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# Beyond the comparator model: A multifactorial two-step account of agency

Matthis Synofzik [a,*], Gottfried Vosgerau [b], Albert Newen [b]

[a] Department of Cognitive Neurology, Hertie Institute of Clinical Brain Research, University of Tübingen, Hoppe-Seyler-Str. 3, 72076 Tübingen, Germany
[b] Department of Philosophy, University of Tübingen, Bursagasse 1, 72070 Tübingen, Germany

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**Abstract**

There is an increasing amount of empirical work investigating the sense of agency, i.e. the registration that we are the initiators of our own actions. Many studies try to relate the sense of agency to an internal feed-forward mechanism, called the ''comparator model''. In this paper, we draw a sharp distinction between a non-conceptual level of feeling of agency and a conceptual level of judgement of agency. By analyzing recent empirical studies, we show that the comparator model is not able to explain either. Rather, we argue for a two-step account: a multifactorial weighting process of different agency indicators accounts for the feeling of agency, which is, in a second step, further processed by conceptual modules to form an attribution judgement. This new framework is then applied to disruptions of agency in schizophrenia, for which the comparator model also fails. Two further extensions are discussed: We show that the comparator model can neither be extended to account for the sense of ownership (which also has to be differentiated into a feeling and a judgement of ownership) nor for the sense of agency for thoughts. Our framework, however, is able to provide a unified account for the sense of agency for both actions and thoughts.


*Keywords:* Internal model; Efference copy; Sense of agency; Ownership; Delusions of control; Thought insertion; Delusions; Schizophrenia; Self; Alien hand

## 1. Introduction

Throughout the last years, computational and experimental evidence has largely extended our understanding of the mechanisms that govern the control and perception of self-action. It largely elaborates on theoretical groundwork that was laid many decades ago by the notion of internal comparison processes (cf. Helmholtz, 1866; Held & Freedman, 1963; Sperry, 1950; von Holst & Mittelstaedt, 1950). According to the most recent versions of this notion (Kawato, 1999; Wolpert, Ghahramani, & Jordan, 1995; Wolpert, Miall, & Kawato, 1998; Wolpert & Ghahramani, 2000; Blakemore, Wolpert, & Frith, 2002; Frith, Blakemore, & Wolpert,

* Corresponding author. Fax: +49 7071 295326.
*E-mail address:* matthis.synofzik@uni-tuebingen.de (M. Synofzik).

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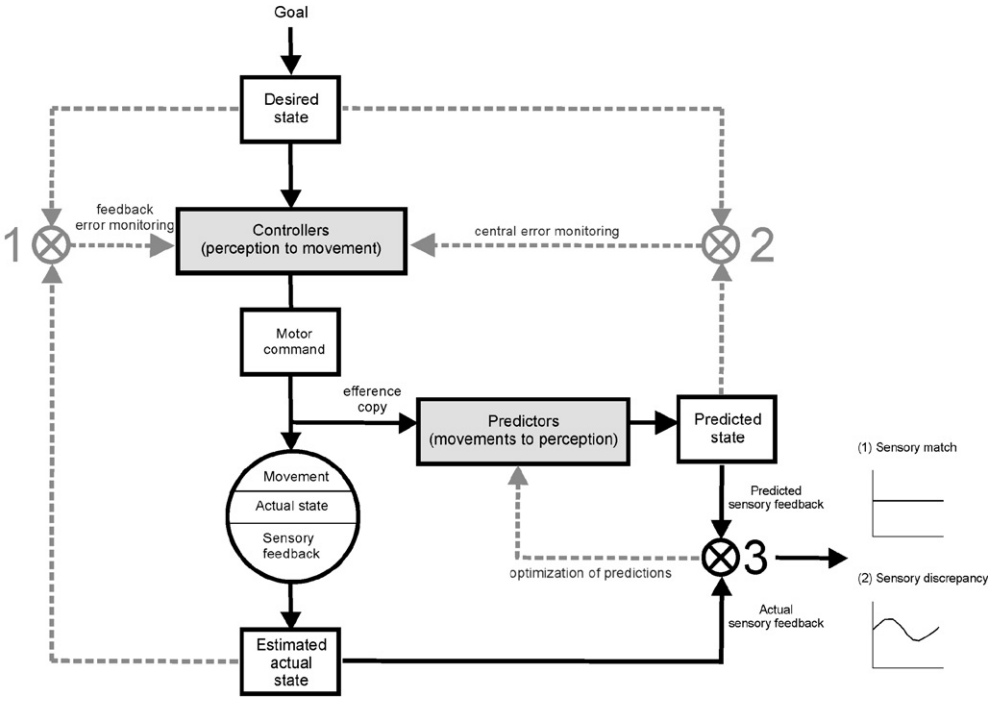


Fig. 1. The neurocognitive comparator mechanism underlying the sense of agency. In a feedback control loop, a comparison between the desired and the actually estimated state allows to calculate a motor error, which is fed back to the system to improve its functioning (comparator 1). On the basis of a given motor command, the system predicts the outcome of one's own behaviour (''predicted state''). Such predictions can be used for feed-forward motor control (''central error monitoring'') of the movement which operates prior to any sensory feedback (comparator 2). Moreover, the predictions can be used to cancel out or attenuate sensory feedback that is self-produced (comparator 3) (for further details see text; figure modified after Frith et al., 2000; Blakemore et al., 2002; Wolpert and Flanagan, 2001).

2000; Lindner, Haarmeier, Erb, Grodd, & Thier, 2006; Wolpert & Flanagan, 2001), the motor system can be considered a control system with the input being a ''desired state'' and the output being the ''estimated actual state'' (see Fig. 1). On the basis of these two representations, the system specifies a sequence of motor commands in order to reach a certain goal. This process is controlled by different comparator mechanisms. In a feedback control loop, a comparison between the desired and the estimated actual state allows to calculate a motor error, which is fed back to the system to improve its functioning (comparator 1). On the basis of a given motor command, the system predicts the outcome of one's behaviour (''predicted state''). When being compared with the initial desired state, such predictions can be used for feed-forward motor control (''central error monitoring'') of the movement which operates prior to any sensory feedback (comparator 2). Moreover, the predictions can be compared to the incoming sensory flow (ex- and reafference) and thus be used to cancel out or attenuate sensory feedback that is self-produced (reafference; comparator 3).

With respect to *sensorimotor control*, the ''comparator model'' (CM) is well-supported by empirical evidence. Especially the last comparator—which compares predicted and estimated actual state—has received wide support from elegant experimental work with all kinds of different sensorimotor sub-systems in both non-human species (e.g. weak electric fish (Bell, 2001) or crickets (Poulet & Hedwig, 2002)) and humans (Blakemore, Wolpert, & Frith, 1998a; Haarmeier, Bunjes, Lindner, Berret, & Thier, 2001; Lindner et al., 2006; Shergill, Bays, Frith, & Wolpert, 2003; Synofzik, Thier, & Lindner, 2006; Voss, Ingram, Haggard, & Wolpert, 2006). Recently, however, the explanatory claim of the CM has been largely extended in that it would not only explain sensorimotor control, but also hold as a *neurocognitive model of self-agency*[1] (Feinberg,

[1] The term ''self-agency'' is used here to highlight the important distinction between detection of agency in general and detection of agency of oneself: While general detection of agency (e.g. of animated objects in the environment) only requires detection of general intentional contingencies between different entities (Blakemore et al., 2003b), self-agency requires self-action, self-action perception or at least intentional sensorimotor contingencies derived from one's own sensorimotor system.

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1978; Frith, 1992; for a recent version and modification see Frith et al., 2000; Frith, 2004, 2005). According to this model, the comparators not only serve a pragmatic, executive function on the level of sensorimotor control, but also assume an evaluation function on the level of action awareness: They may directly underlie our sense of agency (SoA), i.e. the registration that we are the initiators of our own actions (cf. Gallagher, 2000, 2004), in that they "label movements as generated by oneself or an external source" (Shergill, Samson, Bays, Frith, & Wolpert, 2005, p. 2384).

According to the CM, mainly two feed-forward comparators[2] underlie our sense of agency: The comparison between predicted state and desired state (comparator 2, see Fig. 1) evokes a sense of being in control (Frith, 2005), while a comparison between predicted state and estimated actual state allows to self-attribute sensory events (comparator 3, see Fig. 1). In the following critique we will exemplarily focus on the latter comparator (comparator 3) since it is this comparator that is (i) responsible for attributing self-agency to sensory events and that is (ii) currently held responsible for disruptions of agency in schizophrenia patients (Frith, 2005; Lindner, Thier, Kircher, Haarmeier, & Leube, 2005; Shergill et al., 2005). In contrast, the former comparator (comparator 2) (i) cannot explain self-agency for sensory events (since no kind of sensory signal is entered in the comparison process), (ii) is more speculative in character and less well empirically established and (iii) is not primarily used anymore to explain delusions of control in schizophrenia (Frith, 2005). However, most of the following critique regarding comparator 3 applies to comparator 2 as well.

