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The interplay of predictive and postdictive components of experienced selfhood

Marvin Liesner*, Wladimir Kirsch, Wilfried Kunde

Department of Psychology, University of Würzburg, Germany

A R T I C L E I N F O

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A B S T R A C T

Objects that we affect by our body movements can be experienced as being controlled by (agency) and belonging to the own body (ownership). Such impressions of minimal selfhood arise when objects move as predicted prior to the action (predictive component). But they can also arise when otherwise unpredictable object movements turn out to be consistent with (e.g. spatially compatible to) preceding actions (postdictive component). Here we studied how the impact of postdictive components of inferred minimal selfhood in terms of action-object compatibility is shaped by different levels of predictability of these object movements. We found that compatibility between actions and object movements, and to a lesser extent predictability of object movements, affected reported agency while only compatibility affected reported ownership. Importantly, predictive and postdictive factors influenced these measures in an independent manner. We discuss these results against the background of models that assume multiple components of experienced minimal selfhood.

1. Introduction

When people alter objects by their own body movements they often tend to experience control for these object changes which has been labeled as sense of agency (Haggard & Tsakiris, 2009; Kalckert & Ehrsson, 2014). Furthermore, people can to some extent perceive such objects as being part of their own body, even if these objects are noncorporeal and dissimilar to human body limbs as long as they move in accordance with the agent (ownership, Liepelt, Dolk, & Hommel, 2017; Ma & Hommel, 2013, 2015a, 2015b; Zopf, Polito, & Moore, 2018). For example, users of a tool typically experience control over that tool and such tools can become part of the body even up to the level of neural representation (Maravita & Iriki, 2004). Sense of agency and sense of body ownership are assumed to be two cornerstones of the so-called "minimal self", that is "a consciousness of oneself as an immediate subject of experience, unextended in time". (Gallagher, 2000, p. 15). It is this minimal self, originating from the feeling of control over certain perceptual events and the feeling of inclusion of controlled objects to the instance exerting that control that we wanted to investigate in this study. This sets aside all aspects of the "narrative" self, thus the past and future in stories we and others tell about us.

How do such impressions of minimal selfhood arise? One important source of experienced sense of agency and sense of ownership is prediction. Humans predict or anticipate the perceptible effects of their actions, and such anticipation might in fact be a cause of body movements in the first place (Brown, Adams, Parees, Edwards, & Friston, 2013; Shin, Proctor, & Capaldi, 2010). When the actual action effects match those that were predicted, the impression of agency regarding these effects and a sense of ownership of the manipulated object can arise. There is ample evidence for this predictive component of the sense of agency and ownership (for a

* Corresponding author at: Institut für Psychologie III der Universität Würzburg, Röntgenring 11, 97070 Würzburg, Germany.
E-mail address: marvin.liesner@uni-wuerzburg.de (M. Liesner).

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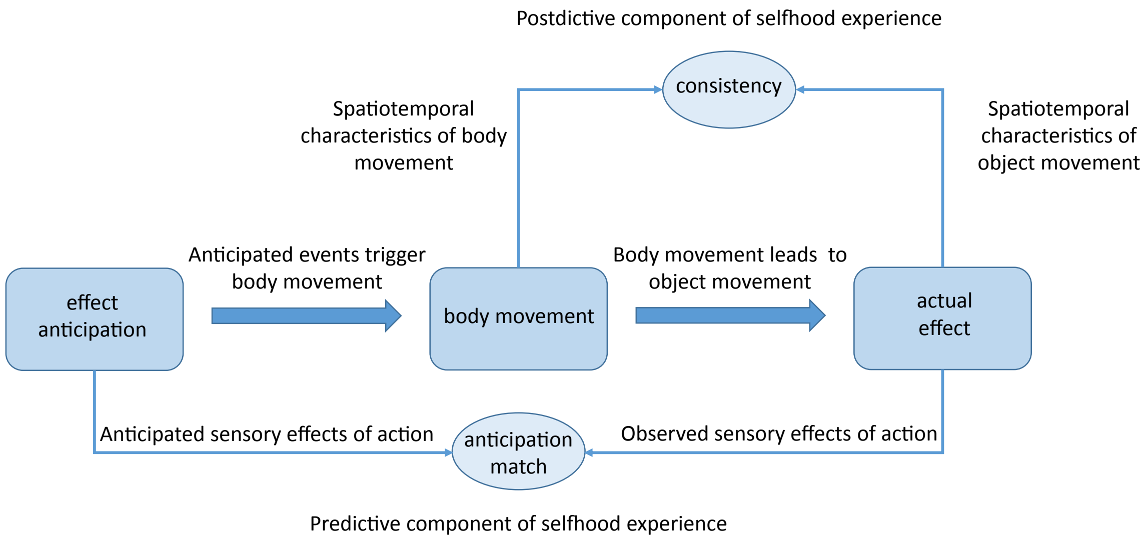

Fig. 1. Predictive and postdictive components of experienced minimal selfhood. Anticipations of certain intended effects trigger body movements, which then trigger certain perceptual effects. Anticipated (predicted) effects are compared to actual effects, which, if matching, induce an impression of agency/ownership (predictive component). Moreover, actual effects are evaluated regarding their spatiotemporal consistency with body movements, which can also induce an impression of agency/ownership (postdictive component).

review cf. Haggard, 2017).

However, people can also have impressions of agency regarding events they did not predict and can perhaps even experience ownership for the involved objects then. For example, when an item drops from the shelf of a supermarket while just passing that shelf, a strong impression of agency for that event can arise, although that event was entirely unforeseen. As another example, amputees can vividly experience seen arm movements of another person as movements of their own phantom limb, although these movements are unpredictable for them (Ramachandran & Rogers-Ramachandran, 1996). Thus, there is likely also a postdictive component that influences the level of experienced selfhood. In other words, people judge "after the act", whether an event might be caused by that act or not (Synofzik, Vosgerau, & Newen, 2008).

