ii) can be met using any representation which can provide information as to the position of the body (e in Fig. 1), such as non-visual feedback, a prediction of the sensory consequences of the action (Frith et al., 2000a; Libet et al., 1983; Obhi, Planetta, et al., 2009) or visual feedback. The lack of false corrections suggests that no subjects had significant problems with (i) keeping track of which trial they were up to (Frith & Done, 1989, p. 362). However, the fact that those with alien control had difficulty correcting errors without visual feedback suggests that they have a deficit in knowing what movement they have performed. This could be due to a lack of access to actual *or* predicted sensory consequences of the action. We will see below that data from self tickling studies and other self recognition tasks suggest that in the case of those suffering delusions of control likely have a deficit in forming or using predicted sensory

feedback. As such it seems that a deficit in the sense of agency and performance on this task by those suffering delusions of control can be explained by the same fact.

Stirling and colleagues (1998) replicate and expand on Frith and Done's findings. They compared the performance of those suffering from schizophrenia with and without delusions of alien control to healthy controls on a variety of self monitoring tasks. Task 1A was designed to test subjects' responses to their own errors. In this task subjects were shown a sequence of numbers. They were required to respond to each number as odd or even with a button press. Errors were elicited by intermittently breaking an alternating pattern of odd and even numbers. Task 1B was similar to task 1A, except subjects had to respond to the spatial location of shapes (left or right). Task 2 required subjects to make a drawing, which could not be identified as a drawing of anything in particular, without visual feedback. They were then shown four copies of the drawing at different orientations and asked to identify the original orientation. Task 3 was similar to task 2 except the subject was told what to draw. Finally task 4 was similar to task 3 except the subject was allowed to watch themselves draw.

The results of these tests suggest that those suffering delusions of alien control have a deficit in their ability to monitor their own actions. In tasks 1A and 1B those suffering from schizophrenia made more errors and took longer to correct them than controls. Overall patients suffering from schizophrenia were worse than controls at tasks 2–4. These patients were worst at task 2 and best at task 4, although they were still not as good as controls on this task (Stirling et al., 1998, p. 679). However, once current IQ was taken into account none of these differences were significant (Stirling et al., 1998, p. 680). This suggests that overall those suffering from schizophrenia are *not* worse at monitoring their actions than controls. However, when comparing those with individual symptoms it was found that those with delusions of alien control, thought insertion or formal thought disorder all performed significantly worse on these tests than controls (Stirling et al., 1998, p. 680). Those with delusions of control performed worse than those with delusions of thought insertion or formal thought disorder. These differences remained significant after IQ was taken into account. Those suffering delusions of alien control are worse at recognising their own actions than healthy controls and those suffering schizophrenia but not suffering delusions of control. Again this could be due to a failure to properly form or access predicted or actual sensory consequences of action.[1]

There are two ways that the comparator model can explain these results. First, these patients may have problems in accessing the non-visual actual sensory consequences of action. This could explain performance on these tasks and deficits in the sense of agency. But, as I argue below, this is likely to be the wrong move. So, importantly there is a second possible explanation of these data. Perhaps these patients have difficulty with detecting errors and knowing what action they have performed amongst alternatives due to a problem with forming predictions. This means they cannot compare the goal state to the predicted sensory consequences of the action (Frith et al., 2000a, p. 1783). Thus, they could not represent that they failed to perform the action they were expecting or, indeed what action they were expecting to perform. This deficit could explain the performance of those suffering delusions of control on the studies discussed above. Furthermore, a deficit in forming or using the predicted sensory consequences would also explain why these patients have a deficient sense of agency as the prediction could no longer be entered into the comparison with actual sensory consequences.

The comparator model can explain these results as being due to a deficit in accessing actual or predicted sensory consequences of action. Which of these deficits do those suffering from delusions of alien control display?

Daprati and colleagues (1997) examined the ability of those suffering delusions of control or verbal hallucinations to attribute actions to their appropriate source. In this study subjects were required to observe a movement and report whether or not it was their movement that they saw. Subjects held their right hand below a mirror while the image in the mirror was recorded and sent via closed circuit television to a screen. The image on the screen was reflected by another mirror such that it appeared to the subject to be in the same place as their hand. The monitor could also display an experimenter's hand (recorded from a different room) such that the experimenter's hand appeared where the subjects hand was. Subjects were required to perform a series of movements of their hand. They saw either their own hand or the experimenter's perform an action and were asked to say whose hand they thought they saw moving (Daprati et al., 1997, p. 77). Subjects were tested under three conditions. They saw (i) their own hand moving, (ii) an experimenter making the same movement they had made or (iii) an experimenter making a different movement.