The argumentation for comparator 3 as underlying our SoA seems convincing: Since there is no intrinsic difference between sensory signals arising as consequences of our own actions and sensory signals arising as results from events in the outside world, we need to resort to an internal central signal, i.e. the internal prediction, and compare it with the actual sensory afference in order to distinguish between externally produced and self-produced events (Frith et al., 2000; von Holst & Mittelstaedt, 1950).[3] If predicted and estimated actual state are *congruent*, the sensory event is attributed to one's own agency. If the sensory feedback is *incongruent* with sensory prediction, an external attribution of the causation of the sensory stimuli occurs (see Fig. 1). This agency registration process usually runs outside of consciousness: Rather than being explicitly aware of the motor representations involved in the comparator process, we experience self-agency by a rather diffuse sense of a coherent, harmonious ongoing flow of anticipations and sensory feedback (Pacherie, 2001). But, for example, in case of a striking mismatch between anticipations and sensory feedback, the comparator output becomes conscious and awareness of one's motor predictions, one's actual movements and the sensory consequences arises (Slachevsky et al., 2001).[4]

The idea of the comparator as a subpersonal mechanism underlying a subject's registration of self-agency has many theoretical advantages: (1) The information necessary for agency is not added to the perception of

[2] Since both comparators draw on an efference copy and the feed-forward computation of a predicted state, it is too simple to view only the former as a part of feed-forward control, while considering the latter only as a part of feedback control (as done, for example, by Gallagher, 2004).

[3] Since there are often misunderstandings, it is important to explicitly clarify that according to the CM the SoA does not arise (i) merely from the presence of an efference copy nor (ii) from the output of an inverse or forward dynamic model responsible for translating a desired action goal into the corresponding exact motor command (sometimes called "controller", Blakemore et al., 2002), but from the *comparison* between the predicted *sensory* reafferences (computed by a forward sensory model sometimes called "predictor", Blakemore et al., 2002) and the actual sensory feedback.

[4] We do not claim that agency registration becomes conscious only in cases of a mismatch. The neurocognitive processes that bring about the consciousness of the registration are in principle distinguished from the registration process itself—however, it seems sensible to conjecture that a mismatch normally triggers consciousness processes. Moreover, we should not confuse the SoA neither with the awareness of preparing to move, which seems to depend on the movement specification process of motor controllers, nor with the awareness of movement initiation, which seems to be based on the predictions of the movement predictors per se (Frith et al., 2000). Both operate as action-antecedents irrespective of the comparison (and potential mismatch) between anticipation and sensory feedback of one's actions and are processed temporally ahead of the action (Lau, Rogers, Haggard, & Passingham, 2004; Libet, Gleason, Wright, & Pearl, 1983). The following distinction emerges: (i) The awareness of preparing to move (e.g. the "urge" to perform an act, cf. Haggard, 2005; Libet et al., 1983) is just one form of an attitude (just like the awareness of thinking that p it is the awareness of wanting to move). (ii) The awareness of movement initiation relies on the ability to become aware of having "sent" a motor command. (iii) The awareness of being the agent of one's actions which includes the feeling of control and which takes into account the action execution and the action consequences (=SoA). For example, the perceptual content of the SoA is also determined by the perception of one's sensory action effects, which are either non-specifically modulated by the presence of an efference copy (Tsakiris & Haggard, 2003, 2005a, 2005b) or specifically attenuated by an exact prediction of a forward model (Bays, Wolpert, & Flanagan, 2005; Shergill et al., 2003).

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an action, e.g. by a higher-order cognitive reasoning process, but is an immediate part of the perceptual registration itself. This registration is not necessarily conscious or explicit, but in fact occurs mostly in an implicit, pre-conscious way. However, it always *frames* our phenomenal content: Depending on the context requirements, it cancels (Haarmeier et al., 2001; Lindner et al., 2006), attenuates (Blakemore, Frith, & Wolpert, 1999; Shergill et al., 2003) or highlights (Synofzik, Schlotterbeck, Leube, Thier, & Lindner, 2005) the experience of our action consequences. (2) The experience of agency is not dependent on conceptual capacities, but functions on a pre-conceptual, subpersonal level. (3) The self-relation involved in agency is not assumed to be represented as *independent* of action-processing, as suggested by many philosophical conceptions (e.g. Descartes' dualism which presupposes an independent self that is able to initiate an act of will unrelated and prior to any bodily movement or Kant's transcendental philosophy which presupposes a transcendental I as an independent unknowable entity which constitutes the SoA by unifying all our sense-experiences). The CM is able to explain the SoA as an *intrinsic* property of the action processing itself (Gallagher, 2004; Haggard, 2005; Legrand, 2006; Tsakiris & Haggard, 2005a, 2005b): Via an efference copy, motor processes directly inform the comparator, which in turn evokes our SoA. Thus, by directly connecting the SoA to action perception and motor processes, the CM seems to be a parsimonious explanation of the SoA.

### *1.1. Differentiating the sense of agency*

To test the contribution of the CM to explaining the SoA, it has first to be clarified what is meant by "sense of agency". In fact, the aforementioned definition of the "sense of agency", i.e. the registration that we are the initiators of our *actions* (and not merely the initiators of our movements which would not comprise the effects), differs from many current definitions of the SoA and holds several advantages. For example, it does not require any direct phenomenal awareness (as the case in Gallagher's notion of the SoA, Gallagher, 2007) or any meta-representations of self-agency (as one might suspect in the notions of the SoA proposed by Frith (2005) or by Stephens & Graham (2000), for a discussion see Gallagher (2004)). Nor does it require the *conceptual ability* to register self-agency (as would be the case when defining the SoA as "the ability to refer to oneself as the author of one's actions", de Vignemont & Fourneret, 2004, p. 2). Yet, it does entail the representation of oneself as causally responsible for the action and its direct effects (as opposed to a "compound sense of agency" which entails a sense of action initiation and a sense of action execution, i.e. "the sense of intending and executing an action", Tsakiris & Haggard, 2005a, p. 387). The representational content of the SoA is not only determined by the action initiation per se (and thus not only by action antecedents), but also refers to the guidance and consequences of one's actions and the causal relation between action intention, action performance and action consequences (for a broadly similar notion with respect to the notion of the content of an "intention-in-action", see Pacherie, 2000).

However, not only the conceptual understanding of the SoA is highly heterogeneous, but also its experimental implementation and testing. This can be best shown by analyzing the SoA in terms of a distinction between feeling of agency and judgement of agency: Whereas *feeling of agency* (FoA) represents the non-conceptual, low-level feeling of being the agent of an action, *judgement of agency* (JoA) refers to the conceptual, interpretative judgement of being an agent. Both have to be distinguished from the *sense of ownership* (SoO), i.e. the sense that my body is moving regardless of whether the movement is voluntary or involuntary (Gallagher, 2000). Experiments claiming to investigate the SoA sometimes test the FoA (e.g. when testing the direct visual result of an internal comparison between predicted and actual sensory action-outcome; Lindner et al., 2005), sometimes the JoA (e.g. by requiring subjects "to indicate whether it was they themselves or the computer" that caused an event to happen; Aarts, Custers, & Wegner, 2005, p. 443), sometimes the SoO (e.g. by asking "You have just seen the image of a moving hand. Was it your hand?"; Daprati et al., 1997, p. 77) or sometimes a mixture of JoA and SoO (e.g. when requiring subjects to judge whether it was "their own movement, their own movement distorted, or the movement of another agent"; Farrer et al., 2003a, p. 325). Hence, the diversity of behavioural and neuroimaging results of these studies seems to be largely due to conceptual differences and confusions.

Relying on these distinctions we are able to investigate the contribution of the CM to the explanation of the SoA. In particular, we will show (1) that the CM does in fact contribute largely in explaining the FoA, yet is

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neither sufficient nor necessary, and that it fails completely to explain the JoA.[5] Correspondingly, (2) it cannot sufficiently account for disruptions of the FoA or the JoA in schizophrenia. Finally, it also fails completely to explain (3) the SoO and (4) the SoA of thoughts. We put forward an empirical and conceptual critique and, moreover, outline a two-step multifactorial account of agency as an alternative framework which keeps the advantages of the CM.

