Body ownership causes illusory self-attribution of speaking and influences subsequent real speaking

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When we carry out an act, we typically attribute the action to ourselves, the sense of agency. Explanations for agency include conscious prior intention to act, followed by observation of the sensory consequences; brain activity that involves the feed-forward prediction of the consequences combined with rapid inverse motor prediction to fine-tune the action in real time; priming where there is, e.g., a prior command to perform the act; a cause (the intention to act) preceding the effect (the results of the action); and common-sense rules of attribution of physical causality satisfied. We describe an experiment where participants falsely attributed an act to themselves under conditions that apparently cannot be explained by these theories. A life-sized virtual body (VB) seen from the first-person perspective in 3D stereo, as if substituting the real body, was used to induce the illusion of ownership over the VB. Half of the 44 experimental participants experienced VB movements that were synchronous with their own movements (sync), and the other half asynchronous (async). The VB, seen in a mirror, spoke with corresponding lip movements, and for half of the participants this was accompanied by synchronous vibrotactile stimulation on the thyroid cartilage (Von) but this was not so for the other half. Participants experiencing sync misattributed the speaking to themselves and also shifted the fundamental frequency of their later utterances toward the stimulus voice. Von also contributed to these results. We show that these findings can be explained by current theories of agency, provided that the critical role of ownership over the VB is taken into account.

agency | body-ownership illusion | rubber-hand illusion | illusory speaking | vibrotactile stimulation

There is growing evidence that the brain does not treat our body as relatively fixed, changing only slowly through time, but that its body representation demonstrates high plasticity. Although this is counter to common sense, a number of findings have shown that simple experimental manipulations can generate the illusion that an external object is part of our body (1, 2), that a plastic manikin (3, 4), and even a body displayed in immersive virtual reality (IVR), is our body (5–7). Furthermore, evidence suggests that such illusions have physiological and psychological consequences. For example, the rubber-hand illusion (RHI), where participants feel a somatic sense of ownership over a rubber hand through synchronous multisensory stimulation on the rubber and corresponding hidden real hand (1), has been shown to lead to a cooling of the real hand (8) as well as an increase in its histamine reactivity (9). The RHI over a black rubber hand can lead to a reduction of implicit racial bias in light-skinned people (10). When light-skinned people have a dark-skinned VB that apparently substitutes their own body, in IVR—as seen directly and in a virtual mirror, and that moves like themselves—they have the illusion that the body is theirs, which also results in a reduction of implicit racial bias (11). When average-sized adults have an illusion of body ownership over smaller or larger bodies, this results in changes in the perception of object sizes (12). Even more remarkably, the illusion of body ownership of adults over a virtual child body leads to overestimation of object sizes and changes in implicit attitudes about the self substantially beyond changes induced by the illusion of ownership of an adult shaped body of the same size as the child (13). Hence the type of body appears to carry with it physiological, perceptual, and even deep-seated attitudinal correlates.

Following on from these findings the fundamental question in the present work is whether the factors that lead to a strong illusion of body ownership with respect to a VB would also lead to illusory agency over a specific action that was definitely not caused by participants, and where current explanations of agency apparently do not apply. "Agency" refers to the sensation of authorship of actions. Under normal circumstances humans are able to trivially distinguish their own motor actions from those of other people; we know when we are the cause of our own volitional motor actions and take responsibility for the effects. This sensation of agency has been the subject of significant study in recent years, and self-attribution of actions has been explained by a combination of feed-forward processing (we predict that we are to do an action and then observe the consequences of having carried it out) (14), with cause preceding effect, no other explanation for the result that is readily available (15), and a requirement for tight temporal binding between the intention to carry out the action and the resulting sensory consequences (16). Specific brain regions implicated in agency have been identified through the study of people with lesions (17), and although there is a significant intersection between brain activity in motor areas when observing someone else carrying out an action and when carrying it out ourselves, there are also additional processes that distinguish self-movement from others' movement (18). Here we show that it is possible to generate an illusion of agency when

Significance

Under normal circumstances we consciously attribute authorship of our actions to ourselves, the sensation of agency. We describe an experiment where participants observed a virtual human character speak and falsely attributed the speaking to themselves. They later shifted the FF of their own voice toward the stimulus voice. This only occurred when the life-sized VB substituted their own and moved with their own movements. A further contribution to the effect was vibrotactile stimulation on the thyroid cartilage synchronized with the speaking. This suggests that agency can be self-attributed even in the absence of prior intention, feed-forward prediction, priming, and cause preceding effect. A critical contributor is the illusion of ownership over the VB that spoke.