An important factor shaping the level of experienced selfhood due to such postdictive processes is action-event "consistency" (Wegner & Sparrow, 2004), that is whether action and event plausibly belong together based on general knowledge. To illustrate the role of consistency, consider a study by Ebert and Wegner (2010). Participants moved a joystick back or forth, and that movement triggered a back or forth movement of a picture on a screen. Participants showed higher degrees of agency in various measures for picture movements that were consistent (spatially compatible), rather than inconsistent (spatially incompatible) with the joystick movement. Importantly, the picture's movement was objectively unpredictable because for a given trial, it was unknown to the participants before their movement whether the picture would move consistently or inconsistently with the joystick, and thus this consistency influence must be based on postdictive processes. Fig. 1 illustrates the described predictive and postdictive components of experienced minimal selfhood.

The present experiments studied in more detail the postdictive component as indexed by influences of action-effect consistency. We were interested to know how the influence of this postdictive component is shaped by the availability, or lack, of predictive components. Thus, we studied the joint influence of two factors on the sense of agency and the sense of ownership as proxies for the experience of minimal selfhood, namely action-effect consistency[1] (consistent or inconsistent) and action-effect predictability (predictable or unpredictable). Concretely, participants were asked to carry out a left or right manual action, which produced a spatially compatible or incompatible movement of an object on a screen. The movement direction of the object was either predictable or unpredictable.

Based on previous research it is hard to judge how predictability of action effects might influence the impact of action-effect consistency since current models usually assume experienced selfhood to be based on a weighting of various selfhood indicators (e.g. Chambon, Sidarus, & Haggard, 2014; Synofzik, Vosgerau, & Newen, 2008), but they do not explain their precise interplay. A first possibility is that consistency and predictability affect experienced agency/ownership independently of each other. Thus consistency of an object movement might increase experienced agency/ownership so as predictability of that movement does, while these influences are additive to each other. Such an outcome would suggest that experienced agency/ownership is fueled by predictive and

[1] One may construe action-effect consistency to be based on predictions as well, because pre-experimental experience suggests, that body movements normally produce spatially consistent feedback (e.g. a rightward hand movement produces the visual experience of a rightward moving hand). Viewed like that, action-effect consistency relates to predictions based on long-term experience, whereas our manipulation of action-effect predictability proper, relates to predictions based on short-term experience in the corresponding experimental session (for a discussion of this issue cf. Dogge et al., 2019; Wirth et al., 2018 and general discussion section).

postdictive processes independently.

A second scenario is that the impact of postdictive components of experienced agency/ownership reduces, once predictability as another source of such selfhood comes in. This outcome is suggested by research showing that at least moderate levels of inconsistency between own body movements and produced object movements are barely noted, providing that objects move in an otherwise predictable manner (Fourneret & Jeannerod, 1998; Knoblich & Kircher, 2004; Müsseler & Sutter, 2009). In other words, people might rely on postdictive indicators to judge the origin of an action, if no prediction of action outcomes is possible. But once such prediction is possible, the weight of postdictive components is reduced. This would result in an interactive influence of predictability and consistency of agency/ownership measures. Our study aimed at manipulating these two components of experienced minimal selfhood independently of each other to investigate their contributions and possible interplay in the emergence of sense of agency and sense of ownership.

We also studied how our experimental manipulations impact performance as measured by reaction times. When the identity of an action effect is predictable, it could in principle already impact the time needed to generate that action, although the effect physically occurs only after action initiation. In fact, reaction times sometimes increase when actions foreseeably produce spatially incompatible action effects (e.g. Kunde, Pfister, & Janczyk, 2012; Pfister & Kunde, 2013; Müsseler, Kunde, Gausepohl, & Heuer, 2008; Müsseler & Skottke, 2011). This is explained by interference between anticipated body-related and anticipated body-external effects during action generation (response-effect compatibility, Kunde, 2001). If no anticipation about upcoming effects is possible no such influence should occur.

2. Experiment 1

Experiment 1 aimed at testing the joint influences of predictability and compatibility of object movements on experienced agency and ownership of the moved objects. Participants were asked to initiate as quickly as possible on an imperative stimulus a hand movement to the left or right. That hand movement started the movement of an object on a screen (i.e. a circular cursor). The movement direction of the object was either spatially compatible or spatially incompatible to the hand movement, and in different conditions that object movement was either predictable or not (cf. Fig. 2). Once the object had started to move, it was under control of the participants, that is, moving the hand by a certain distance or in a certain speed moved the object to the same extent or speed into either the same or the opposite direction, depending on the action-object compatibility. This specific aspect of the procedure will be of relevance when discussing the results later. After each trial participants were asked about the experienced agency for that object movement, and to which extent they felt the object belonging to their body. On top of the predictability of the cursor movement and