Overall patients suffering delusions of control or verbal hallucinations made more attribution errors on this task than schizophrenic patients without these symptoms or healthy controls. Schizophrenic subjects who were not suffering delusions of alien control or verbal hallucinations made more attribution errors than controls, but fewer than those with these symptoms (Daprati et al., 1997, p. 79). For all groups, recognition errors occurred largely in condition ii, that being where the subject saw an experimenter perform the same movement they had made. Consistent with more recent studies (e.g. Farrer et al., 2003b), all subjects made very few errors in the other conditions (Daprati et al., 1997, p. 81). Overall it appears that patients suffering from schizophrenia are worse than healthy controls at attributing an action to its proper source. Those suffering delusions of control and verbal hallucinations have particular difficulty with this task. However, their problem is not exactly the problem we may expect given the content of the delusion. The content of the delusion of alien control suggests that those suffering from this delusion tend to attribute their own actions to an external source. They feel as though someone else acts through their body. However, that is not the problem they have in this study. Rather they tend to attribute the ac-

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[1] It may be objected that these results could be explained by a memory for action deficit and thus may not involve a problem with the comparator at all. Whilst this couldbe the case for Stirling and colleagues' studies 2, 3 and 4, it is not for the study from Frith and Done as well as Stirling and colleagues' 1A and 1B in which we draw inferences about the patients representation of what action they have performed based on real time error correction tasks, as such these are not subject to this objection.

tions of an experimenter to themselves. Clearly patients suffering this delusion have difficulty in attributing actions to their appropriate agent, but the problems they experience in this study are not the same problems that could help explain the delusion.

In order to recognize whether or not the viewed action is one's own on this task one must compare visual feedback with a non-visual representation of the outcome of their action. Recall that representations of the outcome of action are, on the comparator model, derived from information including the predicted sensory consequences of the action (this is important when an alternative explanation of why those with delusions of control fail this task – see below). If the movement looks the same as it feels then it is one's own. If not then it is someone else's (Jeannerod, 2006, p. 176–178). In order to recognize that it is oneself that one *sees* moving then one must recognize that the actions performed have something to do with oneself (Povinelli, 2001, p. 85). This is the function of the sense of agency in this context. However, there are three reasons why one could fail on this task. First, the subject may lack a sense of agency over the movements. Second, the subject may fail to match the *seen* and *felt* representations of the action. In this case the failure of self-attribution has nothing to do with the sense of agency. Third, the subject may have both of these problems. We may think that those with delusions of control should have problems on this task for the first reason, but we could not know *prima facie* which problem is responsible for any particular subject's failure. I argue below that those with delusions of control fall into the third category and have both problems.

Synofzik and colleagues (2008) argue that this study does not provide any measure of the sense of agency, even via judgments of agency. They note that the question subjects are asked in the three conditions is "you have just seen the image of a moving hand. Was it your hand?" (Daprati et al., 1997, p. 77). This question seems to be a measure of the judgement of owning the hand and movement rather than being the agent behind the movement (Synofzik et al., 2008, p. 222), i.e. it asks the subject to judge whether or not the image they see is an image of themself. Given the nature of this question are we entitled to think this study provides a measure of the sense of agency? It is somewhat problematic as the sense of agency is, of course, insufficient for a judgement of ownership of this kind. That being said, the sense of agency is necessary for self recognition of this kind (Carruthers, 2007; Jeannerod, 2003; Povinelli, 2001; van den Bos & Jeannerod, 2002). If this is so then it is possible to operationalise the sense of agency via the judgements of ownership in self recognition tasks provided that the other necessary conditions for the judgements of ownership (e.g. the sense of embodiment, especially the sense of what thing in the world one's body is) is held constant (for a similar study with healthy subjects where the sense of embodiment is varied see van den Bos & Jeannerod, 2002). This being said, I argue next that the deficits displayed by patients suffering delusions of control on this study are not due to deficits in their sense of agency. Rather the problems on this task and the deficits in the sense of agency have a common cause.

4.2. Delusions of control vs. parietal lesions

A further difficulty with interpreting this study is that problems with the task are not specific to the delusion of alien control. Sirigu and colleagues (1999) tested those with parietal lesions on a similar task, in which subjects are required to perform more complex movements. Like those suffering from delusions of alien control, those with parietal lesions tended to over attribute the actions of others to themselves. Unlike those with delusions of control they did not show any other signs of having a deficit in generating a sense of agency. As such it seems that a deficit in the sense of agency is not the only cause of difficulties on this task. As such, are we entitled to suppose that those with delusions of alien control fail this task because of a sense of agency deficit? I will argue that those suffering from delusions of alien control do not fail this task because of a deficit in their sense of agency. Rather these patients' deficit in their sense of agency and their failure on this task have a common cause, namely the difficulty in forming or accessing the predicted sensory consequences of action. Before getting to this, however, I will examine the possibility of explaining the problems displayed by those suffering from parietal lesions on this task without positing a deficit in their sense of agency. Recall that there are three possible reasons why one might fail on this kind of self recognition task, one of which does not implicate the sense of agency at all. Is it plausible that those with parietal lesions fail on this task because they have problems comparing visual and non-visual feedback of the movements they make?