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apparently (*i*) there is no possibility of there having been feedforward prediction, (*ii*) there is no thought or cause preceding the effect, and (*iii*) there is an obvious alternative explanation for the observed action.

Our general hypothesis was that a strong illusion of ownership over a VB would map over to illusory agency with respect to an action—speaking —not executed by the participant, but only carried out by that VB. The voice that each participant heard had a higher fundamental frequency (FF) than his or her real voice. Our specific hypothesis was that a strong illusion of body ownership over the VB would result in the illusion of agency over the speaking. Moreover objective evidence of this effect would be the shift of FF of participants' later utterances toward that of the heard voice.

To study this we exploited an IVR system using a wide field-of-view (FOV) stereo head-tracked, head-mounted display (HMD) with headphones, and full-body motion-capture suit (Fig. 1*A*). Participants experienced a life-sized VB from a first-person perspective that was spatially coincident with and therefore substituted their own body. They saw the VB (or avatar) in a virtual mirror and when directly looking toward themselves (Fig. 1 *B* and *C*). During their experience, the VB uttered a set of prerecorded words. Our specific hypothesis was that the factors that would lead to a high level of body ownership would also result in the participants affirming that they had said the words, thus demonstrating illusory agency. Further evidence for such agency would be whether they would exhibit a shift in the FF of their voice toward that of the stimulus voice in their subsequent real utterances of the same words (19, 20).

We conducted the experiment with 44 participants using a between-groups design, with two binary factors referred to as visuomotor (async and sync) and vibrations (Voff and Von). In the sync condition the movements of the VB were synchronized in real time with the actual body movements of the participant. In the async condition the VB movements were generated from a prerecorded animation and independent of those of the participant.

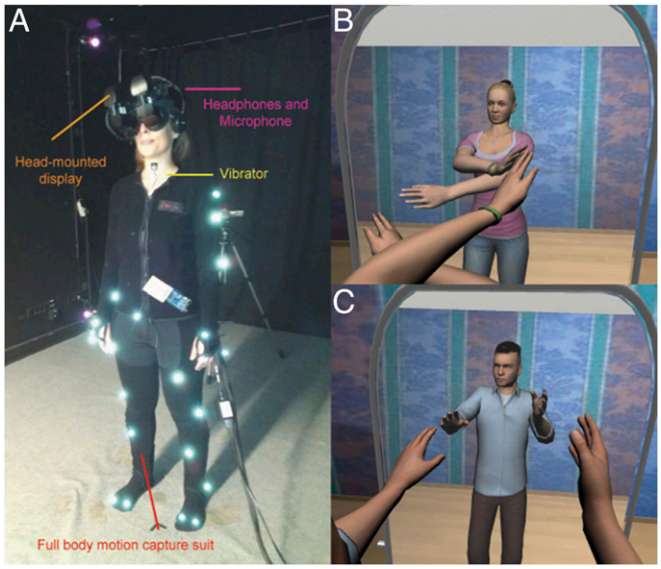

Fig. 1. The experimental setup. The body of the participant was substituted by a sex-matched VB, viewed from 1PP, onto which body and head movements were mapped in real time for the sync condition. The body could also be seen as reflected in a virtual mirror. (*A*) Participants wore an HMD with earphones, a full-body motion-capture suit, and a vibrotactile device. (*B*) The female VB. (*C*) The male VB. *B* and *C* illustrate that the VB (here, the arms) could be seen directly when looking toward their own body, and also in the virtual mirror.

