Title: Synchronous stimulation in the rubber hand illusion task boosts the subsequent sense of ownership on the vicarious agency task

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Abstract

The relationship between sense of agency and sense of ownership remains unclear. Here we investigated this relationship by manipulating ownership using the rubber hand illusion and assessing the resulting impact on self-experiences during the vicarious agency illusion. We tested whether modulating ownership towards another limb using the rubber hand illusion would subsequently influence the illusory experience of ownership and agency towards a similar-looking limb in the vicarious agency task. Crucially, the vicarious agency measures both sense of agency and sense of ownership at the same time, while removing the confounding influence of motor signals. Our results replicated the well-established effects of both paradigms. We also found that manipulating the sense of ownership with the rubber hand illusion influenced the subsequent vicarious experience of ownership but not the vicarious experience of agency. This supports the idea that sense of agency and sense of ownership are, at least partially, independent experiences.

Keywords: sense of agency; sense of ownership; rubber hand illusion; vicarious agency; volition; consciousness

Word count: 4330 words

1. Introduction

When I raise my hand, I feel that the hand that is moving belongs to me. I also feel that I am causing my hand to rise. The feeling of body parts belonging to oneself is known as sense of ownership (SoO) and the feeling of causing and controlling one's actions (and their outcomes) is known as sense of agency (SoA). This example of raising my hand also shows how the experiences of ownership and agency tend to co-occur. This would naturally lead one to assume that these two aspects of self-experience are in some way related to each other. However, there is still much about their exact relationship and whether or not they interact that remains unclear (Gallagher, 2000; Ma & Hommel, 2015; Tsakiris, Longo, & Haggard, 2010; Tsakiris, Prabhu, & Haggard, 2006).

One of the key ways of investigating sense of ownership is through illusions, such as the rubber hand illusion (RHI; Botvinick & Cohen, 1998). In the traditional RHI, an artificial hand is placed in a body congruent position in front of the participant, whose hand is hidden from view. By synchronously stroking the artificial and the real hand, visual and tactile information are combined and the perceived location of the real hand is shifted towards the artificial hand. This is known as proprioceptive drift. Explicit measures also reveal that participants report experiencing sense of ownership over the artificial hand.

With the aim of investigating the interplay between SoA and SoO, most recent studies have created paradigms that allow participants to control the artificial hand. This has been achieved with a range of technologies, such as robotic hands or Virtual Reality (VR) (e.g. Caspar et al., 2015; Kokkinara & Slater, 2014; Ma & Hommel, 2015). In these paradigms, one studies the agency-to-ownership relationship by manipulating objective agency (i.e. actual control) and assessing the effect of this on the experience of ownership. Although there are some inconsistencies in the literature, results from these studies do tend to show that agency influences sense of ownership, and therefore, that these aspects of self-awareness are not fully independent of each other. For example, Ma and Hommel (2015) tested the effect of objective agency on sense of ownership using a virtual

hand illusion. They found that in the active condition, when participants could exercise objective agency, the sense of ownership over the hand was increased. Earlier work on this question by Tsakiris, Prabhu and Haggard (2006) found that objective agency also changes the *kind* of ownership experienced; in their study movement seemed to lead to a more global, unified sense of ownership over the moving body part. These studies suggest that agency influences both the strength *and* nature of ownership experiences.

Although most experiments have focused on the agency-to-ownership relationship, some have looked at the opposite of this: ownership-to-agency (for a review, see Pyasik, Furlanetto, & Pia, 2019). In these studies one manipulates ownership and assesses the effect of this on the experience of agency. These studies typically find that ownership manipulations alter the sense of agency, again, suggesting that these aspects of self-awareness are not fully independent. For example, Burin et al. (2017) used the RHI to manipulate sense of ownership and assess whether this altered the sensory attenuation phenomenon (an implicit measure of sense of agency). They found that sensory attenuation was increased when sense of ownership over the rubber hand was established, suggesting that ownership boosted the sense of agency (see also Burin et al., 2018, for a similar finding).