There is evidence that those with parietal lesions lack access to non-visual *actual* sensory feedback of actions. Those with parietal lesions often perform the required gestures clumsily on these tests (Sirigu et al., 1999, p. 1870). However, when these patients see the experimenter performing the action accurately, these patients do not use this fact to judge that they did not perform the action they saw. Indeed, at times patients remarked that they had performed the actions better then they had on previous trials (Sirigu et al., 1999, p. 1870). In other words, in the condition where the patient and the experimenter attempted the same movement those with parietal lesions could not use the fact that they failed to perform the correct movement to judge that the hand they saw doing the movement accurately was not their own. This suggests that these patients can access the visual feedback of the action but not the proprioceptive feedback. In contrast those with delusions of control and healthy controls could use mistakes in movements as additional cues as to the agent behind the movement they saw (Daprati et al., 1997, p. 78). As such it seems that those with parietal lesions have a deficit in accessing the *non-visual* actual sensory consequences of their movements that is not shared by those with delusions of control. Thus, the poor performance of those with parietal lesions on this test can be explained without needing to suppose that they have a deficit in their sense of agency as the match in the visual modes could, in these cases, be enough to elicit the sense of agency, as in the studies by Farrer and colleagues as well as Jeannerod and Fourneret discussed above.

It is therefore not a problem for the comparator models that patients with parietal lesions fail this task. However, it is still not clear how to interpret the deficits on this task displayed by those with delusions of control as the over attribution of action displayed by these patients is not predicted by a lack of a sense of agency per se.

The comparator model can explain why those suffering delusions of control over attribute actions to themselves without predicting that those suffering parietal lesions have a deficit in their sense of agency. Frith and colleagues have suggested that the predicted sensory consequences can play a role expected of the actual sensory consequences of action in order to allow for faster responses. In particular they can be used to generate a representation of the outcome of the action (Frith et al., 2000a, p. 1772, see Synofzik, Thier, et al., 2006 for experimental evidence for this claim). If this is the case then the comparator model can explain why patients suffering delusions of control tend to over attribute the actions of others to themselves. If the problem underlying the loss of the sense of agency in delusions of control is a lack of access to the predicted sensory consequences of action (as suggested above) then those suffering this symptom could not compare these representations to the visual representations of the action. They would therefore have a reduced ability to compare visual and non-visual representations of the outcome of the action. As such, they may take these representations as representations of the same movement when they are not. Hence, they may over attribute actions to themselves despite having a deficit in their sense of agency. This means that the performance of those suffering delusions of control in this study is not to be explained by a deficit in the sense of agency. Rather the deficit in sense of agency and the performance on this task have a common cause, namely an inability to access predicted sensory consequences of action. The deficit in their sense of agency arises because a lack of access to predicted sensory consequences means that the right comparisons cannot be made. In contrast those with parietal lesions do poorly on this task due to an inability to form or access representations of the non-visual actual sensory consequences of action.

A potential reply here is that a lack of access by the comparison to non-visual actual sensory consequences seems like it should be enough to prevent successful comparisons between actual and predicted sensory consequences being made. This suggests that those with parietal lesions should experience a deficit in their sense of agency after all. When evaluating this concern it is important to keep in mind the importance of visual representations of the actual and predicted sensory consequences of action, suggested by the studies by Fourneret and Jeannerod as well as Farrer and colleagues discussed above. When actual sensory consequences in the non-visual mode are not available it may be that performing the comparison in the visual mode alone is sufficient to elicit the sense of agency. So, without non-visual actual sensory feedback, those suffering parietal lesions can use matches in the visual mode to elicit the sense of agency.

This may not seem entirely satisfactory. It seems that on the comparator model we would not predict that those suffering parietal lesions would always have a sense of agency. Even if a match in visual predicted and actual sensory consequences alone is enough to elicit a sense of agency, the model must predict that those suffering parietal lesions lack a sense of agency for actions they do not see. Yet this is not reported. More problematically we may wonder *why* the lack of non-visual actual sensory consequences has no influence on the comparator's ability to elicit the sense of agency. Why would it be that in this case the lack of a match between predicted and actual sensory consequences in non-visual modes simply *doesn't matter*? At other times a lack of a match in non-visual modes does seem to prevent the sense of agency from being elicited (see discussion of Sato and Yasuda's study below). There is no principle from the comparator model alone by which we could state the lack of a match matters in the normal case but not in the parietal lesion case. Synofzik and colleagues have suggested a 'multifactorial weighting process' in response to this kind of concern. They suggest this kind of model can provide principled way to account for when representations in certain modalities matters more than others. This model therefore seems to be more naturally constrained by these cases than the comparator model. However, I argue below that this more natural constraint comes at the price of unfalsifiability. But before I get to that I consider further evidence that those suffering from delusions of control have problems forming or accessing the predicted sensory consequences of action.

