The Rubber Hand Illusion: Top-Down Attention Modulates Embodiment

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Keywords:	rubber hand illusion, top-down cognition, bottom-up processes, body-ownership, consciousness, selfhood

Abstract

The Rubber Hand Illusion (RHI) creates distortions of body ownership through multimodal integration of somatosensory and visual inputs. This illusion relies on bottom-up (automatic multisensory and perceptual integration) mechanisms. However, the relative contribution from top-down (controlled processes involving attentional regulation and intentionality) influences remains unclear. Following recent work highlighting the putative influence of higher-order cognition in the RHI, we aimed to further examine how changes in cognitive (working memory) load and task instructions—two conditions engaging top-down cognition—influence the experience of the RHI, as indexed by a number of psychometric dimensions. Relying on one of the gold standards for assessing this phenomenology within the RHI, our results confirm the influence of higher-order, top-down mental processes. Whereas task instruction strongly modulated embodiment of the rubber hand, cognitive load only altered the affective dimension of the RHI. Our findings highlight the importance of top-down processes in the RHI. This outcome paves the road to a more scientific understanding of embodiment, and heralds new ways to improve experimental control over the RHI.

Keywords: rubber hand illusion; top-down cognition; bottom-up processes; body-ownership; consciousness; selfhood

The Rubber Hand Illusion:

Top-Down Attention Modulates Embodiment

The current research investigates whether higher-order cognition exerts a top-down influence over the Rubber Hand Illusion (RHI), a perceptual distortion of body ownership (Botvinick & Cohen, 1998). In the RHI, participants' real hands are occluded from their view and replaced with a clearly visible fake rubber arm positioned such that it mimics their actual limb. The peculiar RHI phenomenon arises from stroking the visible fake hand and the occluded real hand simultaneously, which ultimately yields a strange feeling of ownership over the fake arm. This distortion of body representations therefore comes about from seeing the stroking of the fake hand occurring in synchrony with the tactile stimulations proceeding from the stroking of the real occluded hand. Note, however, that a diminished illusion can still arise without synchronous stroking or tactile stimulation (e.g., Samad et al., 2015). Consequently, early conjectures to explain this phenomenon argued that this phenomenon follows from bottom-up multimodal sensory integration of tactile, proprioceptive, and visual inputs (e.g., Armel & Ramachandran, 2003; Botvinick & Cohen, 1998). The experience of embodiment over the rubber hand, therefore, seems to emerge through inferential processes that combine somatosensory, proprioceptive, and visual inputs (Armel & Ramachandran, 2003; Botvinick & Cohen, 1998; Samad et al., 2015; Seth, 2013). However, findings underline some of the shortcomings of this view. Notably, ongoing research efforts highlight the influence top-down processes in the emergence of the RHI, thereby departing from a wholly bottom-up account (Dempsey-Jones & Kritikos, 2014; Kilteni et al., 2015). This contrasting perspective is reminiscent of other evidence that emphasizes the involvement of top-down suggestion in the context of other multimodal sensory integration phenomena, such as the McGurk effect (e.g., Déry et al., 2014; Lifshitz et al., 2013; McGurk & MacDonald, 1976). This debate over the role of top-down versus bottom-up factors in body-ownership echoes recent discussions about multisensory integration more generally (Hartcher-O'Brien et al., 2017).