Although, these studies have been informative, there remain certain limitations with the methods used. First, most, if not all, studies measure the effect of the ownership/agency manipulation on a single outcome variable: sense of agency *or* sense of ownership. However, it is clearly important to understand the effect of this manipulation on *both aspects* of self-experience on the same task. Second, many studies that have examined the effect of ownership manipulations on sense of agency have confounded the dependent variable by having the participant make a movement. This is problematic as previous studies show that movement can influence sense of ownership (e.g. Kokkinara & Slater, 2014; Ma & Hommel, 2015), which in turn can alter sense of agency. For purer measures of SoO and SoA as dependent variables, it is preferable to have a task that does not require movement. Finally, previous studies that have investigated the ownership-to-agency relationship typically use very simple movements (i.e. button presses as in Burin et al., 2017). Although the results are informative, these movements are perhaps less reflective of

the kinds of movements we are more likely to perform in our everyday lives, which tend to be more meaningful, temporally extended and complex.

In order to deal with these issues, we used as our dependent variable the vicarious agency paradigm developed by Wegner and colleagues (2004). In the vicarious agency paradigm, illusory experiences of agency and ownership are engendered in the absence of movement. This allows us to measure both sense of agency and sense of ownership concurrently, whilst also removing the confounding influence of motor activity. Importantly, the movements that form the basis of the task are also common everyday movements that are more complex and temporally extended than those that have been studied previously. We investigated whether modulating ownership towards another limb using the RHI subsequently influenced the illusory experiences of agency and ownership on this vicarious agency task (for a limb that shared the same perceptual features as that used the rubber hand illusion). If there is a relationship between these aspects of self-consciousness, then one would expect that increasing ownership using the RHI manipulation should increase the subsequent experiences of agency and ownership on the vicarious agency task.

2. Methods

2.1 Participants

Thirty participants (18 males) took part in the study. Their average age was 22.1 years (age range = 19-26 years). All participants signed a consent form prior taking part to the experiment. The study was approved by Goldsmiths Ethics Committee.

2.2 Procedure

All participants took part in two testing sessions, which were scheduled a week apart from each other. One testing session consisted of the rubber hand illusion synchronous condition, followed by the vicarious agency illusion. The other testing session consisted of the rubber hand illusion asynchronous condition followed by the vicarious agency illusion. The order of synchronous\asynchronous conditions was counterbalanced across participants.

2.3 Rubber Hand Illusion

Participants were seated at a table facing the experimenter. A box with open sides was placed on the table. Participants were asked to place their hand inside the box, where it was hidden from view. The participant's hand was placed 40 cm away from their midline and the rubber hand, located inside the box, was half way between the participant's hand and their midline. This spatial arrangement is known to elicit a reliable illusion (Holle, McLatchie, Maurer, & Ward, 2011). The rubber hand measured 23 cm in length (from the end of wrist to the tip of the middle finger). The participant could see the rubber hand from a hole the top of the box, while their real hand was always kept hidden from view. Before each trial began, the hole was covered in order to keep the rubber hand concealed and a tape measure was placed on top of the box.

At the start of each trial the participant was asked to indicate where they thought their index finger was located, by reporting a number on the tape measure. For each judgement, the tape measure was placed with a different offset in order to prevent memory effects. The tape measure was then removed along with the covering cloth to make the rubber hand visible. The experimenter stroked both the real and the rubber hand with identical paintbrushes. Each stroke went from the major knuckle to the fingertip and lasted between half a second and one second. In the synchronous condition, both real and rubber hands were stroked simultaneously. In the asynchronous condition, the rubber hand was stroked before the real hand with the asynchrony randomly varied between half a second and one second. Participants were asked to look at the rubber hand throughout the stimulation period, which lasted 120 seconds. After the stimulation had finished, the covering cloth and the ruler were placed back on top of the box. The participant was once again asked to indicate the position of their index finger. The proprioceptive drift elicited by the stimulation was calculated by subtracting the pre-stimulation position from the post-stimulation position.

The same procedure was repeated for both the right and the left hand. The order of the stimulation of the hand was counterbalanced across participants. After both hands had been stimulated, participants were asked to verbally answer a questionnaire.

Eight questions were taken from questionnaires that have been used in RHI studies (Botvinick & Cohen, 1998; Kalckert & Ehrsson, 2012; Longo, Schüür, Kammers, Tsakiris, & Haggard, 2008). Four items investigated the SoO felt by the participant (I felt as if I was looking at my own hand; I felt as if the rubber hand was part of my body; It seemed like the rubber hand began to resemble my real hand; I felt as if the rubber hand was my hand). Four items acted as check questions to control for task compliance, suggestibility or any response bias (I felt as if my real hand were turning rubbery; It seems as if I had more than one right hand; it appeared as if the rubber hand were drifting towards my real hand; It felt as if I had no longer a right hand, as if my right hand had disappeared).