Based on past results we expected that the sync condition would result in a substantially greater illusion of body ownership over the VB than the async condition (11, 13, 21–23). The vibrations factor was designed to enhance the sense of speaking by applying vibratory feedback on the thyroid cartilage to coincide with the period that the embodied avatar was speaking (Von) or no vibratory feedback (Voff). The vibrations were synchronized with VB lip movements that were themselves synchronized with the word being said. Participants were sequentially allocated to one of the four cells of the factorial design in order of attendance to the experiment, with the final numbers as shown in Table S1, with approximate equal distribution of participants in the four cells of the experimental design and sex balance. Details are given in *Materials and Methods* and *SI Materials and Methods* and are shown in Movie S1.

Results

Analysis of Questionnaire Responses. Participants completed a questionnaire immediately after the experiment (Table S2), derived from the original RHI questionnaire (1) and used in our recent research (e.g., ref. 13). Each question was scored on a −3 to +3 Likert scale, where −3 represented least agreement with the statement and +3 most agreement. Two questions were concerned with body ownership (*MyBody* and *Mirror*) with two related control questions (*Features* and *TwoBodies*). Fig. 2 shows that the variables *MyBody* and *Mirror* are positively influenced by sync with median scores of 1 or 2, whereas the two control questions *Features* and *TwoBodies* have median scores of 0 or less. The results that are evident in Fig. 2 are supported by ordered logistic regression of each of the questionnaire scores on the factors visuomotor and vibrations. (The rationale for the statistical methods used is given in *SI Materials and Methods*.) For *MyBody* and *Mirror* there is no significant interaction effect between the two factors and only the main effect of visuomotor is significant ($P < 0.0005$ in each case). There is nothing significant for *Features*. For *TwoBodies* there is a significant effect of vibrations ($P = 0.009$) with Von resulting in lower scores than Voff, but overall the median scores for Von are very low.

Fig. 3 shows the scores relating to the questions on agency, the voice, and speaking. For *Agency* there is no interaction effect, and the main effects of visuomotor and vibrations are significant ($P < 0.0005$ and $P = 0.024$ respectively, ordered logistic regression). It is evident that the sound is interpreted more as originating from the room (*VoiceSourceRoom*) in the async condition, and the scores are substantially lower in the sync condition ($P = 0.033$, ordered logistic regression). Correspondingly *VoiceSourceHead* goes in the opposite direction ($P = 0.004$). The voice tends to be interpreted more as their own by participants ($P = 0.011$) and as the self-speaking ($P < 0.0005$) in the sync condition. However, the idea that the voice was a modified version of the own voice is not significantly different between the conditions. It is clear from the box plot and also the logistic regression that the major contributor of the extent to which participants experienced illusory speaking is the visuomotor factor.

Vocal Production Analysis. The FF of the stimulus voice of the VB was designed to well exceed the average FF of Spanish speakers (Spain) (separately for males and females) (*Materials and Methods* and *SI Materials and Methods*). The FFs of the voices of the participants uttering the same words used in the stimulus were recorded immediately before the experiment (BaseF0). They were recorded again immediately after the stimulation period of the experiment (F0) while still wearing the HMD. The variable of interest is dF = F0 − BaseF0. Each participant carried out 45 utterances before and after the stimulation. This is therefore a mixed-effects design, with fixed-effects visuomotor and vibrations, and random effects "individual subject" and "word", and is appropriately analyzed by a mixed-effects ANOVA. The means and SEs of dF over the full set of data are shown in Fig. 4. The

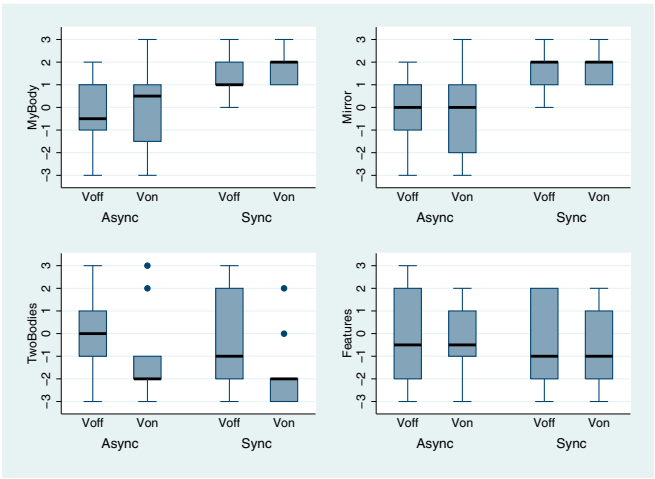

Fig. 2. Boxplots for scores on body ownership. The horizontal black bars are the medians, and the boxes the interquartile ranges (IQRs). The whiskers stretch to the data points that are within the median ± 1.5 IQR, with outliers beyond this shown as single points. *MyBody* and *Mirror* are significantly different between async and sync ($P < 0.0005$, ordered logistic regression) (Table S2).