4.3. Self tickling

Blakemore and colleagues (2000) investigated further the consequences of a deficit in the sense of agency. They begin with the observation that tactile stimulation produced by one's own movements are less intense than those produced by the same movement but done by another person (see for example Bays, Wolpert, et al., 2005; Shergill, Bays, et al., 2003). That is, one cannot tickle oneself (Claxton, 1975; Weiskrantz, Elliot, et al., 1971). This cannot be explained by movement alone (as it is in some conditions, see e.g. Angel & Malenka, 1982). As such, it seems probable that if one cannot discriminate between one's own actions and those of another the intensity of a tactile stimulation should not appear to vary with the agent. That is, if you cannot tell the difference between your own and someone else's actions, you should be able to tickle yourself. Based on this observation, these authors compared responses to self and other produced sensations from those with delusions of alien control (and other symptoms they suggest arise from a deficit in the sense of agency, for example verbal hallucinations) to those of patients with schizophrenia or an affective disorder (but not these symptoms) and healthy controls. The tactile stimulation was produced by moving a piece of foam over the left palm using a lever. This was done by the subjects themselves and by an experimenter. Subjects answered questionnaires about each experience. Those without delusions of control or other symptoms (regardless of diagnosis) reported that self produced sensations were less tickly, intense and pleasant than those produced by the experimenter. Those with delusions of control or other symptoms (regardless of diagnosis) by contrast reported no difference between self and other produced stimuli on any of these scales (Blakemore et al., 2000, p. 1136). This suggests that those with delusions of control could not tell who produced the action. Shergill

and colleagues replicated this result using a different method, but they did not analyse the relationship between particular symptom groups and experience (Shergill, Samson, et al., 2005).

The comparator model can explain why those suffering delusions of control experience self produced tactile stimuli as intense as other produced stimuli. It may be that in normal subjects self produced stimuli appear less intense because they are predicted based on the motor commands (Blakemore et al., 2000, p. 1137). If those suffering delusions of control fail to produce predictions, or lack appropriate access to them, this phenomenon could not occur. Similarly a deficit in predicting sensory consequences would result in an inability to produce comparisons between predicted and actual sensory consequences. Thus the sense of agency could not be elicited.

Taken together the unusual performance of those suffering from delusions of alien control on the self monitoring, tickling and self recognition studies can be explained by a deficit in forming or using the predicted sensory consequences of action. If the comparator model is accurate, such a deficit also explains the deficit in the sense of agency. These studies therefore provide us with support for the comparator model, slightly modified, to include the claim that some forms of actual sensory feedback can be more important than others in certain circumstances.

A problem with many of the studies discussed above in Section 4 [but notably not Frith and Done (1989) or Stirling and colleagues (1998)] is that they do not compare the performance of those with delusions of alien control to patients with all other symptoms. The comparison group is usually those with "passivity experiences". These include patients with delusions of alien control but also verbal hallucinations, delusions of thought insertion, thought withdrawal, thought broadcast, made impulses and made emotions. This makes this data hard to interpret with regards to break downs in the sense of agency over one's body (we might think that the other patients display a deficit in their sense of agency over their thoughts). It is unclear exactly who has the deficits being displayed in these studies. In order to ensure that we are testing only for a deficit in the sense of agency over one's body those suffering from delusions of alien control should be made a separate comparison group. Until the above results are replicated with this comparison group they can only be considered suggestive rather than definitive studies. The above studies suggest that the comparator model, with some modifications, is a viable candidate to explain the sense of agency and deficits in this sense seen in delusions of control.z

4.4. Altering relationships between actual and predicted sensory consequences alters the sense of agency

Sato and Yasuda (2005) performed a series of three studies the first two of which provide some confirmatory evidence for the comparator model in healthy subjects. Sato and Yasuda put forth three hypotheses based on the comparator model. These are

1. Subjects should misattribute self produced actions to others when the actual sensory consequences are discrepant with the prediction.
2. Subjects should misattribute other produced actions to themselves when actual sensory consequences happen to match the prediction.
3. The sense of agency should depend on a match between actual and predicted sensory consequences and not depend on a match between intentions and actual sensory consequences (Sato & Yasuda, 2005, p. 243). In other words a match between the predicted and actual sensory consequences is necessary for the sense of agency to be elicited, whereas a match between an intention and actual sensory consequences is neither necessary nor sufficient. Note that in some circumstances the sense of agency may correlate with their being a match between intentions and actual sensory consequences. Indeed this occurs in the first experiment below. The prediction here is not that such correlations can never occur (in most circumstances there will be a match between intentions and actual sensory consequences when there is a match between actual and predicted sensory consequences), rather the prediction is that there are some circumstances in which the sense of agency is elicited despite the actual sensory consequences not matching the subjects intentions.

They tested 1 by manipulating the outcomes of actions. Subjects first learned a relationship between two button presses and tone produced. In the experimental condition subjects were asked to press the button as they desired to. They heard the tone they expected, a different tone or the tone they had expected delayed to some degree. They were then asked to judge (on a 100 point scale) whether or not they had produced the tone. All subjects responded with 0 when they did not act and with 100 when the result of the action was as expected. However, they responded significantly lower when the tone or timing was altered (Sato & Yasuda, 2005, p. 245). Thus it appears that when the actual outcome is altered from what subjects have been trained to expect, they experience a reduced sense of agency. This is consistent with other studies that show that self produced stimuli are experienced as intense as other produced stimuli when an unexpected delay of .300 s is introduced between one's actions and the sensory outcomes (Bays et al., 2005; Blakemore, Frith, et al., 1999).