Crucially, in order to create a stronger association between the participant's hands, the rubber hands and the experimenter's hands used in the vicarious agency task (see below), both the participant and the experimenter wore a pair of red gloves. The rubber hand was also covered with red gloves.

2.4 Vicarious agency task

The procedure was the same used in Cioffi et al. (2016, 2017). Participants sat on a chair facing a full-length mirror at a distance of 1m. Participants wore over-ear headphones on which were played the action previews. A blue sheet covered the participants' body from the shoulders downwards and a blue curtain was placed behind their back to block their view of the experimenter (see Figure 1).

Participants' arms were placed out of view under the sheet. The experimenter put on another set of headphones to hear the instructions, a blouse that was the same colour as the sheet covering the participant and a pair of red gloves. The experimenter was positioned behind the curtain. The experimenter placed their arm (either left or right) forward through two specific holes in the curtain, so that it appeared where the participant's own arm would have been. Participants were asked to look at the mirror in front of them while the experimenter performed the gestures with either the left or the right hand and to remain still during the experiment.

Each condition consisted of 16 instruction-action trials. On each trial, a tape with the list of 16 unimanual action instructions was played (e.g., “make a waving gesture,” “snap the fingers twice”, “point to the mirror”). The examiner performed an action immediately after each instruction. Each instruction-action trial consisted of one instruction plus action, lasted between 8 and 10 seconds, and had a three second break between trials.

There were two within-subject conditions: in the match condition the action corresponded to the instruction, whereas in the mismatch condition each instruction was randomly matched with a different action (e.g. after the instruction “make a waving gesture” the examiner snapped their fingers). In this mismatch condition, the gesture was different for every repetition of the same instruction (e.g., on the second repetition, after the instruction “make a waving gesture” the examiner pointed to the mirror). These conditions were completed for both the right and left hand separately to control for any possible effects of handedness. The order of match – mismatch conditions and the order of hand tested were counterbalanced across participants.

So as to augment the effects of this manipulation, the list of 16 instruction-action stimuli was repeated from the beginning to the end without interruption three times for each of the four conditions (match/mismatch and left/right hand). At the end of the third repetition of the instruction-action list, the participants were asked to report their experiences by answering 3 questions on a 7-point scale from 1 - not at all- to 7 - very much. In total each participant was given 4 conditions (match right/mismatch right/match left/mismatch left) and therefore provided four ratings for each of the questions reported below.

Anticipation: ‘*’To what degree did you feel you could anticipate the movements of the arm?”*

This control question assesses the success of the manipulation and whether the primes were attended to. This was included because a failure to attend to the primes may explain any putative differences in the agency or ownership effects. If primes are attended to then anticipation judgements should be higher in the match than in the mismatch conditions.

Sense of Agency: *''How much control did you feel you had over the arm's movements?"*
This target question directly assesses the experience of agency.

Sense of Ownership: *''To what degree did the arm feel like it belonged to you?''*
This question provides an additional measure of the effect of the manipulation, examining the impact on sense of ownership over the body part.

A practice session consisting of 3 match and 3 mismatch trials was performed at the beginning of the experiment.

Figure 1. Experimental set-up (based on Wegner et al., 2004). The left picture shows what the participant sees in the mirror placed in front of her. The right picture shows the set up from the side, with the experimenter sitting behind the participant and putting her hand forward so that it appears where the participant's hand would normally be. The picture is taken from Cioffi et al. (2017)

3. Results

Non-parametric tests have been used throughout as most variables failed to meet the criteria for normality on a Shapiro-Wilk test (Shapiro-Wilk test, $p < .05$).

3.1 Rubber hand illusion

The effect of Stimulation (Synchronous/Asynchronous) on Ownership questionnaire ratings was examined by conducting Wilcoxon signed rank tests on the mean ratings

for ownership in synchronous compared to asynchronous trials. These mean ratings were obtained by collapsing mean ratings for left and right conditions into a single score. Participants reported significantly higher ownership (z = -4.79, p < .001) in the synchronous condition (av = 4.95 sd = .79) compared to the asynchronous condition (av = 1.29, sd = .29), (Figure 2).