## 2. Can the comparator model explain the sense of agency?

### 2.1. Registration of self-agency despite a mismatch at the comparator?

Certainly, the CM should not be taken in a too strict version: Not *any* mismatch between predicted and actual state should lead to an evaluation of the event as being externally produced, but only mismatches beyond a certain sensitivity range. Accordingly, experimental evidence has shown that—within a certain range—even distorted sensory action consequences are experienced as self-produced, despite the underlying mismatch at the comparator. For example, in action recognition studies based on hand movements fed back visually with spatial or temporal distortions, subjects also self-attributed those actions presented with a fairly strong deviation from their real actions (up to 15° in space or 150 ms in time; Daprati et al., 1997; Daprati & Sirigu, 2002; Farrer et al., 2003a, Farrer, Franck, Paillard, & Jeannerod, 2003b; Franck et al., 2001). In self-tickling experiments, which introduced a systematically increased spatial or temporal discrepancy between actual movement and sensory consequences, subjects were aware about an increase in sensation, yet did not report that these events are caused by external agents (Blakemore et al., 1998a; Frith, 2005). A study using distorted auditory feedback of one's own voice showed that normal subjects had no difficulty in attributing the heard voice to themselves, even if the pitch of the voice was distorted to a fairly large degree (Cahill, Silbersweig, & Frith, 1996). Thus, even in cases of mismatch between predicted and actual state, self-attribution of sensory events occurs.

These findings are still well compatible with the CM hypothesis: The comparator might have a certain bias or insensitivity in detecting or reporting mismatches—leading to partly fallible agency judgements in experimental conditions with degraded or ambiguous visual cues—, yet its functioning might still be sufficiently fine-grained to correctly determine agency in everyday social interaction. In fact, this limited sensitivity might even be crucial to the notion of the comparator: In case of a slight discrepancy, the altered sensory feedback might nevertheless be accepted as the sensory outcome of one's *own* movement and can be used for the essential continuous recalibration of one's action predictions and motor behaviour (Synofzik et al., 2006). In other words, the comparator might perform a trade-off between the exactness of predictions and the tolerance range in which it is optimizable by external feedback.

Although the CM might explain "self-despite-mismatch" in terms of a bias or insensitivity in the comparator processing, this claim cannot be burdened with a too high explanatory load. First of all, the postulated bias would have only a rather restricted extent, since internal predictions generally work in a highly precise temporally and spatially tuned way (e.g. sensory attenuation of self-produced tactile hand stimulation functions only in time windows of ±300 ms; Bays et al., 2005; Blakemore et al., 1999). Second, and even more importantly: The contribution of the comparator to the SoA becomes extremely limited by this aspect. If, despite equivalent degrees of mismatch at the comparator, a subject might in one case attribute the action to himself, and in another case to someone else, the attribution behaviour could not be explained by comparator mechanisms alone. They would only serve to detect mismatches between predicted and estimated actual state—which of these mismatches would then lead to an external or self-attribution, respectively, would depend on further mechanisms. In line with this argument, various experimental studies show that subjects

[5] For other critiques of the CM accounts of the SoA see, for example, Stephens and Graham (2000) or Jeannerod and Pacherie (2004). Their critique is either based on a rather one-sided intellectualist, high-level "top–down" account of agency (Stephens & Graham, 2000) or on a specific view on the contribution of "shared representations" and simulation to the attribution of self-agency (Jeannerod & Pacherie, 2004). Hence, these critiques are also based on rather costly presuppositions. Our critique does not need to presuppose either one of such premises in order to criticize the comparator account of agency. It would be beyond the scope of this paper to also give a detailed critique of these critiques.

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even attribute the same distorted feedback, i.e. the same comparator mismatch output, to themselves in some cases and in other cases to the world (Franck et al., 2001; Farrer et al., 2003a). The distinction between self-produced and externally produced states, however, can also not be drawn by a higher, "second order" comparator, since the same problem would arise again. In order to learn the effects of its own movement, the system already has to represent which of its movements is caused by itself and which is not (Vosgerau & Newen, 2007); a mere mismatch at the comparator is not sufficient.

One might argue that in all of the above mentioned cases a self-attributive judgement might have overruled a potential underlying feeling of external action causation, as e.g. produced by a comparator mismatch. In other words, the mismatch at the comparator affected only the level of JoA, but not to the level of the FoA. Indeed, in none of the studies the FoA was explicitly measured, such that it can be conjectured—in favour of the CM—that there was a *feeling* of external causation although this was overwritten by the judgment. This would mean that the CM could not explain these results: at most, it could explain a putative feeling of external causation which was not even measured. Hence, we would need a second explanation on top of the CM for why self-agency attribution would occur despite a comparator mismatch. It seems more parsimonious to assume that subjects also had the low-level feeling of self-causation despite the comparator mismatch but in accordance with their attributive judgement.

### 2.2. Efference copy and reafference are not enough

In addition to the "self despite mismatch argument", there is further evidence that the CM is insufficient to explain the SoA. For example, several studies showed that a deafferented person (patient GL) was not only unable to identify the visual consequences of her own movements (Fourneret, Paillard, Lamarre, Cole, & Jeannerod, 2002; Farrer et al., 2003b), but also showed disturbances of her feeling of being in control over her movements when visual feedback was distorted: Under these circumstances, "she reported impressions of not controlling her movements, and not being aware what she was doing" (Farrer et al., 2003b, p. 616). If the feeling of being in control over her actions, however, was primarily based on efferent signals (as suggested in part by Tsakiris & Haggard, 2005a, 2005b, and by Frith, 2005), patient GL should not experience feelings of not controlling her movements, since efferent signals—and pre-action processes in general—are readily available to her. Even if such a feeling was based on a comparison between a motor prediction and a sensory feedback modality, she should feel in control over her movements at least in cases when the visual feedback was congruent to her predictions. Hence, the lack of FoA in patient GL[6] under circumstances of ambivalent visual feedback emphasizes the need for further sensory feedback information to experience SoA, particularly involving proprioception (de Vignemont & Fourneret, 2004; Evans, 1982; Farrer et al., 2003b; Marcel, 2003).[7] Therefore, one either has to extend the CM by assuming that *multiple* sensory feedback modalities (e.g. vision *and* proprioception) have to be entered into the comparator for a sufficient prediction-reafference comparison and the potentially resulting SoA,[8] or revise the CM by claiming that, more general, unspecific efferent-afferent congruencies (e.g. between an action intention and a distal sensory effect) alone or in combination with certain intermodal congruencies (in the case of GL between proprioceptive and visual information) are needed for the SoA.

[6] Patient GL lacks a FoA in the sense that she feels not in control of her movements and does not know what she is doing. She certainly does *not* loose the sense of initiating a movement, i.e. she is aware of trying to do something. According to the aforementioned definition, however, the SoA is not simply congruent with a sense of initiation, since the representational content of the SoA is not only determined by the action initiation per se, but also refers to the guidance and consequences of one's actions and the causal relation between action intention, action performance, and action consequences (see also Footnote 4).

[7] Intermodal congruencies between different sensory feedback modalities alone, however, are certainly neither sufficient for a FoA (e.g., I will not experience FoA if somebody moves my arm, even if there was a perfect congruency between visual and proprioceptive feedback) nor necessary (e.g., one also has FoA with one's eyes shut). An efferent cue in the broadest sense (intention, anticipation, etc.) has to be present (cf. the later discussion on SoA vs. SoO).

[8] The idea of multiple sensory feedback modalities entering the comparator—in particular vision and proprioception—has received preliminary evidence from both behavioural (Synofzik et al., 2005, 2006; Tsakiris, Haggard, Franck, Mainy, & Sirigu, 2005) and neuroimaging studies (Leube et al., 2003).

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The critique that a mere comparison between efference copy and reafference is not sufficient for the SoA receives further evidence when being spelled out in terms of the neural substrates of agency. Neuroimaging studies have demonstrated that the parietal lobe plays a major role in detecting mismatches between actually performed movements and their visual consequences (Farrer et al., 2003a; Leube et al., 2003). Correspondingly, patients with parietal lobe damage show an impairment in detecting mismatches between those movements they had actually performed and those movements that were visually displayed to them (Sirigu, Daprati, Pradat-Diehl, Franck, & Jeannerod, 1999). Yet these patients do not report abnormal agency judgements. Thus, whereas the parietal cortex (probably as part of a parieto-cerebellar network, cf. Lindner et al., 2006) seems to be responsible for detecting mismatches between predicted and actual action consequences (as well as detecting mismatches between different sensory feedback modalities that convey body-related information), agency judgments and probably also agency feelings must depend on neural signals higher in the hierarchy of control and perception, e.g. in frontal or prefrontal areas (see e.g. Fink et al., 1999, Slachevsky et al., 2001). These additional structures ultimately decide about agency feelings and attribution—whether a mismatch at the comparator is reported or not.