Notice that it is an inconsistency between *non-visual* actual and predicted sensory consequences that seems to reduce the sense of agency in these cases. Yet in these cases the visual sensory consequences stay the same. Why does not the match between *visual* predicted and actual sensory consequences of these actions simply overrule the *non-visual* mismatch as was hypothesized for parietal patients above? Again one may worry that the comparator model seems to offer no principled grounds for differentiating these cases. Of course we know that it is the auditory mode which matters for this task, but

the worry is how does the comparator know which modes matter for which task? Again this may be taken as motivation for adding a 'multifactorial weighting process' to the comparator model. This possibility is considered in the final section.

Using a similar test Sato and Yasuda tested hypothesis 2. This experiment was similar to the first except for two factors. Subjects had to push buttons in response to an external stimulus and an additional experimental condition was added. In this condition pushing the button did not produce a tone. Rather a tone was produced automatically some time after the stimulus appeared. This time was specific to each subject as it was their average reaction time from their learning trials. In this condition when the subject's reaction time happened to match their previous average they tended to misattribute the tone production to themselves (Sato & Yasuda, 2005, p. 247–248). Thus it appears that subjects tend to attribute actions to themselves when the outcome of the action happens to match their prediction. This suggests that subjects experience a greater sense of agency over these actions.

The third test was designed to determine whether or not the subjects' awareness of their intentions played any role in generating their sense of agency. In this test subjects had to push one or other button in response to the letter N or H. In the experimental condition subjects were presented with the target letter flanked by distracter letters. They saw one of the following combinations NNNNN, HHNHH, HHHHH or NNHNN. This method produced many errors. Sato and Yasuda supposed that if subjects experienced a reduced sense of agency for errors (that they recognized as errors) then their awareness of their intentions plays some role in generating the sense of agency. Subjects reported no reduction in their sense of agency over their actions that they recognized as errors. As such, Sato and Yasuda conclude that awareness of one's intention plays no role in eliciting the sense of agency (Sato & Yasuda, 2005, p. 249–250).

Although this final result would seem to support the comparator model over an alternative which explains the sense of agency in terms of a match between intentions and the outcome of action it does not. Both models make the same prediction on this task. Even though subjects have the high level intention (the prior intention or proximal intention) to perform correctly, on a model of matching between intentions and actual sensory consequences it is not this intention that would be compared to the actual sensory consequences of their movement. Rather it would be the goal state or motor intention that is involved in this comparison (a in Fig. 1). Furthermore, the goal state itself must specify the incorrect movement or else the subject would not have made that movement. As such, this potential model also predicts that there would be no loss in the sense of agency over incorrect movements.

In this section I have examined the comparator model's ability to explain the performance of healthy and pathological subjects on tasks involving the self-attribution of action. I have argued that the comparator model, with some adjustments, can explain much of this data. Along with the hypothesis that those suffering from delusions of alien control have problems in forming or using a representation of the predicted sensory consequences of action this model can explain (1) why those suffering from delusions of alien control have problems correcting errors in the absence of visual feedback, (2) why those suffering from delusions of alien control have problems attributing actions to themselves, (3) why those with parietal lesions do not have a deficit in their sense of agency despite being poor at action attribution, (4) why healthy subjects cannot tickle themselves, yet those with delusions of alien control can, (5) why healthy subjects have problems with action attribution when the expected outcome of an action is altered and (6) why healthy subjects tend to over attribute actions to themselves when the outcome of an action coincidently matches their prediction. However, to explain these phenomena the comparator model needs to be altered slightly. In particular different modalities seem to matter more in some circumstances. For example, it has had to be proposed that a mismatch between predicted and actual sensory consequences in non-visual modalities, especially proprioception and kinaesthetics, does not matter for those suffering from parietal lesions (provided there is a match in visual representations). Whereas, matching in the visual mode matters little if auditory consequences of action are unexpectedly altered. In the next section I will continue this test of the comparator model, this time against data generated by Wegner and colleagues to test their alternative model.

5. Wegner's studies

Synofzik and colleagues also use the inability of the comparator model to explain the data used to motivate Wegner and colleagues inferential account as motivation for switching to a multifactorial weighting model. As such it is worth considering the studies from Wegner and colleagues and the problems the comparator model may have with them before moving onto the multifactorial weighting model. The 'helping hands' experiment (Wegner, Sparrow, et al., 2004) is an illustrative example. In this study one subject (the participant) stood with their arms by their side, whilst a second subject (the helper) reached under their arms. A screen obscured the helper such that their arms appeared (from the front) to be those of the participant. Both subjects were given head phones. The helpers heard a series of instructions to perform a set of hand movements (e.g. make the ok sign with both hands). The participants were divided into three groups depending on what they heard. One group (the preview group) heard the instructions to the helper whilst the other groups (the control groups) heard either nothing or an instruction to perform a movement inconsistent with that the helper heard. Those in the preview group reported a greater sense of agency over the actions of the helper than either of the control groups (Wegner et al., 2004, p. 841 and 842).