main effect of visuomotor is significant ($z = 8.13$, $P < 0.0005$), similarly for vibrations ($z = 2.51$, $P = 0.012$), and there is a significant and positive interaction effect ($z = 3.55$, $P < 0.0005$). Although the distribution of residual errors is highly symmetric and bell shaped, the distribution is not normal. A plot of residual errors clearly shows three outliers. Removal of these improves the situation somewhat but does not result in normal errors, although the histogram of residual errors is a highly symmetric and bell shaped.

In these fits (with or without the outliers) the coefficient for the main effect of visuomotor (sync = 1, async = 0) is more than double that of vibrations (Von = 1, Voff = 0), and their respective 95% confidence intervals do not overlap. The magnitudes of the coefficients (±SE) are (with outliers removed) visuomotor: 9.7 ± 1.17, vibrations: 2.6 ± 1.15, and interaction: 5.8 ± 1.62.

It is also clear that in the condition (async, Voff) the difference in FF is negative (i.e., it is less after the stimulation than before) which is taken up at the end of *Discussion*. See also *SI Further Analysis of Change in FF*, which provides an alternative analysis where the means of dF within each cell are treated in a fixed-effects only analysis (Table S3).

Summary. The results show that participants in the visuomotor sync condition tended to have a strong subjective illusion of body ownership and agency with respect to the VB, and to attribute to themselves authorship of the VB vocalization. Additionally, the participants in this group subsequently tended to exhibit a higher FF in their vocal productions toward the frequency of the avatar voice. There is a significant contribution of the vibrations (Von) to these effects, but the dominant factor is sync. Moreover, the FF was lower than baseline in the (async, Voff) condition. Agency with respect to the specific event of the avatar vocalization was scored highly in the sync condition. In the (sync, Von) condition more than half of the participants gave the maximum score of +3 on a −3 to +3 scale in agreement with the statement, "It felt as if I was speaking out the words I heard" (Fig. 2).

Discussion

These findings may be considered puzzling because they apparently do not fit with the major theories concerning explanations for the sensation of agency. In what follows we argue that the results can nevertheless be reconciled with current theories, provided that we take into account the issue of body ownership. We also consider an alternative explanation that the results may have been caused by mimicry (the chameleon effect), as studied in the social psychology literature.

The sense of agency can be distinguished from the sense of body ownership in that the former refers to the sense of "my" authorship of an action whereas the second refers to the sensation of experiencing that the action is with respect to my own body (e.g., authorship of moving my body compared with the sensation that it is my body that is moving) (24, 25). We now consider the relationship between agency and ownership. First, it should be noted that although the subjective experience of ownership in the context of the RHI has been found to include agency as a component (26), Sato and Yasuda have provided evidence demonstrating their independence (27). They found that attribution of an action to the self is independent of recognition that it is the self that experienced the action, and vice versa. Similarly Kalckert and Ehrsson (21) found a double dissociation between ownership and agency in the RHI. Agency could be diminished, for example, by varying the time between a finger movement and the observation of the movement, but without reducing ownership. Similarly, ownership could be reduced by rotating the rubber arm to an implausible position but without reducing agency. However, agency and ownership were correlated precisely in the condition where there was also the illusion of ownership over the rubber hand, which corresponds with the findings in ref. 26.