A Wilcoxon signed rank test on the mean proprioceptive drift revealed that participants showed significantly greater proprioceptive drift after the synchronous (av = 2, sd = 1.07) compared to the asynchronous condition (av = .62, sd = .79) (z = -4.16, p < .001), (Figure 3).These results show that participants displayed the classical RHI effects for both ownership questionnaire and proprioceptive drift.

We used a Wilcoxon signed rank test to compare the Ownership ratings to the Check question ratings. As expected, participants reported higher ratings in the Ownership questions compared to the Check questions in both the Synchronous (av = 1.59, sd = .48) (z = -4.79, p < .001) and in the Asynchronous condition (av = 1.14, sd = .33) (z = -2.06, p = .039).

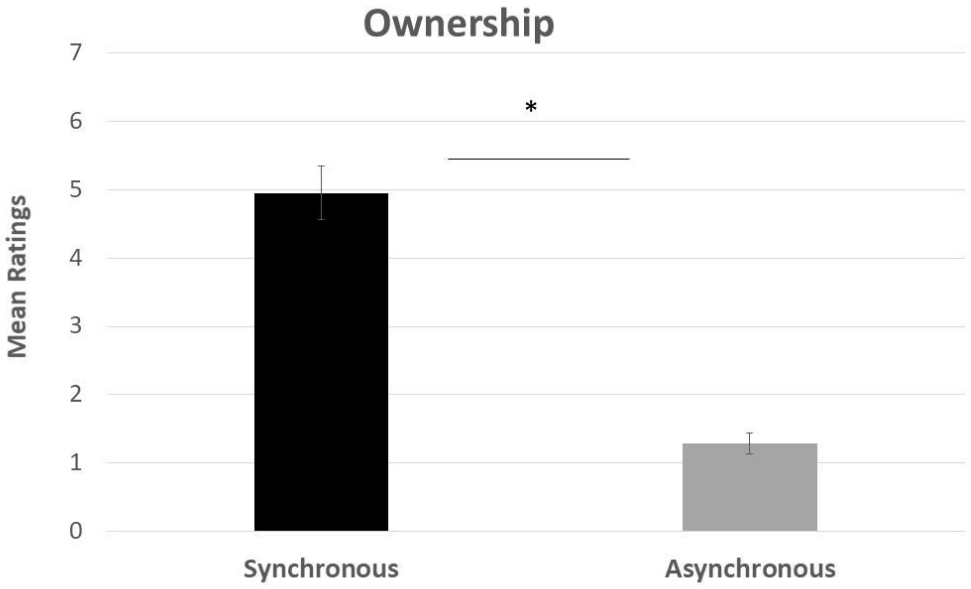

Figure 2. Results of RHI ownership questionnaire. Mean Ownership ratings reported by the participants following synchronous and asynchronous stimulations on the RHI.

*Participants reported significantly higher ownership after synchronous stimulation. Error bars represent standard deviation. * indicates a significant difference (p < .05).*