Along similar lines to this study is the task known as 'I-spy'. As in the helping hands task, in the I-spy task Wegner and Wheatley (1999) attempt to elicit a sense of agency for actions the subject does not control. For this task subjects sat next to a confederate (whom they believed was another participant) looking at the same computer screen. On the screen was a

picture of various toys (a dinosaur, a swan and the like). The subject and the confederate held a small square board over a typical computer mouse. They were asked to use this together to move a cursor in slow circles around the images on the screen. On each trial the subject and confederate would move the cursor for 30 s, after which the subject heard music through their head phones. They were instructed to stop a few seconds after the music began (Wegner and Wheatley, 1999, p. 488). During the movement subjects heard names of items that either appeared or did not appear on the screen. The subject was allowed to make the stop themselves on all but four trials. On these trials the confederate would force a stop on one of the items on the screen (e.g. the swan). These stops were timed so as to be 30 s before, 5 s before, 1 s before or 1 s after the subject heard the name of the item being stopped on (e.g. the swan) (Wegner and Wheatley, 1999, p. 488).

After each stop subjects rated on a 100 point scale how much they intended to make the stop, they were told that 0 meant they merely allowed the stop to happen whereas 100 meant they intended the stop to happen (Wegner and Wheatley, 1999, p. 488). Subjects gave the same scores (on average around 56) for the extent to which they intended to make the stop for when the confederate allowed them to make the stop and when the confederate forced the stop but when the stop location was named 5 s or 1 s before the stop was made. This is significantly more than the ratings given for forced stops when the name of the stop point was given 30 s before or 1 s after the stop (Wegner and Wheatley, 1999, p. 489).[2] This suggests that in this condition subjects may feel they contribute to an action merely due to the presence of a prime.

These findings where expanded on by Aarts and colleagues (2005) 'wheel of fortune' task. In this study subjects sat facing a computer screen showing eight white tiles. Two grey squares moved around these tiles. One square moved anticlockwise and was controlled by the subject pressing and holding the 's' key. The other grey square moved clockwise and was controlled by the computer. After some time (8–10 rotations) the subject received a cue to stop movement by pressing the 'enter' key. At the point the stop cue appeared the grey squares disappeared, after the subject pressed the 'enter' key one of the white squares turned black. The subject was told that this black square represented the location of either their grey square or the computer's at the point the 'enter' key was pressed. Subjects where then asked to rate (on a 1–10 scale) the extent they felt they had controlled the stop point (Aarts et al., 2005, p. 443, 445, 446). In the conditions I am interested in here subjects did not control the point where the black square appeared, instead it always appeared 4 spaces ahead of where the subjects' grey square was when the stop cue appeared, i.e. 4 spaces ahead of the final seen location of the subjects' grey square. Due to the rate of rotation the subjects' square would have stopped at the location of the black square if they pressed the 'enter' key 0.480 s after the stop cue appeared (Aarts et al., 2005, p. 447).

In the experiments of interest here (experiments 1 and 2) four conditions were compared. In experiment 1 these were (1) a subliminal prime task where the location of the black square was to appear flashed black for 0.034 s, 0.046 s before the stop cue appeared, (2) the 'conscious goal task' where subjects were told to try to stop their square on the tile that would turn black and (3) a baseline task where no prime or instruction was given. Importantly in the conscious goal condition (as with the other conditions), subjects were instructed to press the 'enter' key as soon as possible after the stop cue appeared. If subjects adhered to this instruction then their 'goal' to stop at a particular location should not have influenced their action. There is some reason to suppose that subjects did follow this instruction as there was no difference between reaction times for the prime and goal conditions (although both were longer than baseline), suggesting subjects did not adjust their reactions in order to hit the goal square (Aarts et al., 2005, p. 448). These were presented in 2 blocks, 8 baseline trials then 8 trials from either the subliminal prime or conscious goal conditions with each subject receiving only 1 of the 2 test conditions. In experiment 2 the conscious goal condition was replaced by (4) a supraliminal prime condition, where the square which would turn black flashed black for 0.068 s 0.012 s prior to the stop signal appearing (Aarts et al., 2005, p. 450).

Subjects gave higher ratings for their sense of agency over the position of the black square for subliminal prime, supraliminal prime and conscious goal conditions than for baseline (Aarts et al., 2005, p. 447, 450). There was no difference in the ratings given for either prime condition or the conscious goal condition (Aarts et al., 2005, p. 447, 450). This result is especially interesting as it was less likely that participants stopped their square on the tile that turned black in these conditions due to their increased reaction times from baseline (Aarts et al., 2005, p. 448). Thus it seems it is possible to increase subjects' sense of agency over an action when it is, in fact, less likely that they controlled the action. However, exactly what this method probes is called into doubt by a recent replication which suggests the effect of priming is specific to women (Jones, de-Wit, et al., 2008).

Explaining the results of the helping hands, the wheel of fortune and the I-spy experiments on the comparator model is hard, although not impossible. Take helping hands for example. Subjects do not perform the action they see, thus, it seems unlikely that they would get a positive match for an actual/predicted sensory consequences comparison (Synofzik et al., 2008, p. 226). As such it appears the comparator model has no hope of explaining these data.