### 2.3. Congruency between intention and effects is enough

If a mismatch at the comparator is insufficient to trigger a lack of SoA (self despite mismatch argument) and, moreover, a comparison between efference copy and a reafference modality is insufficient to evoke a reliable SoA (patient GL), the question arises whether the comparator might not only be insufficient to explain the SoA but also not necessary. The SoA might result from perceptual and cognitive processing that functions largely independent from any motor processes—and thereby also independent from any comparator output. In fact, with respect to motor control and action perception some authors have argued that under many circumstances the CM can be completely left aside.[9] When subjects plan, monitor and perceive their own actions and the corresponding effects, they often do not primarily represent them in motor-related terms (e.g. their spatio-temporal pattern), but in intentional and perceptual terms (e.g. their underlying goals) (Mechsner, Kerzel, Knoblich, & Prinz, 2001; Mechsner, 2004; Prinz, 2003; Saito, Mushiake, Sakamoto, Itoyama, & Tanji, 2005). Accordingly, one might—at least in some cases—completely leave aside the CM when explaining the SoA and only focus on the intentional and perceptual goal representation. Simple congruencies between motor intention and sensory events—without any involvement of linking efference copy mechanisms—might be sufficient for a person to attribute a sensory event to her own agency (Blakemore et al., 1999).

The idea receives support from various studies. Amputees might experience a FoA for limb movements which are visually presented in the place where their original limbs would have been located (Ramachandran & Rogers-Ramachandran, 1996). For example, under such experimental circumstances, one "patient exclaimed with considerable surprise that all his movements 'had come back'". Moreover, "he now vividly experienced muscle and joint movements in his phantom" (Ramachandran & Hirstein, 1998, p. 1621, for more patient reports of a FoA see Ramachandran & Rogers-Ramachandran, 1996). Thus, amputees might experience a FoA for a phantom, although they do not receive corresponding proprioceptive input and can most probably not resort to an efference copy that—months after amputation—still predicts the exact kinematic state or the exact visual action consequences of the former limb. As emphasized above, the aspect of high and rapid plasticity is central to the notion of internal models—otherwise they would loose all their advantages (e.g. providing the brain with accurate motor and perceptual information when having to compensate for absent or delayed sensory feedback or when performing rapid complex coordination movements). Accordingly, experiments studying the perception of the visual consequences of one's own hand movements have shown that the perceptual awareness of one's own action mediated by internal predictions adapts rapidly when body and context conditions change (Synofzik et al., 2006). To explain the FoA in amputees in terms of the CM would require to presuppose an efference copy that is unmodified months after a traumatic experience and that is, on the one hand, still predicting the exact spatiotemporal sensory action consequences of the

[9] Of course, the claim is not that the CM could be left aside for *all* aspects of motor control and self-action perception. Comparator mechanisms are certainly necessary, for example, for motor learning (see Wolpert & Flanagan, 2001) and even for perceptual learning (Synofzik et al., 2006).

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former limb and thus conveying a FoA, but is, on the other hand, not leading to major deficits in the present predictive sensorimotor behaviour of the amputee. It seems much more parsimonious and hence much more plausible to require only a more general congruency between a motor intention and a sensory effect to account for their experience of FoA.

Even more conclusively, the work of Wegner and his colleagues (for review see Wegner, 2003) reveals that the FoA does not have to be tied to any causal motor mechanism such as the comparator at all. For example, in a "helping hands" pantomime task, subjects experienced high degrees of agency for movements that were in fact performed by another agent, when only the other agent's hands appeared in the place where subjects' hands would normally appear and when subjects could hear instructions previewing each movement (Wegner, Sparrow, & Winerman, 2004).[10] Subjects' own arms remained passive, thus there was most plausibly no efference copy and no comparator involved, but, at most, merely a general cognitive anticipatory or intentional state. This experiment reveals that there are other sources of peculiar action experiences and of self-attribution which do not need to involve any motor actions at all. In this case, a contingency between visual input and previewing instructions/general anticipatory state seems to be sufficient to evoke an (inadequate) FoA in the subjects.

### 2.4. Belief processes

Further studies of Wegner and colleagues (Wegner, 2002) demonstrated that one does not need to change any motor mechanism or sensory input at all to alter agency judgements (JoA). For example, subjects were required to judge letter strings to be words and the screen went blank after each trial either because of a computer signal or because subjects replied correctly; then they were asked who was responsible for the blank screen. On trials with subliminal presentation of the word "I" or "me", subjects tended to self-attribute ambiguous events (Wegner, 2002). Thus, especially the JoA can be determined by factors that are independent from any specific comparator output at the subpersonal level of action control and action perception. In the aforementioned cases, awareness and attribution of agency critically rely on higher-order causal inferences between thoughts and actions on the basis of belief states and intentional stances (Wegner, 2003). More recent research even suggests that specific intentional or goal-directed cognitive states do not need to be involved at all, but only belief-like mental states might suffice to experience JoA (Aarts et al., 2005).

This idea seems to be supported by our intuitive everyday experiences: We often perform movements acknowledging that they were incongruent to our prediction. Yet, we do not attribute their cause to an external origin, but still recognize ourselves as being their agents. For example, I may believe that I am the agent of the action, just because I take into account the fact that I am alone in the room (cf. de Vignemont & Fourneret, 2004). Since there is no other event that might better explain the actual afference in a given situation, we infer that we must have been the agent of the action. In this case, agency is inferred on the basis of higher-order cognitive processing exploiting environmental and contextual cues, but is not evoked by an efference copy or any comparator output.

### 2.5. The multifactorial weighting of authorship indicators

Summing up, there seem to be many cases where the comparator output is neither a sufficient nor a necessary condition for the FoA nor the JoA. Action-related perceptual and motor information—such as efference copies, sensory feedback modalities, and their comparison—is rather entered into a multifactorial weighting process bringing together different sense modalities (e.g. intermodal congruencies), efferent-afferent congruencies, and different levels of cognitive processing that indicate agency of actions for a person (Wegner & Sparrow, 2004). The weighting of these authorship cues might vary in different situations and in different

[10] Whereas Wegner and colleagues often test for perception of causality of body-distant distal effects, e.g. causation of events on a computer screen, they here certainly tested for FoA of one's body movements. This is guaranteed by both the task ("helping hand" pantomime) and the subjects' responses (They were required to respond to the questions "How much control did you feel that you had over the arms' movements?" or "To what degree did you feel you were consciously willing the arms to move?", Wegner et al., 2004, p. 840).

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persons. For example, in presence of an explicit goal, the coupling between motor intentions and the goal might become largely important for the FoA, whereas in absence of an explicit goal the match between proprioception and feed-forward cues with visual feedback might play a major role (Frith, 2005; Wohlschlager, Engbert, & Haggard, 2003). Or, in the absence of reliable proprioceptive cues—like in patient GL—, one is more dependent on a congruency between motor intention and visual action consequences to experience agency. In a similar way, schizophrenia patients with delusions of control tend to rely more on exteroceptive information (such as vision) than on interoceptive cues (such as proprioception and efference copy) when perceiving their actions and experiencing FoA (Synofzik et al., 2005). Depending on the context and the task, also normal subjects can refer more to visual information than to internal action signals, for example to update their FoA if internal and external action signals differ (Synofzik et al., 2006). All these examples support the thesis of a continuous multimodal weighting process when perceiving or inferring agency of one's actions.

### 2.6. Perceptual registration or belief formation? The two-step account of agency

Even if the CM thesis held true, its explanatory value would be restricted to the level of self-action perception: A mismatch at the comparator might explain in some cases why largely distorted sensory feedback of subjects' actions evokes the perceptual experience that the arising sensory events feel strange and discordant to subjects' expectations, in certain tasks even resulting in a feeling of tickliness (Blakemore, Goodbody, & Wolpert, 1998b). Thus, without question, it does certainly contribute to the FoA. Yet is insufficient or even unnecessary to account for it in many cases (see above) and fails completely to explain agency beliefs (JoA), especially why we sometimes attribute sensory events mismatching our sensory predictions to ourselves and sometimes to external sources. Moreover, in case of external attribution, it cannot explain why they are attributed to a certain event or a certain person. Agency beliefs and external attributions—may they be correct or incorrect (as in delusions of control)—cannot be explained by the CM alone: Even if a match at a comparator signals self-agency, a non-match could only signal non-self-agency but not specify the attribution of the agency to someone else. A convincing theoretical account of agency, however, should be able to explain not just why one perceives an action as peculiar, i.e. present a partial account for the FoA, but also why this experience leads to a self-attribution or to an external attribution (JoA)—especially because many experiments measure the JoA rather than the FoA.