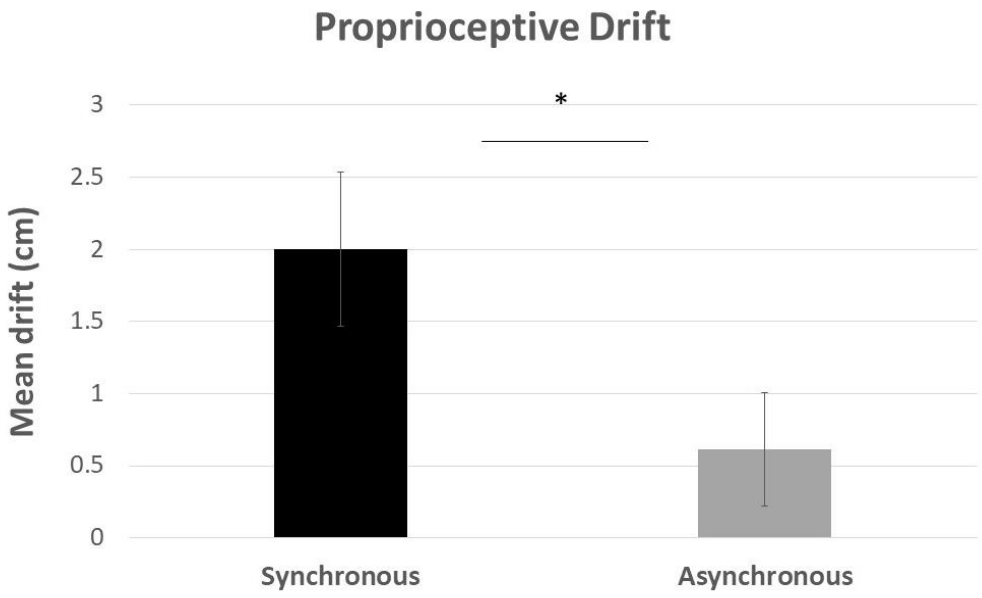

*Figure 3. Results of RHI proprioceptive drift. Mean proprioceptive drift shown by participants following synchronous and asynchronous stimulations on the RHI. Participants showed significantly greater drift towards the artificial hand after synchronous stimulation. Error bars represent standard deviation. * indicates a significant difference (p < .05).*

3.2 Vicarious agency illusion

To examine the overall effect of Condition (Match vs Mismatch) across RHI stimulations (synchronous and asynchronous), mean judgements for each condition following synchronous and asynchronous RHI stimulation were collapsed into a mean single score. For example: (anticipation match condition following synchronous RHI stimulation + anticipation match condition following asynchronous RHI stimulation)/2). These average scores were then analysed using Wilcoxon signed rank tests.

The effect of Condition (Match vs Mismatch) on 'Anticipation' ratings was examined using a Wilcoxon signed rank test on the mean Anticipation match ratings vs mean Anticipation mismatch ratings. Participants reported significantly higher anticipation

in the match conditions compared to the mismatch conditions ($z = -4.8$, $p = < .01$) (Figure 4). This shows that differences in attention to the actions or instructions, or any response bias, are unlikely to explain agency or ownership effects.

The effect of Condition (Match vs Mismatch) on 'Agency' ratings was examined using a Wilcoxon signed rank test on the mean Agency match ratings vs mean Agency mismatch ratings. Participants reported significantly higher sense of agency in the match compared to the mismatch conditions in the vicarious agency task ($z = -4.73$, $p < .01$), (Figure 4).

The overall effect Condition (Match vs Mismatch) on 'Ownership' ratings was examined using a Wilcoxon signed ranks test on the mean Ownership match ratings vs the mean Ownership mismatch ratings. Participants reported significantly higher sense of ownership in the match compared to the mismatch conditions ($z = -4.64$, $p < .01$), (Figure 4).

Overall, these results show that the experimental manipulation was successful, as participants experienced higher SoA and SoO in the match conditions compared to the mismatch conditions.