At this point the advocate of the comparator model may be tempted to propose that studies like helping hands simply probe a different phenomenon. It may be the case that they measure judgements of agency and not the sense of agency. Might subjects in the helping hands study be forming judgements that they influenced the action without having a feeling of doing so? This seems unlikely. The reports given by subjects seem best described as reports of a sense of agency. For exam-

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[2] One potential explanation for this result is that subjects attempted to stop on the named item during the forced stop conditions. If this is the case then the higher scores would reflect the attempt to do this. Wegner and Wheatley investigated this possibility, but concluded that while subjects reported performing visual searches for the named items, they did not seem to be making any attempt to stop on them during the forced stop trials as they made no attempt to stop on them during the free stop trials (Wegner and Wheatley 1999 p. 489).

ple the question they are asked specifically mentions the subject's feelings, e.g. "how much control did you feel that you had over the arms movements?" (Synofzik, 2008; Wegner et al., 2004).

Another explanation arises from the possibility that subjects may perform slight movements consistent with the heard instruction in the helping hands study. Indeed being told to imagine a certain movement causes muscle contractions consistent with that movement (Wegner et al., 2004, p. 847; Jacobson, 1932). Could these movements and the accompanying comparisons cause a sense of agency over the seen movement of the arms? Wegner and colleagues (2004) tested this possibility by examining the effect of performing specific movements on the sense of agency ratings given. Subjects were told either to mimic the movement described whilst still keeping their arms by their side or to perform a distracting movement, i.e. tapping the side of their legs (Wegner et al., 2004, p. 843–844). Those who were instructed to mimic the action described gave higher ratings for their sense of agency over the seen action than those who were given no instruction (Wegner et al., 2004, p. 844). This suggests that performing a movement similar to that which is seen may increase one's sense of agency over the seen action. However, there was no difference between the sense of agency ratings given by those performing distracter actions and those given no instruction (Wegner et al., 2004, p. 845). This suggests that the seen action does not need to match the predictions being made by the motor system in order for one to experience a sense of agency over it.

Despite this a general response is open to the advocate of the comparator model. The key step is to understand how priming the name of an action, the final location of a cursor or the stopping place of a square can cause one to feel they are, to some extent, the agent of an action that they do not control. Jones and colleagues (2008) suggest that the primes may act as a kind of "proxy predicted state" (Jones et al., 2008, p. 578). I take it that their proposal is that the prime stimulus is somehow misrepresented as a prediction of what is about to happen based on the motor commands and compared to actual sensory feedback causing an erroneous sense of agency to be elicited when they match. If so then the comparator model can explain these data. Future work could focus on whether and how such representations could be misused.

Once again it appears that a largely modified comparator model can explain this data. We have two forms of modification here, first is to allow that in general representations of the actual sensory consequences of action in certain modalities matter more than in others, second is to allow the possibility of some mental representations being mistaken for actual or predicted sensory consequences by the comparator. The amount of modification to the model needed is becoming incredibly large and none of these modifications is predicted by the initial presentation of the model. This gives us reason to look elsewhere for an explanation for the sense of agency. In the next section I consider the multifactorial weighting model advocated by Synofzik and colleagues. I argue that even though this model is more naturally constrained by the data than the comparator model it seems to be unfalsifiable, hence the comparator model is to be preferred until specific hypotheses as to how weights are assigned are provided.

6. Multifactorial weighting

In this paper I have been examining the possibility that the comparator model can provide an account of the sense of agency. Several case-by-case adjustments have had to be made in order to make the comparator model viable. For example, the data seems to suggest that in some cases the non-visual actual sensory consequences do not play much of a role in eliciting the sense of agency. In describing the approach to the comparator model above Synofzik et al. state:

> The strategy he [GC] uses is to show that each particular case we discussed can very well be explained with a somewhat adjusted [comparator model]. This strategy of adjustment is, we are ready to admit, a possible strategy. The crucial point is, however, that such adjustments are necessary for *each* case (Synofzik, Vosgerau, et al., 2009, p. 521).

And later:

> Although there might be a certain kind of comparator story for each and every case, there is *no* such story which would be able to deal with all of the cases equally. What happens to the other inputs in particular cases [i.e. the non-visual actual sensory consequences in the parietal lesion patients-GC]? Note that a missing input always yields a mismatch at the comparator when compared to an existing input *unless* it is ignored all together. This means that the explanation of the comparator model can only succeed when some of the multiple inputs are indeed ignored (be they zero = missing or not). This is to say that there must be some process of selecting the relevant inputs for the comparator for each and every particular case. This is exactly what we call the weighting process (Synofzik, Vosgerau, et al., 2009, p. 522).

It is important to note that the account of the comparator model presented above does indeed follow this strategy. For each problematic case assumptions are made as to which inputs the comparator finds important for eliciting a sense of agency in order to offer an explanation. However, no explanation is available for why only some inputs matter in each case. Why is it that a match between *visual* actual and predicted sensory consequences *alone* is enough to elicit the sense of agency in some cases (for example in the self monitoring studies Frith & Done, 1989; Stirling et al., 1998)[3] and at other times it is not (see study 2 in Sato & Yasuda, 2005, in some cases deafferented patients lack an experience of agency even when visual feedback

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[3] Recall also that in order to account for why those with parietal lesions don't have deficits in their sense of agency a comparison of visual sensory consequences must 'trump' the non-visual sensory consequences.

is congruent with the action they perform Synofzik et al., 2009)? Given this, why would a mismatch between non-visual actual and predicted sensory consequences prevent the sense of agency from being elicited in some cases (delusions of control) and not others (parietal lesions)? The comparator model cannot easily answer these questions.