In our own work, including the experiment described in this paper, we have used synchrony between real and VB movements to induce a strong ownership illusion and agency (critically always in the context of first-person perspective of a VB spatially coincident with the real body, which we refer to here as 1PP). This allows us to make use of the framework of Tsakiris et al. (28) who argue based on earlier findings (in the context of the RHI) (29) that when ownership is caused by passive tactile stimulation, it does not generalize beyond the point being stimulated (e.g., a specific finger). However, when it is based on active movement, it generalizes to the whole hand. They explain this by noting that the primary somatosensory cortex is segmented, so that stimulation of one specific point on the body surface normally does not affect any other point (e.g., a point on one finger only affects that finger). However, in the primary motor cortex different movements can

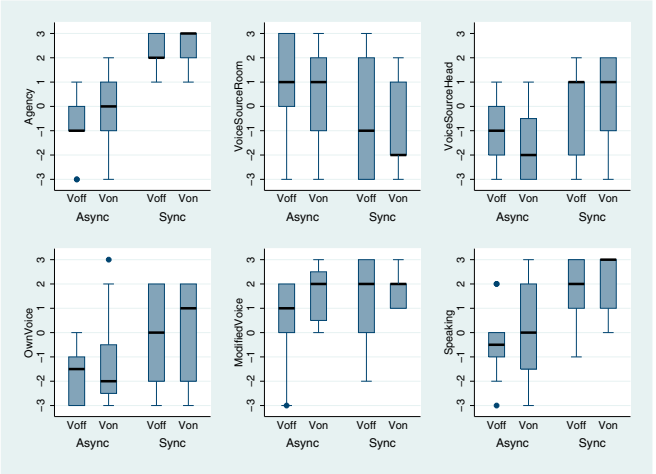

Fig. 3. Boxplots for scores on agency and speaking. *Agency* is significantly different between the visuomotor conditions ($P < 0.0005$) and the vibrations conditions ($P < 0.024$). The differences between the visuomotor conditions are significant for *VoiceSourceRoom* ($P = 0.033$), *VoiceSourceHead* ($P = 0.004$), *OwnVoice* ($P = 0.011$), and *Speaking* ($P < 0.0005$). There are no other significant differences. All significance levels are with respect to ordered logistic regression (Table S2).

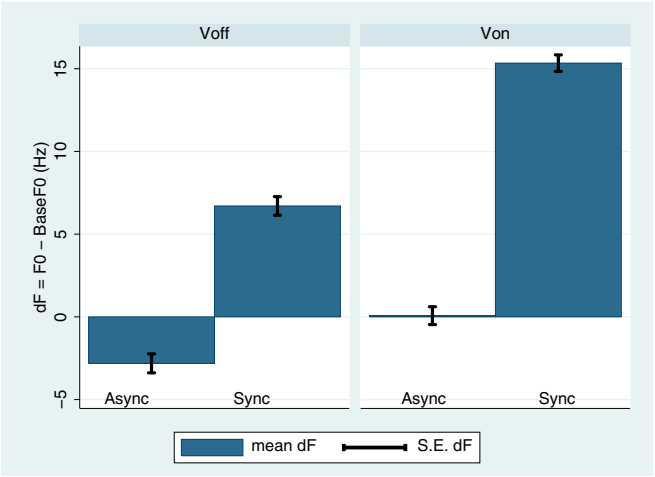

Fig. 4. Bar chart for dF by visuomotor and vibrations.

overlap in their activations (so moving one finger has shared activation with many other possible movements). In our setup, participants spent 5 min moving with visuomotor synchrony (in the sync condition) —thus, of course, continuously activating multiple areas in the motor cortex—and continued moving for more than another 5 min during the talking phase. Because it is known that seeing and hearing a talking face activates many cortical motor areas (30), it is possible that when the avatar spoke, the resulting motor area activations overlapped with earlier and ongoing activations, providing a unified experience with all of the actions attributed to the self.

The participants in our experiment observed an event (the avatar speaking), and those in the sync condition—and especially those who additionally experienced Von—tended to retrospectively attribute authorship of that event to themselves. Our explanation suggests that this was due to the 1PP body-ownership illusion, and the agency caused by the synchrony between real and VB movements. We propose that under these circumstances specific acts that are carried out by the VB but not by the participant are also attributed to by the participant to him- or herself, generalized from the agency associated with the body movement. Put simply, the inference may be, "This is my body, I am moving it—it spoke, so I must have been the one that did the speaking."