Thus, although the SoA appears phenomenally as a central and uniform processing module, it represents in fact a complex supramodal phenomenon of largely heterogeneous functional and representational levels.[11] Thus, it seems inevitable to assume a gradual multi-level model of agency with bottom–up and top down-processes. Within this model, the most basic levels consist in sensorimotor processes, while the most elaborated levels comprise conceptual and meta-representational processes. In particular, one has to distinguish at least two different steps (see Fig. 2):

(1) On the primary perceptual level of the *feeling of agency* (FoA) the non-conceptual, low-level feeling of being an agent of an action is represented. At this level, an action is merely classified as self-caused or not self-caused. In particular, the action is not attributed to myself—the self is only implicitly represented in the FoA. Therefore, no external attribution is possible at this level: There is no such thing as a feeling that, say, Chris has caused my action. In other words, the FoA is exclusively first-personal in that the self is only represented implicitly. Thus, at the perceptual level the Generality Constraint (Evans, 1982) is not fulfilled since one action can only be represented as caused by me or not caused by me; it cannot be rep-

[11] Interestingly, this model of the SoA (and the SoO, see below) is in close formal analogy to recent models of other internal neurocognitive representations, namely of spatial representation and of spatial neglect: Spatial representations are supramodal internal representations which result from integration and transformation of multimodal information into an internal coordinate-system (Thier & Karnath, 1997). Analogue to disturbances of the SoA (e.g. delusions of control), disturbances of spatial representation (e.g. spatial neglect) seem to result from an impaired integration and transformation of this multimodal information (Karnath, 1994, 1997). The idea of agency and ownership as complex multi-level phenomena is in close analogy to the idea that the self and human self-representations are complex multi-level phenomena of largely heterogeneous functional and representational levels (cf. Knoblich, Elsner, Aschersleben, & Metzinger, 2003; Newen & Vogeley, 2003).

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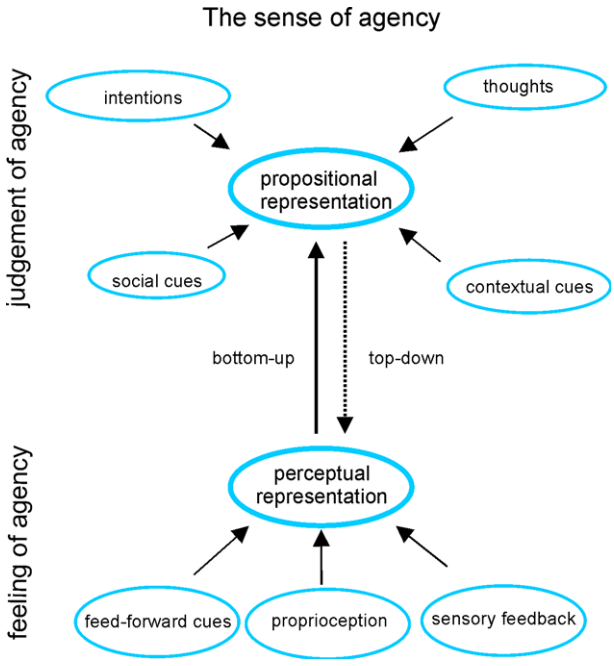


Fig. 2. The two-step account of agency. The basic non-conceptual feeling of agency is produced by a gradual and highly plastic subpersonal weighting process of different action-related perceptual and motor cues (feeling of agency). This pre-conceptual core is further processed by conceptual capacities and attitudes (e.g. beliefs, desires) to form an attribution of agency (judgement of agency). The extent to which the feeling and judgement of agency, respectively, contribute to the overall SoA depends on the context and task requirements. Thus, the SoA is a dialectic combination of both, bottom–up-processes and top–down processes.

resented as caused by someone else. Hence, perceptual agency representations are not compositional and have no object-property structure, and are therefore non-conceptual (Vosgerau, in press). The FoA is a ''supramodal phenomenon'' in that it results from the aforementioned weighting and integration process of the different action-related authorship indicators. In case of congruency between these indicators (e.g. a match between internal prediction and visual feedback), the experience of action is withhold from further processing and we experience self-agency by a rather diffuse sense of a coherent, harmonious ongoing flow of action processing. In case of incongruency between these indicators (e.g. a mismatch between proprioception, motor intention and visual feedback), we experience an action as strange, peculiar and not fully done by me. This experience might—inter alia —result from a mismatch at the comparator (or a conflict between other authorship indicators).

(2) On the secondary level, the *judgement of agency* (JoA) is formed as an explicit conceptual, interpretative judgement of being the agent. Here, the pre-conceptual basic feeling of agency is further processed by conceptual capacities and belief stances to form an attribution of agency. For example, a mismatch between different authorship indicators (e.g. at the comparator) triggers (i) a primary basic feeling of not being the initiator of some event and (ii) a second interpretative mechanism which looks for the best explanation, resulting in a specific belief formation about the origins of the change in perception: I can either believe that I am the author of the action despite the mismatch or I can assume that someone or something other than me is causing that action. If an external agency attribution occurs, it is an open question to whom the action is attributed. How the belief formation is performed depends on our way of rationalizing our actions, i.e. our way of giving a (more or less) plausible explanation for our experiences. This rationalization does not depend on the comparator output and not even on reliable introspection, but rather on ad hoc theorizing about oneself (Vosgerau & Newen, 2007) as influenced by contextual cues and belief states. Especially, one's personal background beliefs, for example in form of a narrative self-structure, might gain major importance for the question if and to whom external agency attribution occurs (Gallagher, 2004; Stephens & Graham, 2000). Under certain circum-

stances—especially in cases of a strong mismatch (for example, an experimentally induced visuomotor mismatch)—, we are able to go beyond an unreflected acceptance of our perceptual experience and ad hoc beliefs to focus on contextual cues or on stored knowledge about our actions and ourselves, which might then lead either to a self-attribution or to an external attribution of the action.

The extent to which the feeling and the judgement of agency, respectively, contribute to the overall SoA depends on the context and task requirements. In certain unambiguous, stable circumstances, the feeling of agency might be so strong that the belief formation mechanism does not need to be further instantiated (e.g. when lifting my arm in an unambiguous context I have an SoA without further explicit or conceptual interpretation). In other words: In everyday life we normally do not need to form beliefs and judgments about self-agency but can take the FoA at face value. The more agent-ambiguous, external, arbitrary or culturally mediated the effects of actions become, however, the more importance is given to the belief formation mechanism (e.g. in ambiguous experimental situations). The belief formation processes resulting in a JoA might also phenomenally overwrite the agency feelings in certain situations (e.g. when secondarily realizing that one has been the initiator of an effect just because one was the only one around, one will phenomenally experience agency in the full sense although it primarily didn't feel like oneself had caused it). Thus, the SoA is a dialectic combination of both bottom–up processes (as emphasized by Frith, 2005; Gallagher, 2007; Jeannerod & Pacherie, 2004) *and* top–down processes (as emphasized by Stephens & Graham, 2000). In other words, our account offers a genuinely new way how to reconcile previously unreconciled, seemingly dichotomous types of agency theories.[12]

Future experiments have to investigate and disentangle the FoA and the JoA. For studying specifically the FoA, implicit, non-conceptual measures need to be further developed (e.g. sensory attenuation, vegetative parameters), thus ruling out the potentially confounding effect of higher cognitive capacities, which would reflect the influence of the cognitive process of the JoA, but not the sensorimotor weighting process putatively constituting the FoA. Results from measures on this level have then to be compared to results from the level of agency judgements and belief formation (e.g. explicit verbal judgments).[13]

Summing up our analysis in terms of this two-step account, we have shown that the CM is neither sufficient nor necessary to account for the FoA and that it fails completely to explain the JoA. At least the latter failure might be less troublesome if one would merely claim that the comparator was only a rather primary, basic mechanism for the SoA.[14] Instead, the more basic level of the FoA is most suitable accounted for by a multimodal weighting process of different agency indicators, whereas the conceptual level of JoA is best explained by belief formation processes that take into account the low-level FoA, but also other factors like background beliefs and rationalization modules.

## 3. Can the comparator model explain delusions of control in schizophrenia?

### *3.1. The umbrella term "self-monitoring"*

It was recently claimed that the CM of agency straightforwardly explains delusions of control in schizophrenia (e.g., Frith, 1992; Frith et al., 2000; Gallagher, 2004; Knoblich, Stottmeister, & Kircher, 2004; Lindner et al., 2005). As articulated by Frith, in schizophrenia patients "something is wrong with the generation of a forward model and the representation of the predicted state of the system" (Frith et al., 2000). Even the most recent versions of the CM account of delusions is not more precise, contending that "patients with delusions of

[12] Although the most recent approach by Shaun Gallagher (2007) supports the notion of a multifactorial account of agency, which we have worked out in much more detail here, it still treats "bottom–up" and "top–down" approaches of agency as unreconciled, dichotomous alternatives.

[13] A first preliminary example for disentangling feeling and judgement can be seen in a study investigating the *sense of ownership* (Tsakiris, Hesse, Boy, Haggard, & Fink, in press). Thus, this study can also be taken as empirical support for our suggestion that the distinction between feeling and agency does not only apply to the sense of agency, but also to the sense of ownership.