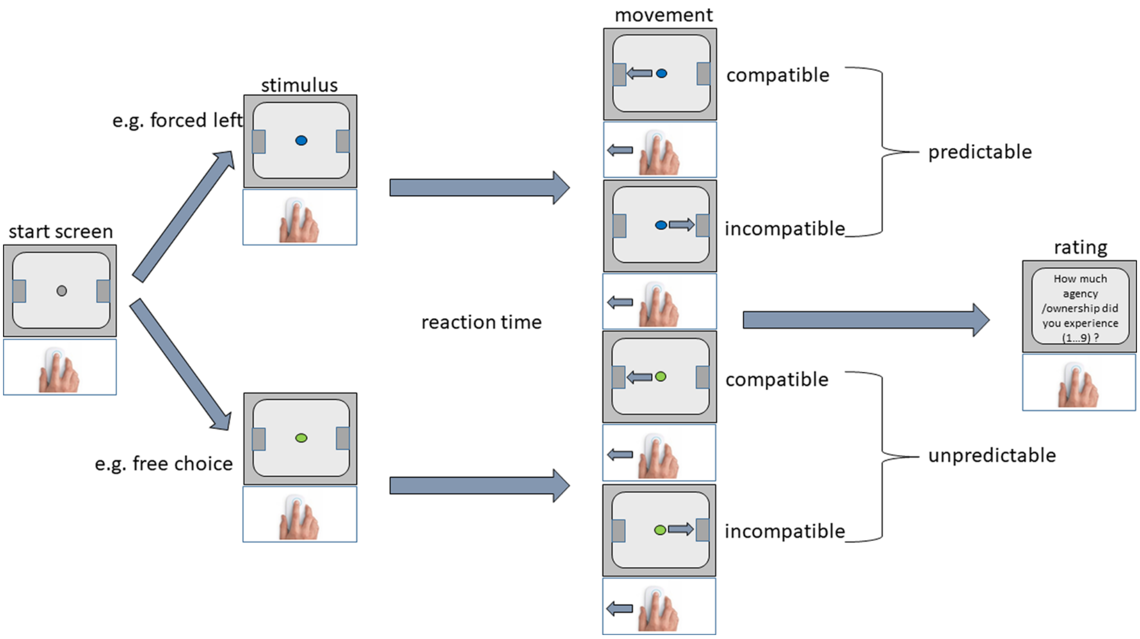

Fig. 2. Schematic overview of (non-deviant) trials in Experiment 1. Participants were asked to move their hand to the left or right depending on the color of a cursor (or to freely choose where to move with one of the three colors). This triggered a movement of the cursor in either a spatially compatible or spatially incompatible direction, which in different conditions was either predictable or not. After the cursor movement participants judged experienced agency and ownership regarding the cursor movement. For simplicity, in the figure only two out of three different kinds of stimuli are shown and the two displayed outcomes for forced left reactions are labelled as predictable while the two displayed outcomes for free choice reactions are labelled as unpredictable. Importantly though, all possible combinations of stimuli (3 colors), compatibility (2 levels) and predictability (2 levels) were presented to participants in the experiment so that also both free choice and forced choice trials could include either predictable or unpredictable action effects.

its compatibility to the hand movement, we additionally varied whether the hand movement direction was freely chosen (free choice trials) or prescribed by a specific color of the cursor (forced choice trials).

We expected to find higher ratings of agency and ownership with spatially compatible rather than incompatible object movements, and with predictable rather than unpredictable object movement directions, with a possible interaction between them. We also expected lower reaction times when hand movements triggered cursor movements which were foreseeably compatible rather than incompatible with the hand movement (e.g. Schwarz, Pfister, Wirth, & Kunde, 2018) whereas no such difference should occur, when cursor movement direction was unpredictable, because at the point where reaction time was measured, object movement direction was yet unknown to the participants.

2.1. Material and methods

2.1.1. Ethics statement

The present study and all follow-up studies have been approved by the ethics committee of the institute for psychology of the University of Würzburg under the reference number GZEK 2018-33 and are all in line with the Declaration of Helsinki.

2.1.2. Participants

24 participants (16 female, 8 male; 23 right-handed, 1 left-handed; $M_{Age} = 26.54$, $SD = 7.47$, min = 19, max = 51) were tested in Experiment 1 and received either course credit or 8 euros per hour for their participation. All participants were recruited through an online platform used by the University of Würzburg for this purpose and had to give their informed consent before their participation.

2.1.3. Apparatus and stimuli

The experiment was performed in a laboratory, which allowed for parallel testing of up to five participants. Stimuli were displayed on LCD monitors (24", BenQ XL 2411, BenQ) with a resolution of 1920 × 1080 pixels and a 100 Hz refresh rate. All stimuli were presented using Eprime (version 3.0, https://www.pstnet.com/). All hardware and software was identical on all used computers and for all tested participants. Participants were seated approximately 60 cm in front of the screen with their left hand placed in front of the keyboard which was in a central position directly in front of the screen and their right hand placed on the computer mouse which was located on the right-hand side from the participant's point of view in a middle position between the screen and the participant.

2.1.4. Procedure and task

At the beginning of each trial, participants saw a grey circle on a black background and two grey target boxes left and right of the circle on the screen. After a predefined delay of either 1500 ms or 2500 ms for half of the trials respectively, the circle was filled with a color indicating for the participants which action to perform. If the color of the circle changed to blue, participants had to move the mouse to the left, if the color changed to red, participants had to move the mouse to the right and if the color changed to green, participants were free to move the cursor to either of the two sides (color-response mapping was counterbalanced between participants for the stimuli which required a response to the left or right). Participants were instructed to respond to the color change as fast as possible and also to try to keep their right and left movements approximately in balance during the free choice trials. Upon response by mouse movement the circle moved simultaneously and visible to the participants behind one of two target boxes on the screen, either by moving in the same direction as the participant moved the mouse (compatible condition) or in the opposite direction of the mouse movement (incompatible condition, cf. Fig. 2). Reaction times were measured as the time interval from the color change of the cursor until the mouse had been moved approximately 0.59 mm to either the left or right from the central starting position. Furthermore, 1/9 of the trials in every block were "deviant" trials in which the circle moved in a 45°, 135°, 225° or 315° angle from the starting point in the center of the screen. Participants had to react upon these deviant trials by pressing the space key within 500 ms after the movement offset to avoid an error message. The purpose of these deviant trials was that we wanted to make sure that participants did not solely focus on their hand movement and ignored the visual feedback of the circle. For later analyses however, these trials were excluded. After every trial, participants had to state on a 9 point Likert scale (Likert, 1932) how much they had the impression to control the circle (agency rating) and how much they had the impression that the circle was part of their body (ownership rating).