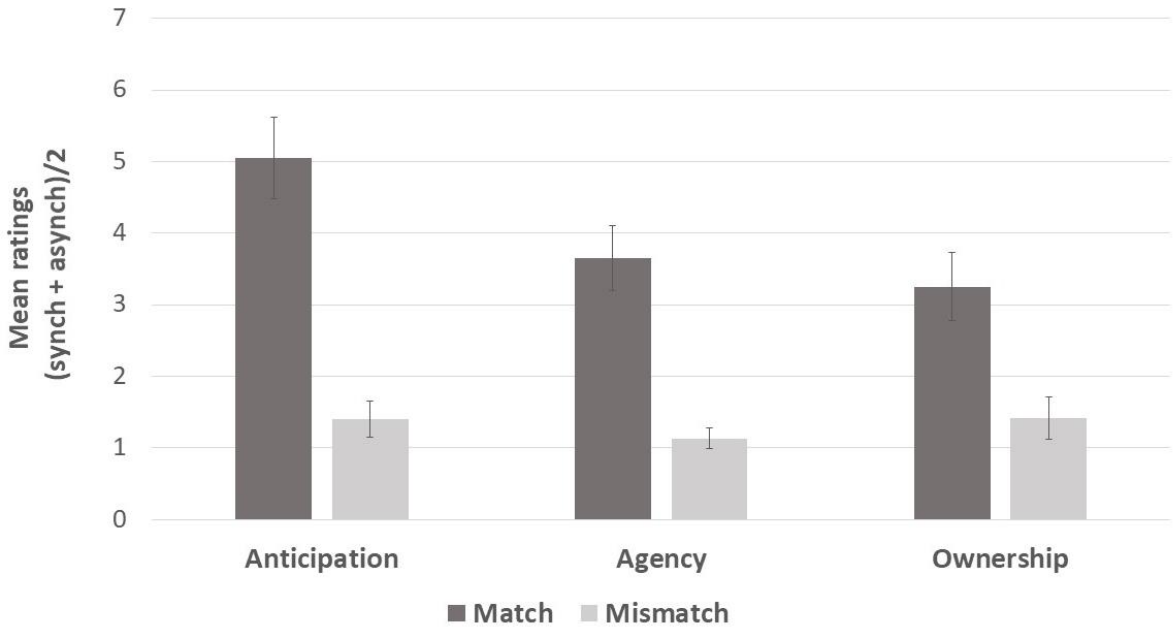

Figure 4. Results of vicarious agency task. Mean ratings for Anticipation, Agency and Ownership at the vicarious agency task for match and mismatch conditions. Mean ratings were obtained by averaging mean judgments for each condition following synchronous and asynchronous RH stimulations. Error bars represent standard deviation.

3.3 Rubber Hand Illusion + Vicarious Agency Task

To examine the effect of the RHI stimulation (Synchronous vs Asynchronous) on the magnitude of vicarious agency illusion, we first calculated the difference between match and mismatch trials for a) the agency question (Agency effect), b) the ownership question (Ownership effect), and c) the anticipation question (Anticipation effect). We then compared the magnitude of each of these effects for the synchronous vs. asynchronous conditions (see Table 1 for mean ratings for each conditions). These were tested using non-parametric pairwise comparisons.

A Wilcoxon signed rank test on Ownership ratings following synchronous vs asynchronous RH stimulation showed that synchronous stimulation induced a significantly greater illusion of ownership compared to asynchronous stimulation ($z = -2.71$, $p = .007$) (SoO Synch: av = 2.23, sd = 1.22; SoO Asynch: av = 1.43, sd = 1.04), (Figure 5).

A Wilcoxon signed rank test on Agency ratings following synchronous vs asynchronous RHI stimulation showed there was no significantly greater illusion of agency following the synchronous stimulation compared to the asynchronous stimulation ($z = -1.66$, $p = .098$) (SoA Synch: av = 2.63, sd = 1.01; SoA Asynch: av = 2.4, sd = 1.2), (Figure 5). This suggests that the rubber hand manipulation bolstered the sense of ownership on vicarious agency task but *did not* influence the sense of agency.

As predicted, the type of stimulation did not influence the ratings for the check question (i.e. Anticipation), as shown by a Wilcoxon signed rank test between anticipation effect in synchronous vs asynchronous stimulation ($z = -1.07$, $p > .250$) (Anticipation Synch: av = 3.53, sd = 1.57; Anticipation Asynch: av = 3.77, sd = 1.19), (Figure 5).

To further examine the relationship between the ownership scores in the RHI task and the Agency and Ownership scores in the vicarious agency task, we ran Spearman correlations between the RHI scores (questionnaire; proprioceptive drift) and the vicarious agency task scores (Agency effect/Ownership effect/Anticipation effect). There was no significant relationship between RHI scores and Agency or Anticipation effects ($p > .05$). However, there was a notable, but not significant, correlation between RHI *questionnaire* scores and the Ownership effect ($r (30) = .301$, $p = .098$). Although non-significant, these results may lend further tentative support for the idea that vicarious sense of ownership is selectively bolstered following the RHI manipulation.

Table 1. Mean ratings and standard deviations for each question (Anticipation/Agency/Ownership) for each vicarious agency condition (Match/Mismatch) following each RHI stimulation (Synchronous/Asynchronous).