[14] This might be what Frith and others have in mind, but fail to clarify in their work. Instead, in employing the CM to explain delusions of control in schizophrenia patients, they imply that the CM would also account for the JoA, since delusions are defined as belief states.

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control are abnormally aware of the sensory consequences of an action and cannot accurately predict the consequences of their movements'' (Frith, 2005, p. 766). Corresponding to these vague formulations of Frith's account, experimental evidence to support the thesis of an impaired comparator is drawn from most heterogeneous experiments. Especially the concept of a ''breakdown of self-monitoring'' (Blakemore, Smith, Steel, Johnstone, & Frith, 2000; Kircher & Leube, 2003; Knoblich et al., 2004) has become a popular umbrella term to explain a wide array of deficits in action control and action perception in schizophrenia patients with delusions of control, often disguising the mechanisms that were exactly investigated. Here, we first clarify the terminology and the exact understanding of the CM in relation to delusions of control, before we show that the CM thesis of delusions of control does not hold in the light of recent experimental evidence and the previous analysis of the SoA.

### *3.2. A deficit in monitoring internal signals for motor control or for perception?*

Experimental evidence for the CM was initially drawn from motor experiments which demonstrated that schizophrenia patients had difficulties in on-line corrections of movements in absence of visual feedback. This was interpreted as a deficit in ''central error monitoring'' of the movement pattern (Frith & Done, 1989; Malenka, Angel, Hampton, & Berger, 1982; see also Fig. 1, comparator 2). Delusions of control, however, are primarily deficits on the perceptual level, not on the motor level. One cannot easily conclude from one deficit to the other, since an impairment in motor performance does not necessarily have to be related to an impairment in a perceptual or intentional judgement (Anscombe, 1957; Eilan & Roessler, 2003; Fourneret, Paillard, Lamarre, Cole, & Jeannerod, 2002; Proust, 2003) and vice versa. This assumption is supported by recent computational (Wolpert et al., 1998) and behavioural (Flanagan, Vetter, Johansson, & Wolpert, 2003; Synofzik et al., 2006) findings that distinguish between internal models for motor control, which predict and optimize trajectory parameters of a movement (sometimes called ''forward dynamic model'' (Wolpert et al., 1998) or ''controller'' (Blakemore et al., 2002)), and internal models subserving the perception of one's movements, which predict the sensory consequences of one's movements and deal with the resulting sensory feedback (''forward sensory model'' (Wolpert et al., 1998) or ''predictor'' (Blakemore et al., 2002)). Accordingly, experimental evidence for the CM thesis of delusions of control should not be drawn from studies investigating motor control but from studies testing for motor awareness and action perception.[15]

Indeed, recent experiments showed that schizophrenia patients are unimpaired in their ability to use forward modelling to make predictive alterations of grip force in routine situations (Delevoye-Turrell, Giersch, & Danion, 2002) or to automatically adjust their hand movements when overcoming discrepancies between these movements and their visual consequences (Fourneret, Franck, Slachevsky, & Jeannerod, 2001; Knoblich et al., 2004). However, they exhibit an impaired awareness of their movements. Several studies using experimental self-attribution tasks based on visual feedback distortion of hand movements showed that—compared to healthy controls—schizophrenia patients had more problems in recognizing the feedback manipulations and showed a stronger tendency to attribute what they saw to their own agency, even if feedback information was clearly different from the action performed (Daprati et al., 1997; Fourneret et al., 2001; Franck et al., 2001; Knoblich et al., 2004; for an over-association of actions with action effects in the domain of time-awareness see Haggard, Martin, Taylor-Clarke, Jeannerod, & Franck, 2003). This behaviour, however, which was termed ''hyperassociation'' or ''overattribution'', cannot be explained by the CM. If the patients were not able to form representations of the predicted sensory consequences of their actions, they should misattribute self-produced sensory information to external sources rather than exhibit hyperassociations (Lindner et al., 2005).

In addition to these explanatory problems, most studies leave open—or contradict each other—where exactly the processing of the comparator might be disturbed: (i) in the formation of an adequate prediction of the sensory consequences (Lindner et al., 2005), (ii) in the comparison and weighting process between prediction and sensory feedback (Synofzik et al., 2005) or (iii) in accessing the comparator output. Furthermore, there is contradictory evidence as to whether schizophrenia patients with delusions of control show hyper-

[15] Accordingly, Frith recently re-stated his thesis, now claiming that ''for patients with schizophrenia the primary problem is not of control of the motor system, but of awareness of control of the motor system'' (Frith, 2005, p. 756), more specifically, that ''in patients with delusions of control something goes wrong with the mechanism by which the sensory consequences are predicted'' (Frith, 2004, p. 20).

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awareness of proprioception (Frith, 2005) or of other usually unconscious aspects of motor control (Pacherie, 2001; Spence, 2001), or whether they are "hypoaware" of these internal action-related signals (Synofzik et al., 2005).[16] These problems show that (i) even if the CM thesis of delusions of control is specified to deficits in perceptual awareness—leaving aside potential deficits in monitoring motor performance—it is still too undetermined to give an adequate account of delusions of control in schizophrenia patients and that (ii) it should be applied in a much more differentiated and cautious way.

### 3.3. Impaired perception of one's actions—but also an impaired comparator?

The studies which find "hyperassociations" of sensory events in schizophrenia patients can be taken as a good example for illustrating an important requirement when testing the CM thesis of delusions of control: Even if experiments showed that schizophrenia patients are impaired in perceiving their actions, they must furthermore also demonstrate that this impairment is indeed due to a deficit in the comparator and not due to a deficit in any other perceptual processing. The "hyperassociations", for example, can be better explained by the aforementioned multimodal integration account than by the CM. It would suggest that schizophrenia patients with delusions of control carry out a particular form of intermodal weighting of action signals: As recent experiments have shown (Synofzik et al., 2005), they might tend to rely more on external action signals (e.g. visual feedback) than on internal cues (proprioception and efference copy) when perceiving their actions and inferring agency. This might explain why they also self-attribute ("hyperassociate") those external sensory events to their own actions that are largely manipulated. Furthermore, it provides an account for why delusions of control do not occur constantly—as to be claimed by the CM (cf. de Vignemont & Fourneret, 2004)—, but only episodically: Misattribution of self-produced sensory information to external sources occurs especially in those circumstances where external cues of action-information are not available or ambiguous (Lindner et al., 2005). If the impairment lies in an inadequate integration and weighting process of different authorship indicators, then the "break-down in self-monitoring" might be readily explainable without postulating a deficit in the comparator: Rather than being impaired in feed-forward modelling, schizophrenia patients might, for example, fail to adequately combine intentions and proprioceptive feedback with visual feedback when perceiving their actions and inferring agency.

In fact, for explaining anomalous perceptual experience of one's own actions in schizophrenia patients, many more dysfunctions in perceptual processing are conceivable that do not need to postulate a deficit in the comparator. For example, the anomalous FoA might also be grounded in an unspecific tendency to misperceive agency, which is completely unrelated to any comparator functioning. An experiment of Blakemore and colleagues showed that when patients with delusions of persecution were observing simple animation sequences, these patients attributed intentional behaviour to the moving shapes in conditions where other patients (and controls) attributed no intentionality (Blakemore, Sarfati, Bazin, & Decety, 2003a). The failure of agency attribution might also result from a very unspecific failure of monitoring internal cognitive sources. Various studies demonstrated that schizophrenia patients show deficits in monitoring internal cognitive sources in tasks that do not use any action control or action perception at all. For example, they are impaired in discriminating between internally generated mental events (e.g., fantasies) and memories of externally derived events (Johnson & Raye, 1981), in deciding whether a thought was self-produced or not (e.g., Morrison & Haddock, 1997) and whether a thought was just imagined or also verbalized (Henquet, Krabbendam, Dautzenberg, Jolles, & Merckelbach, 2005; Keefe, Arnold, Bayen, McEvoy, & Wilson, 2002). In other words, even if there is growing evidence that schizophrenia patients with delusions of control are impaired in the perception of their actions—making the thesis of a break-down in self-monitoring highly convincing—compelling evidence linking these perceptual deficits directly to deficits in the comparator is still rare (see Lindner et al., 2005,as an exception). Unspecific perceptual impairments or impairments in higher-order cognitive processing, e.g. a failure to disambiguate complex signals on the basis of accurate inferences from context situations, can often not be ruled out.

[16] The confusion between "hypo-" and "hyperassociations" might partly result from the failure to distinguish between SoA and SoO.

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### 3.4. Impaired perceptual experience or impaired belief formation?