This explanation is compatible with the widely accepted internal motor control models of agency, and we argue that the critical evidence for this is the drift of FF of participants' own later utterances toward that of the VB in the (sync, Von) condition. In the forward model of motor control, an efference copy of a motor command to achieve a goal is used by the CNS to predict the sensory consequences of motor action, and before the act has been realized, the predicted outcome is compared with the goal. Then after the act the actual sensory feedback is compared with the predicted, and the extent to which these cohere contributes to agency. However, an inverse model computes the detailed sequence of the motor commands necessary to achieve the goal. It is argued that this inverse model is not available to consciousness (17). In the case of our experiment the forward model apparently cannot apply, there is no preparation for action, and there can be no comparison between the sensory outcome and goal because there was no goal, only the observation of an act. However, this only applies to the first utterances by the VB. We propose that once the avatar starts speaking, the body ownership results in a retrospective intention to act that then mobilizes the same brain areas as in a prospective intention to act.

Normally a preparation for action results in a conscious intention to act. We propose that in this case there is an additional feedback circuit where the observation of apparent self-action results in an activation of preparation for action circuits which then give rise to the sensation of agency with respect to the specific act. We suggest that the inverse model is fully mobilized. If the act is ascribed to the self, then after the first few words are spoken the retrospective intention to act would require the CNS to compute how to actually reproduce the vocalization that was ascribed to the self, especially if there were an expectation of subsequent speech. When the participant is later asked to vocalize those same words, the CNS has already prepared the motor commands to make this possible—and indeed the vocalizations were carried out with the higher frequency associated with the heard voice. Essentially, therefore, we can say that the body ownership that resulted from the sync condition generalizes to retrospectively produce the same CNS computations as if the person had really spoken. The fact that the production of the vocalization was clearly influenced by the heard voice in the (sync, Von) condition suggests that there must have been some preparation of the motor system for action, and therefore there must have been an influence via the internal model as suggested.

Wegner and Wheatley argued that the attribution of an act to the self is based on the same mechanisms as the perception of causality in general—in other words that a specific act carries the sensation of agency when it satisfies the general conditions for attribution of causality (31). They identified three necessary conditions for an agentic relationship between the thought before an action and the act itself: (*i*) priority, "the thought should precede the action at a proper interval"; (*ii*) consistency, "the thought should be compatible with the action"; and (*iii*) exclusivity, "the thought should be the only apparent cause of action." These principles seemingly do not apply to our experiment because, given the unexpected nature of the VB speaking, there was no thought intentionally related to this before its occurrence. However, as argued above, this only applies to the first word spoken by the avatar, and that this first word or at least the first few words spoken established prior thoughts in participants in the form of expectations for the subsequent speaking. In this case the priority and consistency requirements might have been met. However, the exclusivity requirement would still not be satisfied because there was an entirely plausible, obvious (and true) alternative explanation that the avatar was talking by itself.

A similar consideration applies to priming, the idea that "Authorship is likely to be inferred when the agent has action-relevant thoughts that occur prior to the action" (ref. 32, p. 839). In particular Wegner et al. (32) describe an experiment that has some similarity to our own but where their participants looked at themselves in a mirror in which the substitute rubber arms they saw moving (arranged so that it could seem as if they were the arms of the participants) were actually moved by a confederate. Participants tended to attribute authorship to themselves in the condition when there was a prior instruction to carry out the movement. In the case of our study we suggest that the initial utterances acted as primes for the subsequent ones. Moreover the vibrations experienced in the Von condition would also eventually have acted as primes in the sense that this particular stimulus was always associated with the speaking in that condition. However, it remains to be explained how the exclusivity requirement could be satisfied in our experiment. We turn to this next.

Wegner et al. (32) provided a set of authorship indicators as conditions for the judgment of agency. Here we mention only those that could be relevant to our setup. The indicator referred to as "body and environment orientation cues" is concerned with knowing about the body and its affordances and those of the environment. In our case, in the sync condition, there was a strong illusion of body ownership over the VB that could be seen directly and in the mirror (Fig. 2).