The experiment consisted of three types of blocks, with the order of type of block counterbalanced across participants: In two of the blocks, the circle always moved either only in the same direction as the mouse or only in the opposite direction, thus the circle movement was predictable for the participants. In the remaining block, the circle moved compatibly and incompatibly in 50% of the trials each in random order, thus the circle movement was unpredictable for the participants. Before the first presentation of each block, there was a short practice session for the respective response-effect mapping. Please note that there were no explicit instructions regarding the response-effect mapping, but participants learned the relationship between the direction of their hand movement and that of the cursor movement (or the fact that there was none) from experience. The predictable blocks included 24 free choice and forced choice trials each plus 6 deviant trials and were presented twice to every participant resulting in 108 trials overall each, while the unpredictable block included 48 free and forced choice trials each plus 8 deviant trials which were also presented twice resulting in a total of 208 trials with half of the trials representing compatible and the other half incompatible blocks. Thus, unpredictable blocks were twice as long as predictable blocks since they always included both compatible and incompatible trials while predictable blocks always included either only compatible or only incompatible trials. Counterbalanced over all conditions, half of the trials were preceded by a short (1500 ms) or a long (2500 ms) interstimulus interval (ISI) respectively. Overall,

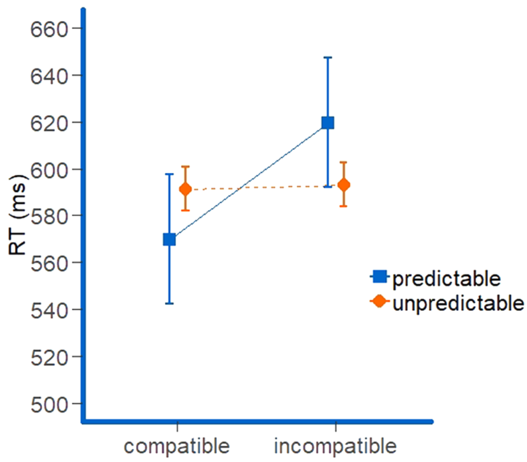

Fig. 3. Mean reaction times as a function of action-effect compatibility and action-effect predictability in Experiment 1. Error bars represent 95% paired-difference confidence intervals (Pfister & Janczyk, 2013).

every participant thus completed 96 trials in each cell of compatibility × predictability combinations, excluding practice and deviation trials. The overall duration of the experimental session was approximately 45 min per participant.

2.1.5. Data preprocessing

We excluded all trials from analyses in which participants showed the wrong response to the stimulus because errors could only be made in forced choice trials and thus the manipulation of free choice and forced choice otherwise could have been confounded with possible effects related to these errors. Furthermore, we also excluded all deviant trials, all trials with missing data in either reaction times or ratings and all trials with reaction times < 150 ms (which has been suggested as a minimum time window for categorization processes, see e.g. Delorme, Rousselet, Macé, & Fabre-Thorpe, 2004; Rousselet, Fabre-Thorpe, & Thorpe, 2002) or > 1500 ms from analyses. The overall error rate was 9.30%.

2.2. Results

2.2.1. Reaction times

Mean reaction times (RTs) we entered into a 2 × 2 × 2 repeated measures analysis of variance (ANOVA) with the factors compatibility (compatible vs. incompatible), predictability (predictable vs. unpredictable) and type of trial (forced choice vs. free choice). Reaction times were lower for compatible than for incompatible trials ($F(1, 23) = 8.51$, $p = .008$, $\eta_p^2 = 0.27$; $M_{compatible} = 581$ ms, $SD = 98$ ms; $M_{incompatible} = 606$ ms, $SD = 110$ ms). Moreover there was an interaction between compatibility and predictability ($F(1, 23) = 8.67$, $p = .007$, $\eta_p^2 = 0.27$), but no significant main effect of predictability ($F < 1$). RTs were significantly lower for predictably compatible than for predictably incompatible reaction times ($t(23) = 3.09$, $p = .003$, one-tailed, $d = 0.63$; $M_{compatible} = 570$ ms, $SD = 100$ ms; $M_{incompatible} = 620$ ms, $SD = 124$ ms), but almost identical in the unpredictable condition ($|t| < 1$, $d = 0.07$; $M_{compatible} = 591$ ms, $SD = 106$ ms; $M_{incompatible} = 593$ ms, $SD = 104$ ms; cf. Fig. 3). Furthermore, RTs were lower for free choice as compared to forced choice trials ($F(1, 23) = 8.87$, $p = .007$, $\eta_p^2 = 0.28$; $M_{free} = 576$ ms, $SD = 96$ ms; $M_{forced} = 611$ ms, $SD = 115$ ms). Finally, the three-way interaction compatibility × predictability × type of trial ($F(1, 23) = 4.06$, $p = .056$, $\eta_p^2 = 0.150$) was marginally significant. This interaction reflected a larger compatibility influence in forced choice as compared to free choice trials when compatibility was predictable, but no qualitative difference in the effects of compatibility and predictability for different types of trials (both simple effects of compatibility were still significant in the predictable condition when free and forced choice trials were analyzed separately, both $ps < 0.015$). The larger compatibility effect is likely due to the overall slightly higher RTs in forced choice trials as compared to free choice trials, as action-effect compatibility influences typically increase with RT (e.g. Wirth, Pfister, Janczyk, & Kunde, 2015). The reduction of reaction times in free choice compared to forced choice trials has been reported before (e.g. Hinrichs & Suelzer, 1978; Kiesel et al., 2006). However, since this was not the focus of the present study, we will not touch these points in more detail here.

2.2.2. Ratings

The same ANOVA's for agency and ownership ratings revealed a main effect of compatibility for agency $F(1, 23) = 17.84$, $p < .001$, $\eta_p^2 = 0.44$, as well as for ownership, $F(1, 23) = 5.55$, $p = .027$, $\eta_p^2 = 0.19$ indicating higher ratings for compatible than for incompatible trials (agency: $M_{compatible} = 6.51$, $SD = 2.17$; $M_{incompatible} = 4.27$, $SD = 2.21$; ownership: $M_{compatible} = 3.55$, $SD = 2.44$; $M_{incompatible} = 2.55$, $SD = 1.61$). Neither the main effect of predictability nor the predictability × compatibility interaction was significant (all $ps > 0.1$) even though both ratings were descriptively higher in the predictable than in the unpredictable condition (cf. Fig. 4).