	Synch Match	Synch Mismatch	Async Match	Async Mismatch
Anticipation	5.1 (1.3)	1.6 (.7)	5 (1.2)	1.2 (.5)
Agency	3.8 (.9)	1.2 (.5)	3.5 (1)	1.1 (.3)
Ownership	3.7 (1.1)	1.4 (.7)	2.8 (1.1)	1.4 (.6)

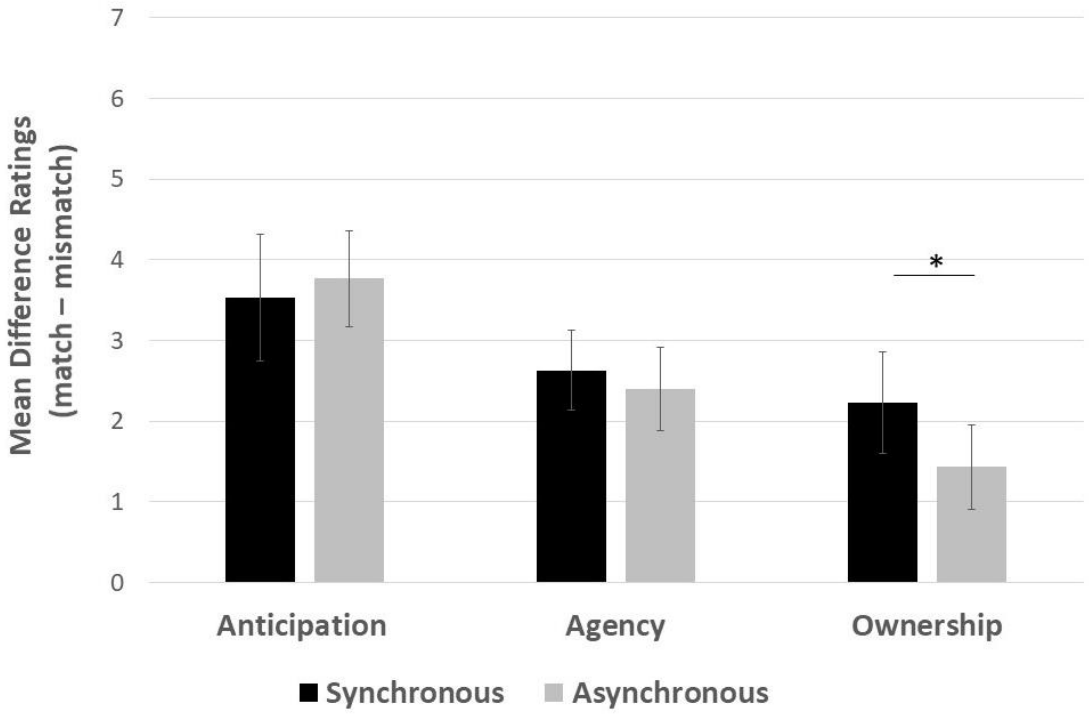

*Figure 5. Results of RHI stimulation on vicarious agency task. Mean difference ratings (match minus mismatch) reported in the vicarious agency task for Anticipation, Agency and Ownership following RHI synchronous and RHI asynchronous stimulation. Participants reported greater SoO over the hands in the vicarious agency task following synchronous compared to asynchronous stimulations. No difference was found in Anticipation and Agency ratings. Error bars represent standard deviation. * indicates a significant difference ($p < .05$).*

4. Discussion

This work sought to shed light on the relationship between sense of ownership and sense of agency. While this relationship has been extensively investigated, it remains unclear (Ma & Hommel, 2015; Tsakiris et al., 2010, 2006). In our experiment, we modulated ownership using the RHI and assessed the subsequent effect of this on experiences of ownership and agency on the vicarious agency task. Our results showed that there was only an effect on the ownership outcome variable.

Before discussing our key result, it is worth highlighting the fact that we were able to replicate the well-established effects of both paradigms. Participants felt higher SoO towards the rubber hand after synchronous, compared to asynchronous stimulations. Equally, the proprioceptive drift towards the rubber hand was greater following synchronous compared to asynchronous stimulations. With regards to the vicarious agency task, participants reported higher Anticipation (check question), SoA and SoO in the match conditions, compared to the mismatch conditions.

Our key result suggests that SoO and SoA are, at least partially, independent experiences. Were they not, we would expect that synchronous stimulation in the RHI would influence the vicarious SoA as well as the vicarious SoO. Instead, we did not find such modulation for the SoA. This result is consistent with certain previous studies. For example, Walsh et al. (2011) showed that the sense of ownership was not increased by voluntary movement (which promotes sense of agency). As suggested by Walsh et al., this dissociation between agency and ownership may be explained by the fact that agency is not necessarily body-specific, given that we can exercise control over both corporeal (e.g. hands) *and* non-corporeal objects (e.g. tools). Our finding lends further support to the idea of a *possible* dissociation between the experiences of ownership and agency.