Experiments claiming that delusions of control would result from a deficit in the comparator have furthermore to demonstrate that the misattributions genuinely result from a failure at the level of perceptual experience of the action (FoA) rather than being secondary to a failure on the level of belief formation (JoA). Studies showing that schizophrenia patients are impaired in the verbal attribution of action agency (e.g. Daprati et al., 1997; Farrer et al., 2003a; Franck et al., 2001) fail to draw this distinction. Thus, they cannot reject the claim that schizophrenia patients might have the same experiences as normal subjects (normal FoA), yet reconstruct and rationalize them in an anomalous way (anomalous JoA). This, however, would be necessary given the well known difficulties of schizophrenia patients in rationalization processes, formal reasoning, conceptual thinking (Liddle, 1987; Subotnik et al., 2006) and—of special importance for the present purposes—in attribution behaviour (Humphreys & Barrowclough, 2006; Martin & Penn, 2002).

If it could be demonstrated that schizophrenia patients with delusions of control indeed have an impaired FoA, it has to be shown in the next step that this impairment is due to a deficit in the comparator rather than due to any other unspecific deficit in the perceptual processing of one's own actions within the complex weighting and integration process of different authorship indicators (e.g. an unspecific tendency to misperceive agency, see above). But even if these impairments are best explained by a deficit in the comparator (as, for example, well demonstrated by Lindner et al., 2005; Shergill et al., 2005), this deficit itself would be insufficient to cause the misattribution.[17] In order to transit from abnormal experience to delusional belief, an unusual belief formation processing—i.e. on the level of the JoA—must be postulated. Only by such an idiosyncrasy in the belief formation process it could be explained why schizophrenia subjects (i) do not accept an alien experience as a strange experience (as, for example, healthy subjects or most neurological patients with alien motor phenomena would do) but (ii) form out a delusional agency hypothesis about this experience and (iii) maintain it despite different stored encyclopedic knowledge about their behaviour and despite the testimony of others (Davies, Coltheart, Langdon, & Breen, 2001). Such an explanation needs to give an account of abnormalities in the belief formation system with respect to a person's way of action rationalization and self-theorizing.

Furthermore, a deficit in the comparator cannot provide any explanation for the semantics of the delusional belief: Why is it that agency attribution fails only in certain semantic contexts that are often highly specific to the history of the delusional individual? And why does it have its specific semantic content (e.g., an action is caused by a stranger or by God)? To explain this, one would have to integrate information from a person's broader belief system and narrative self-structure. In other words: If the CM thesis of delusions of control was correct, it could only explain why schizophrenia subjects have an abnormal experience of their own action (i.e. an abnormal FoA). Yet this is not enough to explain why they form out delusional beliefs with a certain content (i.e. have abnormalities in the JoA).

In conclusion, the CM thesis of delusions of control in schizophrenia is often used as an unclear and blurry concept insofar as evidence is drawn from strongly heterogeneous levels of behaviour: From automatic mechanisms to perceptual distinctions and even to meta-representational cognitive process involving explicit first-person judgements—all of these levels are taken to support Frith's model. To sum up, future thorough investigations of disruptions of agency in schizophrenia have to address the following points:

- intensify and elaborate the conceptual work (e.g. clarifying what it means and what is required to attribute agency to an agent, to "monitor" one's actions, etc.)
- reflect the differences in the measures and levels which are drawn to support the respective agency theses (e.g. motor domain, perceptual domain, subpersonal level, conscious level, feeling of agency, judgement of agency, etc.)

[17] As pointed out above, we need to assume a distinct belief formation process for external attribution of agency anyway, even when the perceptual feeling is construed as being very rich in content (as e.g. in Pacherie et al., Bayne, 2006). Therefore, we do not try to construe a so-called endorsement account but rather a hybrid account which fits better to the complex structure of agency. However, the judgments we assume are not—contrary to Pacherie, Green & Bayne—explaining the perceptual content but rather explaining the perceived fact, just as the belief that the lines are of the same length does by no means explain my perceptual experience in the Müller–Lyer illusion.

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- control for possible confounding factors in studies investigating the agency attribution process (e.g. general source monitoring deficit, general tendency to misattribute actions, etc.)
- specify the CM thesis of delusions of control (e.g. deficit in forming an efference copy, in forming internal predictions, in comparing predicted and actual state, in accessing the comparator output) and alternative theses (e.g. a deficit in intermodal weighting of different authorship indicators).

## 4. Can the comparator model explain the sense of ownership?

In an attempt to elaborate on Frith's model, it was proposed that a version of the comparator would not only underlie our sense of agency but also our sense of ownership (SoO), i.e. the sense that part of my body is moving regardless of whether the movement is voluntary or involuntary.For example, Shaun Gallagher contends that "a match at the feedback comparator provides a sense of ownership" (Gallagher, 2000, p.16).[18] Yet, it is highly unconvincing that the CM could possibly account for the SoO, since one also has a SoO for one's limbs in case of passive movements: If my arm is moved by someone else, I nevertheless have the feeling that *my* arm is moved. In this case, however, no efference copy—and thus no comparison—is triggered. For the SoO, one can completely leave aside any efferent information and feed-forward modelling. It can be satisfactorily explained by intersensory matching, e.g. between proprioception and visual input (Botvinick, 2004). In fact—often neglected by recent works on the SoO (Ehrsson, Spence, & Passingham, 2004, 2005; Jeannerod, 2004)—even *uni*modal information suffices for the SoO, especially proprioceptive signals: When I close my eyes and my arm is moved by somebody else, proprioception is enough to envoke the feeling of "mineness" of the arm movement. (Of course, however, not *any* intersensory matching or unimodal experience have to trigger a SoO: Even when the texture and taste of food in my mouth seem to give a coherent sensory experience, I do not feel the food as belonging to my body. Thus it seems that further non-sensory, cognitive top–down influences, e.g. a non-visual body scheme (Tsakiris & Haggard, 2005a, 2005b), seem to be needed to constitute a SoO.).

Moreover, recent research has also neglected another fact about the SoO: Like the SoA, also the SoO appears phenomenally as a central and uniform processing module, while in fact it represents a complex supramodal phenomenon of largely heterogeneous functional and representational levels. In particular, a non-conceptual, perception-like level of ownership, i.e. the feeling of ownership (FoO), and a conceptual, belief-like level of ownership, i.e. the judgement of ownership (JoO), have also to be differentiated. For example, in patients exhibiting an "alien hand syndrome", (i) some patients have a feeling of alienness about their hand, without forming out a false (somatoparaphrenic) belief about the ownership of their hand (e.g. patient LA-O in Bisiach & Geminiani, 1991), while (ii) other patients do not accept their peculiar body experience as a strange experience, but form out a delusional ownership hypothesis about this experience and maintain it despite different stored encyclopedic knowledge about their body and despite the testimony of others (e.g. patient A.R. in Bisiach, Rusconi, & Vallar, 1991).

To sum up: At its basic level, the SoA seems to be the subjective correlate of neural events responsible for integrating efferent-afferent contingencies, whereas the SoO is the subjective correlate of the neural events involved in registering self-specifying intersensory contingencies (and assimilating them into a pre-existing body scheme). For both senses, a parietocerebellar network seems to underlie the integration of multisensory information and the resolution of discrepancies between the input of the different modalities by means of transmodal recalibration and remapping (for the SoO see: Botvinick & Cohen, 1998; Ehrsson et al., 2004, Ehrsson, Holmes, & Passingham, 2005; Tsakiris et al., in press; for the SoA see: Farrer et al., 2003a; Leube et al., 2003; Lindner et al., 2006). The prefrontal cortex might be responsible for the self-attribution of the multisensory information in both cases, yet it gains a special importance as the basis of the SoA, since here simple intersensory correlations or unimodal inputs are not sufficient but have to be complemented by a contingency with corresponding motor intentions, which are at large part formed and stored in the prefrontal cortex (Mushiake, Saito, Sakamoto, Itoyama, & Tanji, 2006). Recent studies have tried to reveal the different

[18] It seems that even in his latest publications Gallagher hasn't changed his view. He still suggests that it is "an ecological, sensory-feedback model that delivers a sense of ownership for action" (Gallagher, 2005, p. 190).

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functional roles of the SoO and the SoA, suggesting that while the SoO conveys only a local and fragmented body-awareness, the SoA integrates distinct body-parts into a coherent, unified awareness of the body (Tsakiris, Prabhu, & Haggard, 2006). It will be a challenge of future work (i) to further explore the distinct functional roles in psychophysical studies and (ii) to directly contrast both senses in neuroimaging and lesion studies.

Many recent experiments claiming to investigate agency, however, do not even differentiate between the both senses (see above). Accordingly, the corresponding imaging data would not reflect the neural basis of the SoA, but the neural substrate of a strongly heterogeneous mixture of different levels of different self-senses. What is needed is an explicit theory about systematically relevant levels of agency experience and agency belief formation. Experimental paradigms must then be designed to adequately operationalize and control these different levels. Such a project would be analogue to and maybe even part of a research programme probing the neural signature of self-consciousness (Newen & Vogeley, 2003).