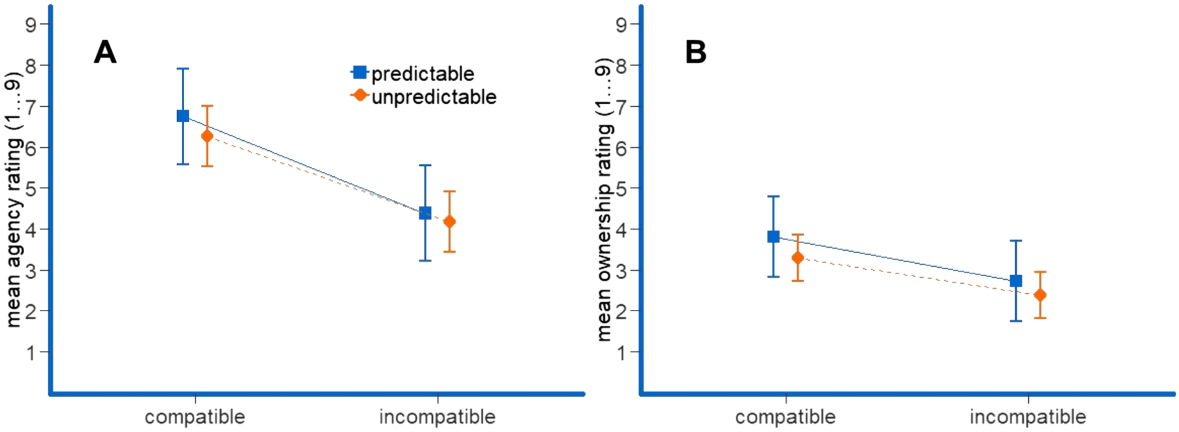

Fig. 4. Mean agency (A) and ownership (B) ratings for Experiment 1 as a function of action-effect compatibility, and action-effect predictability. Error bars represent 95% paired-difference confidence intervals calculated separately for the predictable and unpredictable condition (Pfister & Janczyk, 2013).

2.3. Discussion

Experiment 1 revealed that experienced agency for an object movement and the feeling of ownership regarding this object are lower when that movement is inconsistent rather than consistent to the hand movement that triggered that object movement. However, experienced agency and ownership were essentially independent of whether the movement direction was predictable or unpredictable. This is a rather unexpected finding given the generally strong evidence for predictability on these measures in previous studies (Ma & Hommel, 2015a). One may argue that participants formed no prediction of cursor movements at all even in cases where this was possible. However, this is unlikely given the strong influence of predictable action-effect compatibility on RTs, which must be based on prediction of cursor movement, because at the point in time of RT offset, the cursor movement was only predictable but not yet perceptible. Also, as expected, this influence of predictions on RTs was represented both in a benefit through the prediction of compatible and in an interference through the prediction of incompatible object movements so that we assume that predictions were still made in both of these conditions. These results are in line with previous studies demonstrating an influence of response-effect compatibility on action generation (e.g. Kunde et al., 2012; Pfister & Kunde, 2013; Müsseler et al., 2008; Müsseler & Skottke, 2011; Schwarz et al., 2018).

A more tenable explanation for not observing an influence of predictability on our measures is that judgements of agency and ownership might rely on predictions other than that of object movement direction. This was possible because of the choice of the mouse as the response device, since the object on the screen always moved continuously with the participant's hand, once it had started to move. This might have led to the formation of "micro-predictions" after the movement had been initiated so that due to the matching of continuous movement of both the hand and the object on the screen participants updated predictions about the continuation of the movement, which then overshadowed the initial predictions regarding movement direction made before movement initiation. Such rapid updating of the predictions about the consequences of one's own motor actions in response to visual feedback has been shown before (e.g. Izawa & Shadmehr, 2011; Synofzik, Lindner, & Their, 2008). Thus, an action-effect mapping is needed where initial predictions made during action generation cannot be overridden by predictions made while the response is transformed into an object movement. In Experiment 2, such an approach is implemented.

3. Experiment 2

Experiment 2 is identical to Experiment 1 except that here participants triggered object movements by pressing a key, instead of moving a mouse. However, the keypress had no impact on the object movement anymore *after* that keypress had been initiated. Thus the object movement direction was (in)consistent and (un)predictable only with respect to the location of the keypress. Because of the discrete nature of this response, an updating of predictions after response initiation due to perceived effects was not possible anymore in this experiment.

The lack of an influence of action-effect predictability on selfhood ratings casts some doubt on the credibility of these ratings, despite our explanations of the absence of this otherwise robust influence. Thus, Experiment 2 did not only serve to better disentangle predictive from postdictive components, but also to investigate whether our ratings were even sensitive for a manipulation of predictability.

3.1. Materials and methods

For brevity reasons we will mainly focus on the differences to Experiment 1 in this section.

3.1.1. Participants

24 participants (15 female, 9 male; 19 right-handed, 5 left-handed; M_{Age} = 27.33, SD = 10.96, min = 19, max = 67) were tested in Experiment 2 and received either course credit or 8 euros per hour for their participation. As in Experiment 1, all participants were recruited through the same online platform and again had to give their informed consent before their participation.

3.1.2. Apparatus and stimuli

The experimental setup was the same as in Experiment 1, except that, in this experiment, participants used the arrow keys of the keyboard instead of the mouse as response device. Therefore, the keyboard was placed right in front of the monitor with the arrow keys being vertically aligned with the center of the screen and the participants were asked to place the index and middle finger of their dominant hand on the right and left arrow keys.

3.1.3. Procedure and task

Procedure and task were exactly the same as in Experiment 1 except the different response device. After key presses the circle moved, again visible to the participants, with a constant speed of 12 pixels per frame resulting in a rash, yet clearly visible movement until it had fully disappeared behind one of the target boxes. There was a slight difference to Experiment 1 in the order of the blocks, though, because the unpredictable block was in Experiment 2 always either the first or the last block, but never inserted between the two predictable blocks. Whether it was presented before or after the predictable blocks was counterbalanced between participants. We used these orders to be able to identify possible effects that predictable or unpredictable action effects might have had on agency and ownership ratings when participants had not experienced the other predictability manipulation yet. Again, there were no explicit instructions regarding the predictability.

3.1.4. Data preprocessing

As in Experiment 1, we excluded all trials with missing data for either the reaction times or the ratings, all deviant trials and also all trials with reaction times < 150 ms or > 1500 ms and/or errors. The overall error rate was 4.56%.