It is important to note that most of the studies that have looked at the relationship between agency and ownership have adopted the agency-to-ownership approach. That is, they manipulated agency and assessed the resulting impact of this on ownership. However, there are some more recent exceptions to this using the opposite approach; namely, ownership-to-agency. For example, Kilteni and Ehrsson

(2017) used a RHI set-up and showed that establishing ownership over a rubber hand increases the magnitude of sensory attenuation (an implicit measure of sense of agency). A similar finding has also been reported by Burin et al. (2017).

Our experiment also adopted this ownership-to-agency approach, but unlike the experiments mentioned above, we found that manipulating sense of ownership did not have a knock-on effect on sense of agency. This is an important counterweight to these studies, suggesting that there might be certain situations in which changes in sense of ownership do not translate into changes in sense of agency. One possible explanation for our result is that we measured sense of agency using only an explicit rating scale, whereas Kilteni and Ehrsson (2017) used an implicit measure (sensory attenuation). It might be that our higher-level measure of sense of agency was not sensitive enough, or indeed, was perhaps confounded by other factors.

It is also worth considering the potential presence of a response bias, namely participants reported higher ownership in the vicarious agency task because they tended to give an answer similar to the answer given for the ownership question in the RHI task. While it is possible that a response bias is at work following the RHI task, this would not explain the increase in the *difference* of the ownership judgements in the vicarious agency task, which is the crucial outcome of the manipulation. Similarly, it can be argued that the differences between the two tasks, coupled with the time interval, are potential barriers for a transfer effect to take place. While future work should aim to fine-tune the experimental procedure to minimise any barriers to the transfer effect, the change in the magnitude of the ownership effect (match-mismatch difference) that occurs after RHI inducement is consistent with the existence of a transfer effect.

The vicarious agency paradigm used in our experiment brought certain methodological advantages, which may be of use to those carrying our further research in this. First, the paradigm allows us to measure our dependent variables, agency and ownership, *concurrently.* This provides more information to the researcher and also offers the possibility of further exploring the relationship between these variables in a way that other measures do not. Second, the vicarious agency task is a passive one from the point of view of the participant. This is

important as it removes the potential confound of movement related signals from our measures of interest. This is particularly relevant given that movement may influence sense of ownership, which in turn, may influence sense of agency.
In this way, the vicarious agency task provides a relatively pure measure of our effects.

In conclusion, our results show that subjective ownership and subjective agency are partially independent experiences with changes in SoO not resulting in changes in SoA. However, further behavioural and neurophysiological evidence is needed in order to understand this complex relationship.

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Figure captions

Figure 1. Experimental set-up (based on Wegner et al., 2004). The left picture shows what the participant sees in the mirror placed in front of her. The right picture shows the set up from the side, with the experimenter sitting behind the participant and putting her hand forward so that it appears where the participant's hand would normally be. The picture is taken from Cioffi et al. (2017)

*Figure 2. Results of RHI ownership questionnaire. Mean Ownership ratings reported by the participants following synchronous and asynchronous stimulations on the RHI. Participants reported significantly higher ownership after synchronous stimulation. Error bars represent standard deviation. * indicates a significant difference ($p < .05$).*

*Figure 3. Results of RHI proprioceptive drift. Mean proprioceptive drift shown by participants following synchronous and asynchronous stimulations on the RHI. Participants showed significantly greater drift towards the artificial hand after synchronous stimulation. Error bars represent standard deviation. * indicates a significant difference ($p < .05$).*

Figure 4. Results of vicarious agency task. Mean ratings for Anticipation, Agency and Ownership at the vicarious agency task for match and mismatch conditions. Mean ratings were obtained by averaging mean judgments for each condition following synchronous and asynchronous RH stimulations. Error bars represent standard deviation.

*Figure 5. Results of RHI stimulation on vicarious agency task. Mean difference ratings (match minus mismatch) reported in the vicarious agency task for Anticipation, Agency and Ownership following RHI synchronous and RHI asynchronous stimulation. Participants reported greater SoO over the hands in the vicarious agency task following synchronous compared to asynchronous stimulations. No difference was found in Anticipation and Agency ratings. Error bars represent standard deviation. * indicates a significant difference ($p < .05$).*