Consistent with views that argue for the involvement of top-down processes, the current study explores the relative contribution of top-down factors in two different ways: (1) by varying the availability of cognitive resources through a straightforward working memory load manipulation; and (2) by providing different instructions to participants concerning their attention. A large body of work establishes the impact of cognitive load on working memory and voluntary attention, which ultimately alters how individuals engage certain tasks (e.g., Baddeley, 2000; Jonides, 1981). Accordingly, we propose to utilize this classic experimental strategy with the purpose of hindering top-down resources involved in working memory and voluntary attention while participants undergo the RHI. This manipulation therefore targets top-down resources pertaining to working memory and the ability to fully attend to the synchrony of visuotactile inputs. We reasoned that the inferential process yielding distortions of body representations might rest on these processes. Our rationale follows from recent findings highlighting the central role of top-down processes and inference procedures in multisensory integration (Cao et al., 2019). Likewise, we aimed to evaluate how instructions about the focus of attention could alter the integration of tactile, proprioceptive, and visual inputs. Thus, we hypothesized that prioritizing tactile/proprioceptive or visual stimulations may impair the inferential process by disrupting the balance between both inputs (Déry et al., 2014; Lifshitz et al., 2013). Together, these experimental manipulations probe how top-down cognition shapes the RHI.

Mechanisms of Body Ownership Illusions

In recent years, researchers have attempted to uncover the mechanisms underlying the emergence of body ownership illusions—a research program that largely focus on how these distortions may inform the phenomenology of selfhood (Kilteni et al., 2015; Tsakiris, 2010, 2017). Here, body ownership—that is, the feeling that our body is ours—is viewed as an intrinsic constituent of our conscious experience. Studying the RHI can therefore inform these views by emphasizing the breakdown of this phenomenological dimension. In the classic framework of the RHI, the synchronous presentation of tactile and visual sensory events leads a person to feel like a fake hand is their own (Botvinick & Cohen, 1998). Researchers originally suggested that the RHI relies on the intermodal matching of vision, proprioception, and touch, wherein the brain seemingly integrates these sensory inputs across temporal and spatial planes to generate a unified and coherent body representation (Armel & Ramachandran, 2003; Botvinick & Cohen, 1998; Ehrsson et al., 2004). Ultimately, the RHI procedure distorts our normal sense of ownership by fusing the rubber hand to these representations (Armel & Ramachandran, 2003). Beyond this primary account, further investigations have uncovered additional factors that contribute to the illusion (Tsakiris, 2010, 2017). Evidence shows that location in space, handedness, anatomy, posture, texture, incorporeability, affect, and individual differences such as awareness of internal body signals can modulate people's experience of the illusion to some extent (Dempsey-Jones & Kritikos, 2017, 2019; Kilteni et al., 2015; Tsakiris, 2017). Even though researchers have identified some basic principles related to the RHI, few studies have directly explored its cognitive and attentional aspects. The current experiment addresses a gap in the current literature, as the role of such higher order cognitive processes remains largely unknown. Our research aims to provide critical information regarding the role of higher cognition and attention in body ownership.

Cognitive Dimensions of Body Ownership Illusions

Our methodology was twofold. First, our approach aimed to impact the availability of cognitive resources using a working memory load manipulation. We reasoned that engaging working memory resources towards a secondary task may impair the processing of sensory inputs, wherein working memory capacities contribute to binding information together. We accordingly examine whether a secondary task would impair the RHI. Our second manipulation aimed to assess the centrality of visual processing, such that instructing participants to emphasize somatosensory inputs over visual ones would likely decrease the strength of the illusion. This strategy follows from the idea that multisensory integration likely involves a weighting procedure for fusing both sensory signals (Kayser & Shams, 2015). Accordingly, overweighting tactile/proprioceptive modalities over the visual one could change the emergence of the RHI. The current approach follows from research on the McGurk phenomenon—a perceptual illusion similarly based on multisensory integration (McGurk & MacDonald, 1976). Although the McGurk effect and the RHI differ in several respects, both phenomena seem to rest on the dominating influence of the visual system. Skewing this dominance via task instructions may therefore alter the phenomenon.

Are cognitive resources necessary for the RHI?