3.2. Results

3.2.1. Reaction times

Mean reaction times (RTs) we entered into a 2 × 2 × 2 repeated measures ANOVA with the factors compatibility (compatible vs. incompatible), predictability (predictable vs. unpredictable) and type of trial (forced choice vs. free choice). There was neither a significant main effect of compatibility, nor a significant main effect of predictability nor a significant interaction between the two factors (all $ps > 0.24$). However, there was a marginally significant effect of type of trial ($F(1, 23) = 4.05$, $p = .056$, $\eta_p^2 = 0.15$), with slightly lower RTs in the free choice as compared to the forced choice condition, and a significant compatibility × type of trial interaction ($F(1, 23) = 5.18$, $p = .032$, $\eta_p^2 = 0.18$). Mean RTs of each condition and the size and significance (based on a paired t-test, one-tailed) of the compatibility effect in each predictability by trial type combination are listed in Table 1.

3.2.2. Ratings

The same 2 × 2 × 2 repeated measures ANOVA with the factors compatibility (compatible vs. incompatible), predictability (predictable vs. unpredictable) and type of trial (forced choice vs. free choice) was conducted for agency and ownership ratings respectively (cf. Fig. 5).

Agency was rated higher in predictable than in unpredictable blocks ($F(1, 23) = 6.56$, $p = .017$, $\eta_p^2 = 0.22$; $M_{predictable} = 5.57$, $SD = 2.22$; $M_{unpredictable} = 4.69$, $SD = 2.10$), and in compatible than incompatible trials ($F(1, 23) = 26.05$, $p < .001$, $\eta_p^2 = 0.53$; $M_{compatible} = 6.23$, $SD = 2.09$; $M_{incompatible} = 4.03$, $SD = 2.40$), with no interaction between these factors ($F < 1$). The influence of compatibility was slightly stronger in forced choice than free choice trials ($F(1, 23) = 5.37$, $p = .030$, $\eta_p^2 = 0.19$ for the interaction of trial type × compatibility), while the influence of predictability was slightly stronger in free choice than in forced choice trials ($F(1, 23) = 4.43$, $p = .047$, $\eta_p^2 = 0.16$ for the interaction of trial type × predictability). The three-way interaction also reached significance, reflecting a slightly stronger modulating influence of trial type on compatibility in the unpredictable condition compared to the predicable condition ($F(1, 23) = 6.86$, $p = .015$, $\eta_p^2 = 0.23$). However, as shown in Fig. 5, compatibility and predictability had clearly additive effects in both, forced choice trials and free choice trials (both F's < 1 for the compatibility × predictability interaction in forced and free choice trials).

Table 1
Means and standard deviations of reaction times in Experiment 2 for all predictability × compatibility × type of trial combinations.

		Compatibility		
		Compatible	Incompatible	difference
Free choice	Predictable	572 ms (97 ms)	569 ms (107 ms)	−3 ms, $p = .41$
	Unpredictable	584 ms (104 ms)	576 ms (91 ms)	−8 ms, $p = .39$
Forced choice	Predictable	582 ms (126 ms)	604 ms (117 ms)	22 ms, $p = .026$*
	Unpredictable	607 ms (115 ms)	609 ms (123 ms)	2 ms, $p = .13$