Perhaps we can suppose there are two versions of the comparator model. One comparator ignores everything but vision in eliciting the sense of agency, the other makes use of other sensory modalities. It seems that both of these comparators must be evoked to explain disparate phenomena. Does this mean that we must suppose that we have two distinct versions of the comparator with no way of predicting when one overrules the failures of the other? Even if this were true it would not account for the cases where the comparator is apparently mistaking other mental representations for predicted or actual sensory consequences.

To solve this kind of problem Synofzik and colleagues introduce the notion of a multifactorial weighting process. They suggest that the inputs to the mechanism that elicits the sense of agency are weighted for importance in each case. The inputs include, but are not limited to the comparison of actual sensory consequences to predicted sensory consequences. In the case of parietal lesion patients the fact that non-visual actual sensory consequences are absent may give a weighting of zero to any comparison they would usually enter into. There are, however, other ''agency cues'' such as predicted visual consequences, actual visual consequences, their comparison and predicted non-visual sensory consequences all of which could contribute to the sense of agency being elicited. This also allows us to state why the comparison of non-visual actual and predicted sensory consequences matter in other cases. They are given a weighting greater than zero. So the mismatch between predicted and actual auditory consequences interferes with the sense of agency in Sato and Yasuda's second study. Although there is still much to discover about how such a weighting process works this notion seems to offer a powerful amendment to the comparator model.

Synofzik and colleagues seem to offer a more parsimonious explanation of the sense of agency based on a multifactorial weighting process. Once it is fully understood multifactorial weighting of the inputs to the comparator may explain why in some cases vision seems to matter more than other sensory modalities and in other cases the opposite is true. But then, as Synofzik and colleagues note "The weighting process takes the entire explanatory burden as soon as we wish to explain different cases with *one and the same* model" (Synofzik et al., 2009 p. 522). The upshot of this is that in attempting to provide the strongest possible case for the comparator model we end up seeing that Synofzik and colleague's model is more parsimonious. Crucially a multifactorial weighting model is more naturally constrained by these findings than a comparator model could be.

However, this strength of the model also seems to give rise to a serious problem. It is not clear what, if anything, could falsify the multifactorial weighting model. In the case of the comparator model all we need to falsify it is a case of the sense of agency over one's body being elicited when no representations of actual sensory consequences or predicted sensory consequences are present or when no comparison between these representations is possible. As we have seen, some take the case of the sense of agency over phantom limbs to be exactly such evidence. As it turns out these cases have not provided such evidence, but it is always possible that such evidence could arise. The comparator model is an unfalsified, but highly falsifiable model. In contrast it seems that no such evidence could be, in principle, marshalled against the multifactorial weighting model. On this model, if the sense of agency is elicited when one or other agency cue (say a representation of actual sensory feedback) is absent it can *always* be proposed that the errant cue is given a weight of zero, with the remaining cues (predicted sensory feedback, motor intentions and their comparison) being more highly weighted so as to elicited the sense of agency. Even if it seemed that in some circumstances the sense of agency was elicited by just one factor, then it could just be proposed that in that circumstance the other cues are given a weight of zero. What else could falsify this model? Perhaps a case of the sense of agency being elicited in the absence of all the proposed agency cues will suffice? However, in that case another cue could always be proposed and given a weight of one. More strongly if no representations of actual sensory feedback, predicted sensory feedback, motor intentions, their various comparisons or any other proposed agency cue are possible, then it would be surprising if any bodily action had taken place and such a case would surely falsify any proposed model of the sense of agency. At the very least it would *also* falsify the comparator model.

The price of having a model easily constrained by the current data seems very high indeed. It is not clear what could, in principle, falsify the multifactorial weighting model. This is due to the fact that no hypothesis as to how weights are assigned has been put forward. As such, errant cues can always be given a weight of zero. In order to argue for this model Synofzik and colleagues need to predict what could falsify their model and test the model against this prediction. This will likely mean the addition of a hypothesis as to how weights are assigned to cues in a context dependent way. Preferably this would be something that would not also falsify the comparator model. However, given the nature of these models that may not be possible.

7. Conclusion

In this paper I have presented the case for the comparator model. I have defended this model from a common objection, namely that there seem to be cases where the representation of actual sensory feedback does not contribute to the sense of agency being elicited. In making these arguments we have seen that the comparator model needs to be constrained by the experimental data and does not survive exactly in its initial form. In particular at sometimes representations of actual and predicted sensory feedback in the visual mode seems to matter more than such representations in non-visual modes. At other times the opposite may be the case. In response to this I have considered the multifactorial weighting model advocated

by Synofzik and colleagues. This model seems to be more naturally constrained by the findings discussed in this paper. However, without a hypothesis as to how weights are assigned to each agency cue, this comes at the price of apparent unfalsifiability and thus the comparator model currently has stronger support.

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