A further relevant authorship indicator is "direct bodily feedback", referring to feedback "from body to brain ... proprioceptive and kinesthetic sensations from muscles, skin, joints, and tendons as well as from the vestibular system". This occurred throughout the experience for those in the sync condition because the VB moved synchronously with their own movements. Moreover, for the specific event of speaking, those in the Von condition had the associated vibrotactile feedback which further positively influenced the illusion of authorship over the speaking. Moreover this, combined with the visible lip sync (which occurred in all experimental conditions), would fall under the "visual and other indirect sensory feedback" indicator, and could have contributed further to agency.

Putting these together, the experience of participants in the (sync, Von) condition is that they would have had a full-body-ownership illusion with respect to a body that was seen and heard talking, and where the seen visual movement of the lips and the sound of speaking were synchronized with vibrotactile stimulation just at that point on the body associated with the act of speaking. The exclusivity requirement could therefore be moderated by a degree of uncertainty caused by the body-ownership illusion. In other words, the alternative explanation for the cause of the talking ("it is the virtual character doing the talking not me") ceases to be effective when the virtual character seen in the mirror could indeed be me.

In this context it is worth noting that the type of illusory agency that we have found is similar to mirror-touch synesthesia (MTS) except in motor activity rather than touch (see ref. 33 for a recent review). An individual with MTS will actually experience the tactile sensation of seeing someone else touched. We would predict that were such individuals embodied in a VB using our method, they would directly feel the tactile stimulation associated with a visually presented tactile stimulation on the avatar's body. It was reported in ref. 34 that mirror-touch synesthetes have an enhanced sense that another's face is their own simply as a result of observing the other face stroked, indicating a change in mental representation of self. It was argued in ref. 33 that this confusion between self and other may be at the root of an explanation for MTS at the neural level. We suggest that similarly the confusion of ownership between the avatar body and the participants' own bodies plays an important role in explaining our results.

A quite different explanation for the vocal production effect concerns mimicry, referred to in the social science literature as the chameleon effect (35), where people tend to unwittingly mimic the behavior of others with whom they interact, which in turn leads to more positive attitudes toward the other and enhanced social interaction. In the neuroscience literature it has been observed that observation of others' actions leads to internal motor representations of the actions, which in turn may facilitate mimicry—in other words, a shared motor representation between perception of others' action and self-action. For example, Van Ulzen et al. (36) showed that the motor system resonates with unobtrusive nonverbal behavior of another person, specifically face touching (FT) that has nothing to do with the purpose of the action being observed. Regarding the implications for mimicry, they suggest that "there is a tendency to immediately mimic the inconspicuous FT but that the emission of this tendency into observable mimicry behavior is controlled by an inhibitory mechanism that is susceptible to the social context" (ref. 36, p. 352). Hogeveen and Obhi (37) found that motor resonance as the result of action observation in another person was more likely to occur if there had been prior social interaction with the other, although this did not apply when the other was a robot rather than human. In any case, it is clear that for human–human interaction, there is a shared representation between action observation and self-action (18).

It could be argued that the (almost exact) mimicry in our experiment between self-movements and the movements of the avatar resulted in a chameleon effect which then generalized to the specific event of talking. In other words, because the avatar reproduced the global body movements of the participants (in the sync condition), there would be a high degree of empathy toward the avatar and reciprocally the participants would find themselves unwittingly mimicking the avatar's voice production. However, in terms of motor resonance, the situation is more complex—because the participants were themselves actually making the movements that were synchronously reflected back to them in the movements of the avatar. Hence, more than there being just some shared representation between observation and action, these coincided because the movements of the avatar were those of the self. The interesting question then arises as to how the generalization to vocal production occurred. This could be due to the mechanism discussed earlier of the nonspecificity of motor production, so that activation in one area is associated with activation in other areas. So although the social mimicry explanation cannot be ruled out, it is unlikely because unobtrusive and unconscious mimicry between the participant and avatar did not take place: The avatar moved almost exactly the same as the person (except for the act of talking).

Having discussed the issue of agency above, we now turn to the remaining issues of ownership over the avatar voice, and a possible explanation for the reduction of frequency compared with baseline in the (async, Voff) condition. A recent study (19) explored how normal individuals in whom the self-monitoring system is intact, perceive the identity of an external voice, referring to their setup as the "rubber voice illusion". More specifically, participants talked into a microphone while receiving auditory feedback that was either their own vocalization or someone else's voice in temporal synchrony. The results suggest a sense of ownership over a stranger's voice when participants experienced an alignment between their own vocal motor movement and the resulting sensory events, reporting the stranger's voice being a distorted version of one's own voice.