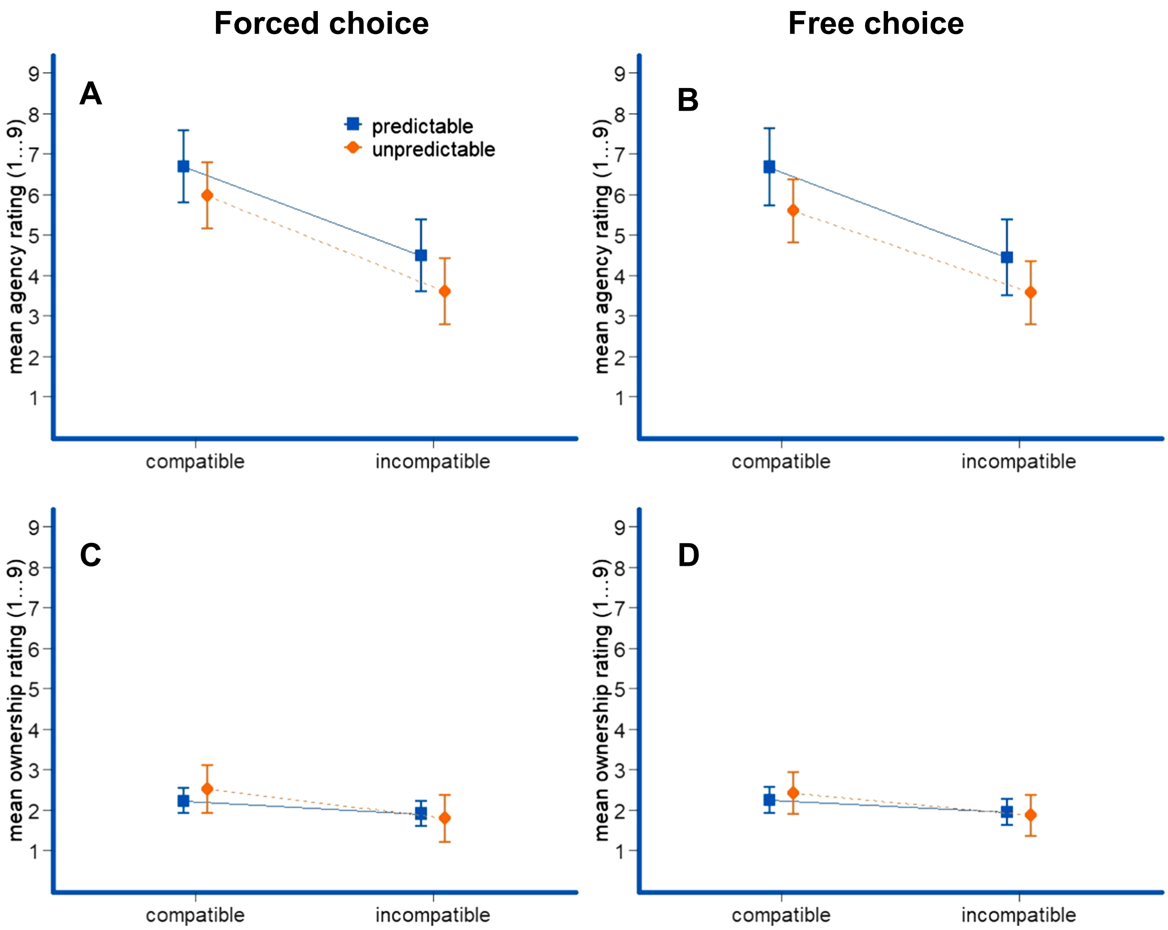

Fig. 5. Mean agency (A and B) and ownership (C and D) ratings for forced choice (A and C) and free choice (B and D) trials in Experiment 2. Error bars represent 95% paired-difference confidence intervals calculated separately for the predictable and unpredictable condition (Pfister & Janczyk, 2013).

Ownership was marginally significantly higher with compatible than with incompatible trials ($F(1, 23) = 3.86$, $p = .062$, $\eta_p^2 = 0.14$; $M_{compatible} = 2.35$, $SD = 2.14$; $M_{incompatible} = 1.88$, $SD = 1.69$), but unaffected by predictability ($F < 1$) with also no interaction between these factors ($p = .12$). Moreover, the influence of compatibility was stronger with forced choice than free choice trials ($F(1, 23) = 6.61$, $p = .017$, $\eta_p^2 = 0.22$), and this moderating influence of trial type was slightly stronger in unpredictable rather than predictable blocks ($F(1, 23) = 4.70$, $p = .041$, $\eta_p^2 = 0.17$).

3.2.3. Between experiments analysis

To further investigate potential differences between the two experiments we analyzed the data from both experiments together in a 2 × 2 × 2 × 2 split-plot ANOVA with the three within subjects factors as stated in the previous analyses and the additional between subjects factor Experiment (1 vs. 2). For brevity, we will not repeat effects already described in the previous analyses but focus on differences between experiments, thus effects that include the factor experiment.

For reaction times, compatibility has a stronger influence in Experiment 1 than Experiment 2 ($F(1, 46) = 4.60$, $p = .037$, $\eta_p^2 = 0.09$), and this compatibility effects tended to be stronger in the predictable condition of Experiment 1 as compared to all other conditions ($F(1, 46) = 3.38$, $p = .073$, $\eta_p^2 = 0.07$ for the three-way interaction compatibility × predictability × experiment). Neither for agency ratings nor for ownership ratings were there significant effects including the factor experiment (all *ps* > 0.08).

3.3. Discussion

Experiment 2 tested how postdictive influences of experienced minimal selfhood of object movements are affected by the predictability of these movements. The only (un)predictable aspect of the object movement was now movement direction, while other aspects such as movement speed or extent which were contingent on hand movements in Experiment 1 were now constant. Regarding agency we found both, indicators of postdictive influences on selfhood (higher experienced selfhood with action-effect consistency) and indicators of predictive influences (higher experienced selfhood with action-effect predictability), which were independent of each other. Thus, the influence of postdictive components is not modulated by the availability of predictive components. Regarding ownership, the ratings were generally low, and affected by action-effect consistency alone.

The fact that we found an influence of predictability on at least agency ratings in Experiment 2 also re-establishes confidence in these ratings and their sensitivity to predictive influences, which was somewhat doubtful after Experiment 1. This supports our assumption that the absence of an effect of predictability on selfhood ratings in Experiment 1 is due to other processes, like e.g. rapid prediction updating after movement onset (e.g. Izawa & Shadmehr, 2011; Synofzik, Lindner, et al., 2008). This argument is supported by the observation that the level of experienced agency with predictable rather than unpredictable object movements in Experiment 2 resembles more those of Experiment 1 where predictable and unpredictable movements did not differ. This accords with our conjecture that the short exposure to predictable aspects of the object movement in Experiment 2, such as object movement speed while moving the computer mouse, replaced the lack of predictability of movement direction prior to action onset.

Noteworthy, despite the significant influence of predictability on agency in Experiment 2, we found no influence of predictability on ownership ratings in Experiment 2. We note though that overall level of reported ownership with the noncorporeal objects used here was generally low, suggesting a floor effect (e.g. Everitt, 2006). In other words, lack of predictability of object movements was unlikely to reduce the already low experienced ownership any further so that our results possibly underestimate the influence of predictive processes on ownership experiences.

Agency was slightly stronger affected by predictability of cursor movements in free rather than in forced choice trials. This accords with the general observation that action effects exert stronger influences in intention-based (free choice) rather than stimulus-based (forced choice) situations (e.g. Herwig & Waszak, 2012; Pfister, Kiesel, & Melcher, 2010; Waszak et al., 2005). However, in replicating Experiment 1, action effect consistency affected RTs less in free choice than forced choice trials (where no significant influence was observed in Experiment 2). As noted before, this might be due to the again significantly higher RT level of forced choice trials, which is known to increase such compatibility effects in RTs. Furthermore, also the influence of compatibility on agency was slightly larger in forced choice than in free choice trials so the precise influence of free and forced choice trials on the different components of experienced agency and how this relates to performance, which was not one of the main focusses of this study, still needs some further clarification through future research.

4. General discussion

The current study explored how predictive and postdictive factors jointly contribute to experienced agency over, and ownership of, noncorporeal objects which are manipulated by the agent. The results can be summarized by saying that both predictive and postdictive components do contribute to experienced selfhood, but that postdictive components had a stronger influence. Our results thus support models that assume various sources of experienced selfhood (Chambon, Sidarus, & Haggard, 2014; Farrer, Valentin, & Hupé, 2013; Sidarus & Haggard, 2016; Synofzik, Vosgerau, & Newen, 2008). Importantly, we found mainly independent influences of predictive and postdictive sources on experienced selfhood. Thus, the addition of action-effect predictability did not reduce the influence of action-effect consistency, if it had an influence at all.