## 5. Can the comparator model explain the agency of thoughts?

The sense of agency in thoughts recently became a lively debated topic mainly because of the investigation of the positive symptom ''thought insertion'' in schizophrenia. Patients suffering from thought insertion experience thoughts which they claim to be inserted into their minds by other people or alien forces. The best description of this phenomenon is that the patients experience a thought in their stream of consciousness while they do not experience themselves as the author of this thought.[19] Following Frith's account, Campbell (1999, 2004) developed a philosophical account of the SoA and thought insertion. It assumes that there is a comparator comparing intentions to think with the actual thoughts in the stream of consciousness. If they match, the occurrent thought is experienced as produced by me; if they do not match, the thought is experienced as alien. In order to make the CM work for thoughts, however, thoughts have to be characterized as motor processes.

### *5.1. Are thoughts motor processes?*

If thoughts were motor processes in the sense of Frith, then there would be an (unconscious, subpersonal) intention to think a thought *p* which is fed into a module specifying the ''thought command'', which ultimately causes the occurrence of the thought *p* in the stream of consciousness. However, there are several difficulties with this view (Gallagher, 2004; Vosgerau & Newen, 2007): First, the ''intention to think'' is a very unclear notion and contradicts the everyday experience of unbidden thoughts. Second, analogue to the case of action perception, the misattribution of the inserted thoughts cannot be explained by a failure of the comparator since it can—at best—explain a strange feeling about the thought but not any attribution to specific external sources (see above). Third, thought insertion is mostly limited to relatively short episodes and often restricted to certain thought contents. These limitations cannot be explained by a general comparator breakdown.

Another crucial point is why evolution should have established such a mechanism at all. Campbell suggests that it ''help[s] to keep your thinking on track'' (Campbell, 2004, p. 7). Because the actual thought is compared with the intention to think, goal-headed thinking becomes possible. However, goal-headed thinking normally proceeds from one thought to another. In order to keep thoughts on track it would be necessary to compare two different thoughts and not some intentions with thoughts. If so, for every thought there would have to be another thought to generate the sense of agency, which leads to an infinite regress (see also Gallagher, 2004).

The thread of an infinite regress does not vanish when supposing the intentions to be unconscious (Vosgerau & Newen, 2007). In order to be comparable, the intention and the actual thought must have the same content *p*, i.e. the only difference between the two is that the one is unconscious and the other is not. First, all the

[19] In the literature, many others speak of the sense of ownership which is lost in thought insertion. However, this is not quite right since the patients do experience the thoughts as occurring in their ''inner space'', i.e. as something which they own. Indeed, it is entirely unclear how someone could experience a thought without a sense of ownership. This seems to be the point that Coliva (2002) has in mind when arguing against Campbell (2002): she fails to draw the distinction between the ownership of thoughts and the authorship of thoughts (the ''two strands of ownership'', how Campbell (2002) calls them). That the two come apart is also evident from everyday experiences, when, e.g., reading an article: there will be a lot of thoughts in your mind that are not yours but those of the authors of the article you read!

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work done in thinking would then be already done at an unconscious level, which contradicts the phenomenology of thinking and which would make the "keeping thoughts on track" function impossible. Second, if intentions are unconscious thoughts[20] and thoughts are motor processes, then for every intention there must be another intention to generate it. This still leads to an infinite regress. Characterizing thoughts as motor processes hence leads to a dilemma: Either intentions are thoughts and we face an infinite regress, or intentions are unconscious and then conscious thinking is a mere epiphenomenon such that the comparator and the SoA could not have any function at all.

Doubtlessly, thoughts can be the cause of motor actions: The thought that I am hungry, for example, may lead to a movement toward the refrigerator. Hence, it seems plausible that thoughts are better characterized as possible intentions that trigger motor processes. This is not to say that every thought is an intention nor that every intention is a thought. In the case of reasoning, thoughts are essentially connected with other thoughts; and—concerning propositional attitudes in general—thoughts are systematically interconnected with other propositional attitudes. However, thoughts in this sense are clearly different from motor processes. The explanation of thought insertion has therefore to start somewhere else.

### 5.2. Thought insertion in schizophrenia

Analogous to our account of agency judgements (see above), also delusions of control and thought insertion have to be explained at least by two factors (Davies et al., 2001). First, there must be some kind of "strange feeling" on the level of the FoA and second, there must be a different processes that leads to the stable misattribution on the level of JoA. As already mentioned above, there are multiple factors that are examined in order to attribute an action. It is likely that the same is true for the agency of thoughts. Various factors, e.g. background beliefs, concordance with the self-image and the line of thoughts, cognitive "effort", are taken into account by some sort of a "rationalization" module which generates a coherent and plausible story about the own mental life. This module is important to dissolve possible inconsistencies in the factors (much in the sense of the theory of dissonance by Festinger, 1957, 1964).

The fact that most inserted thoughts are of a specific content suggests that the "strange feeling" stems from the content of the thought. In general, schizophrenia patients show increased intensity of negative emotion experiences compared to healthy subjects (Aleman & Kahn, 2005). Therefore, one plausible explanation of thought insertion might be that patients experience an abnormally strong emotional aversion against certain thought contents. If in a patient a negative thought pops up (like unbidden thoughts in healthy people), it cannot be integrated into the intellectual self-image since it contradicts very basal convictions (e.g., "I am not evil"). For these cases, the rationalization module has different strategies: Suppressing the thought, which is possible only for a limited duration of time, or attributing the origin of the thought to someone else. The fact that the cause of the "strange feeling" is a strong emotional response accounts for the stability of the patient's delusional explanation which is immune to more plausible explanations like the one of the psychiatrist (i.e. it accounts for the fact that it is delusional).[21] To test this idea, future research should concentrate on linking the specific content of thought, its emotional value and the subject's experience of it to the circumstances and personal history in which it occurs (for early case descriptions, see Erichsen, 1973).

However, some phenomena often called "thought insertion" might in fact be verbal hallucinations, where the hallucinated inner speech is reported as thoughts. However, it seems reasonable to draw a clear distinction between inner speech and thoughts and therefore to label this kind of delusion verbal hallucination (Vosgerau

[20] Saying that intentions are not thoughts would leave the question of how the content of a thought (and this is what thoughts are individuated by) is generated open, for it would merely be shifted to an unconscious level. In other words, all the interesting things about thoughts would happen at an unconscious level, and the motor process generating an actual thought would be merely a mechanism to bring it to consciousness.

[21] Bayne and Pacherie (2005) also dispute the role of emotions and affective states in delusions in general. However, they do not claim this factor to enter into the formation process of the delusional thought (as we suggest) but discuss the embedding of the delusional thought into emotive and affective behavior. We think that for the special case of thought insertion this point is not the most problematic and hence refrain from further discussion.

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& Newen, 2007).[22] Indeed, such verbal hallucinations occur with and without delusional beliefs according to our two-step account: There are (i) subjects that experience voices as alien but nevertheless do not attribute them to any external source and (ii) subjects that attribute these alien voices to specific persons (Cahill et al., 1996). The most plausible explanation is that both groups suffer from the same deficit in the perceptual system while only the first group has an adequate functioning belief formation processing.

## 6. Conclusion

The CM is well suited to provide a parsimonious, elegant way of understanding the brain's and body's interaction with the world: In case of self-produced somatosensory stimulation—for example when we touch ourselves (Blakemore et al., 1999; Shergill et al., 2003; Voss et al., 2006) or when we perform eye movements (Haarmeier et al., 2001; Lindner et al., 2006; von Holst & Mittelstaedt, 1950)—the actual sensory consequences match the prediction and thus are specifically attenuated. Conversely, the salience of sensations that have an external cause are accentuated since these sensory events do not match any internal predictions (Blakemore et al., 1998b; Shergill et al., 2005). Elaborating on this idea, the CM has initiated a stimulating research programme probing the neurocognitive underpinnings of the SoA and, thereby, one basic feature of self-consciousness. Indeed, it provides a good explanation for a basic element of our SoA for actions: the perceptual experience of strangeness and peculiarity if the prediction is discrepant to the actual sensory feedback. Yet it is not well designed to give a sufficient picture for understanding the SoA and its disruptions in schizophrenia. Sometimes the comparator is not even required as a necessary condition. Future research should focus on both more precise conceptual and more detailed experimental work on necessary and sufficient conditions for the experience of agency. The preliminary multifactorial two-step account as proposed here provides a promising framework for this challenging investigation.

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[22] Inner speech can be thought of as a form of imagination. A thorough analysis of the distinction between thoughts and imaginations can be found in Bayne and Pacherie (2005). Inner speech would qualify as a perceptual imagination, according to their terminology (we belief propositional imaginations to be thoughts with a special attitude to it, just like assumptions are in mathematical proofs, for example).

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