In our study, we explored how the alignment between motor feedback from a substituted VB that then subsequently vocalized words associated with visible lip sync and vibrotactile stimulation resulted in participants perceptually experiencing themselves as talking and categorizing a stranger's voice as their own. Research involving online voice perturbation and FF shifting has shown that people tend to compensate for a change of FF in the real-time auditory feedback during vocal production, either by shifting their FF in the direction of the feedback signal (19, 20) or in the opposite direction (20, 38, 39). The participants in our experiment in the sync condition tended to follow the stimulus rather than compensate for it in the opposite direction. It is argued in refs. 20, 38, and 39 that following the stimulus voice can serve to bring the participant's voice to agree with that of the external source, whereas compensating works as an error-correction mechanism to return the signal closer to that intended by the speaker. In our study the change was therefore not an error correction but rather signifying ownership over the voice in the (sync, Von) condition, and it was likely to be error correction in the (async, Voff) condition. This also accords with the questionnaire responses (Fig. 3, *OwnVoice*).

Increasingly surrogates will represent people through online avatars and in robotic form where the robot actions may even be caused by interpretations of a person's brain activations (40). One corollary of this trend toward surrogate representation is that the concept of agency will come increasingly to the fore in ethical, legal, and societal arenas. If my representation in a remote location carries out some act, I may claim or deny agency over that act, which has consequences for my personal, legal, and social responsibility. If, as we have shown in this paper, a person may attribute agency over an act to themselves, even though they

had no intention to act and played no part in its production, it becomes essential to understand this scientifically. From a societal, legal, and ethical point of view, unraveling the truth between "I caused an action but attributed it to another agent," "I thought I caused the action but did not," and "I correctly attributed the action to myself," will become vital.

Materials and Methods

Participants attended the experiment at prearranged times. Upon arriving, they were given an information sheet to read, and after they agreed to continue with the experiment, they were given a consent form to sign. The experiment was approved by the Comissió Bioètica of Universitat de Barcelona. Before the experiment started, participants were seated in front of a laptop fitted with a headset and were instructed to read out in a clear voice nine target words displayed in sequence. Each word was recorded five times, in random order, using audio editing software, and used as baseline data for later analysis. Next, participants were fitted with an HMD, a body-tracking suit, a pair of headphones, and a microphone. The view seen through the HMD was calibrated using the method described in ref. 41.

When the experiment started, participants were in a virtual room that included a virtual mirror. The body of the participant was substituted by a sex-matched VB, seen from the 1PP. The participant's head and body movements were mapped in real time to the VB in the sync condition but were based on a prerecorded animation for the async condition. However, participants always saw the scene based on correct head tracking. Participants could see the body both by looking directly toward their real body and also in the virtual mirror (Fig. 1 *B* and *C*). They were asked to perform a simple set of stretching exercises that had previously been demonstrated to them by the experimenter (thus experiencing either sync or async). They were asked to continue performing these exercises by themselves and also look around the virtual room in all directions. During this visual exploration participants were asked to state and describe what they saw, to make sure they were paying attention and that the system was working properly. After the exploration period (5 min), participants were asked to focus on their VB and face in the mirror and avoid looking away in other directions, while still occasionally performing exercises with their bodies. During the following 5 min 21 s, the prerecorded stimulus voice was played through the headphones while the avatar's lips moved synchronously with the spoken words. Each word was played 14 times. During this period participants assigned to the Von condition also experienced vibrational feedback on the thyroid cartilage that was synchronized to the syllables of the words.

After this stimulus period, the HMD displayed a black background with written instructions to read out loud the nine target words that then appeared in front of them in random order. Each word was recorded five times. After removing the HMD, the participants were asked to complete the postexperimental questionnaire. Next they were paid and debriefed. The whole procedure lasted between 20 and 30 min. The experimental operator (female) was present throughout the entire experiment.

Further information is given in *SI Materials and Methods* and Movie S1.

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