However, future research is warranted to test the generality of this independency of postdictive and predictive components. For example, action effect consistency might get a higher weight for judging agency, if participants had never experienced predictability of such effects, or conversely, get a lower weight once predictability had been experienced before. Consider a plane pilot with strong predictions about the effects of his or her steering inputs. Regardless whether the pilot's movements are transformed spatially consistently (such as when moving the yoke to the left and the plane turning to the left) or spatially neutral with respect to the input operation (such as when moving the yoke towards the pilot and the plane gaining height), the pilot will experience strong agency over the plane movements. Even the first encounter of an unpredicted movement of the machine though (e.g. due to a malfunction) may result in a breakdown of agency experience, be that movement spatially compatible to the input operation or not. By contrast, a novice without any predictions or expectations about the translation of steering inputs into plane movements might spontaneously gain the impression of agency on that same broken plane when the machine moves spatially compatibly rather than incompatibly to his or her input operations, even though it does not respond predictably at all.

Some hints for this speculation come from a more detailed analysis of Experiment 2. When looking at only the first half of trials it is possible to compare those participants who had only experienced predictable cursor movements with those who had only experienced unpredictable cursor movements up to this point of the experiment (basically a between participants manipulation of predictability). Though not significant, the influence of action-effect compatibility (the rating differences between incompatible and compatible trials) was considerably smaller for those participants who had only experienced predictable cursor movements as compared to those who had never experienced such predictability ($M_{predictable} = 2.38$, ($SD = 2.70$) vs. $M_{unpredictable} = 2.88$ ($SD = 2.46$), $t(22) = 0.47$, $p = .64$, two-tailed, $d = 0.19$ for agency; $M_{predictable} = 0.36$ ($SD = 1.18$) vs. $M_{unpredictable} = 0.92$ ($SD = 2.04$), $t(22) = 0.83$, $p = .42$, two-tailed, $d = 0.34$ for ownership). Thus, possibly the mere experience of predictability attenuates the weight given to compatibility at any later point in time[2]. This might explain why people who use tools that move in a

[2] This speculation is supported by another, methodically somewhat different experiment not reported here, in which action effect predictability was varied *between* participants. This experiment revealed a significant interaction between compatibility and predictability for both agency ($F(1, 30) = 11.91$, $p = .002$, $\eta_p^2 = 0.28$) and ownership ($F(1, 30) = 8.69$, $p = .006$, $\eta_p^2 = 0.23$) ratings, indicating stronger compatibility effects for participants for which the action-effect mapping was always unpredictable ($d_{Agency} = 1.91$, $d_{Ownership} = .98$) compared to those for which it was always predictable ($d_{Agency} = .83$, $d_{Ownership} = .55$).

perfectly predictable manner often feel about equal degrees of agency irrespective of whether that tool movement is spatially consistent or inconsistent to their hand movements (Knoblich & Kircher, 2004; Müsseler & Sutter, 2009).

While we have drawn here a picture of distinct components for perceived selfhood, one can think about a closer similarity of these two components. One way doing so was to consider that the influence of compatibility also reflects a kind of prediction, though a prediction based on knowledge acquired through live-long experience prior to the experiment. Normally, perceptual feedback of motor output is compatible to that motor output. For example, moving the right hand produces visual feedback of that movement on the right side. Based on this experience, participants might still “predict” that body movements will more likely produce compatible visual effects, even when this was technically not so in the unpredictable conditions they faced here (for similar arguments, cf. Dogge, Custers, Gayet, Hoijtink, & Aarts, 2019; Wirth, Steinhauser, Janczyk, Steinhauser, & Kunde, 2018). In other words, the influence of compatibility might reflect long-term predictions, while the influence of predictability proper in our experiments might reflect short-term predictions. If construed that way, one can conclude that both long-term predictions and short-term predictions based on the present experimental context influenced sense of agency in our experiments.

A final word regarding the relationship of experienced agency and ownership is in order. Body ownership, as the unique feeling that one’s body belongs to oneself (Gallagher, 2000), and agency, the feeling that one can control and cause perceivable actions in the world (e.g. Moore & Obhi, 2012; Haggard, Clark, & Kalogeras, 2002), together represent aspects of a minimal sense of self which is guided by sensorimotor processes (Tsakiris, 2010). It is therefore suggested that, even though not the same, there is reasonable overlap between these two concepts and that both concepts to some extent represent the integration of an event or object into the self (Synofzik, Vosgerau, & Newen, 2008; Tsakiris, Schütz-Bosbach, & Gallagher, 2007). It is thus also not surprising that we could observe similar patterns of results for both measures despite differences. While we were interested in differences between conditions, rather than absolute values, it is fair to say that that the level of experienced ownership for the manipulated objects was generally low, though in the range of similar settings where hand movements affect artificial objects (cf. Ma & Hommel, 2015a). As already touched in the discussion of Experiment 2, these generally low ratings for ownership might have also contributed to the absence of predictability effects on ownership. However, as Gallagher (2000) already mentioned in his introduction of the “minimal self”, the prerequisites for experiencing a sense of ownership are probably higher and more complex than for experiencing a sense of agency since information from more sources (e.g. proprioceptive or tactile feedback) need to be integrated and match for a sense of ownership to emerge. One might thus also question to what extent such low reported explicit senses of ownership are actually comparable to the sense of ownership as it can be observed in, for example, the rubber hand illusion (Botvinick & Cohen, 1998) or other paradigms where there is a much larger feature overlap between the body and the incorporated object and where an integration of the object into the body of the agent seems much more likely (Hommel, Müsseler, Aschersleben, & Prinz, 2001) and has already been shown to be stronger (Kalckert, Bico, & Fong, 2019). Therefore, it remains to be clarified whether pure correlation between one’s own movement and an object movement is sufficient to perceive this object as being part of one’s self or body. One approach that might help to shed further light on this issue would be to investigate how more implicit measures of ownership, such as proprioceptive drift (Tsakiris & Haggard, 2005) are affected by the factors we investigated. This is something we aim to address in future research.

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Declaration of interest

The authors declared that there is no conflict of interest.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.concog.2019.102850.

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