While cognitive resources play a central role in cognitive control, automatic processes generally operate successfully without them (Evans, 2008). In spite of recent progress in the field, however, the extent to which the RHI relies on automatic processes and cognitive resources remains vague. To answer questions about the involvement of cognitive resources in psychological phenomena, researchers commonly employ a cognitive load manipulation (e.g., Bodner & Stalinski, 2008), which purportedly taxes working memory resources. Here, evidence shows that cognitive load interferes with attention processes (de Fockert et al., 2001; Lavie, 2010; Lavie et al., 2004), multisensory integration (Andersson et al., 1998; Redfern et al., 2001), and proprioceptive ability (Goble et al., 2012). Note that these processes are likely involved in the RHI. Furthermore, research shows that working memory contributes to filtering certain sensory stimuli at an early processing stage of processing, as revealed by corresponding changes in precortical sensory responses (Sörqvist et al., 2012). Accordingly, some researchers propose that engaging working memory resources via a secondary task likely affects the ability of attention to act as a gatekeeper for early sensory inputs (Sörqvist et al., 2012). Hence, multisensory integration may require some form of interaction with working memory for binding sensory inputs and generating a unified percept (Quak et al., 2015). This viewpoint aligns with previous findings showing a strong relationship between perception and working memory (Soto et al., 2010). Following this construal, our experimental approach aimed to test whether cognitive load would interfere with sensory processing prior to multisensory integration, which in turn would hamper the emergence of the RHI.

Evidence of such effects of load also exists for other illusions based on multisensory integration. For example, attentional load weakens the McGurk effect, which indicates that cognitive resources are also necessary for this perceptual illusion (Alsius et al., 2014; Alsius et al., 2005; Alsius et al., 2007; Buchan & Munhall, 2011a, 2012). Interestingly, cognitive load can also have a reverse, strengthening effect, for example in the sound-induced flash illusion—a separate multisensory integration phenomenon where people perceive a single flash as two separate ones when two short sounds are simultaneously played (Michail & Keil, 2018). As such, although cognitive load affects multisensory integration illusions, the direction of the effect appears contingent on the type of illusion. Nevertheless, if multisensory integration rests on top-down factors such as attention and working memory, cognitive load should weaken the RHI (similarly to what we observe in the McGurk effect).

Can instructions affect the RHI?

An emerging literature highlights the top-down influences of instructions on cognition, behaviour, and physical states (cf. Brass & de Houwer, 2017). In particular, this body of research demonstrates that several factors, including task instructions, may influence and distort perception. For example, attentional instructions can influence the dynamics of perception in the context of binocular rivalry and ambiguous figures (Liebert & Burk, 1985; Paffen & Alais, 2011; Toppino, 2003). In the case of multisensory integration, one sensory modality can dominate the others and yield cross-model biases (Cao et al., 2019). In the RHI, the sense of sight predominates over the sense of proprioception and affects body ownership (Botvinick & Cohen, 1998). The assumption that researchers can alter this preferential treatment is therefore central to the current work.

There is considerable evidence that attention does play a substantial role in multisensory integration (Fernández et al., 2015; Koelewijn et al., 2010; Mozolic, Hugenschmidt, et al., 2008; Mozolic, Joyner, et al., 2008; Senkowski et al., 2005; Talsma et al., 2007; Talsma et al., 2010; Talsma & Woldorff, 2005). Hence, attending to a specific modality may tune down the processing of other modalities, whereby unattended sensory channels and their corresponding neural signal hardly influence the emergence of percept (Knudsen, 2007; Laurienti et al., 2002; Mozolic, Hugenschmidt, et al., 2008; Mozolic, Joyner, et al., 2008). Consistent with these findings, previous work alludes to the direct role of attentional factors in the RHI (Tsakiris, 2017). For instance, individuals showing higher interoceptive sensitivity—a predisposition to attend to, perceive, and report internal bodily signals such as heartbeats accurately—typically experience a weaker RHI (Schauder et al., 2015; Tsakiris et al., 2011). In the present work, rather than operationalizing interoception as a trait, we attempt to experimentally manipulate it via explicit instructions. We instructed participants to focus their attention on internal body signals (i.e., toward tactile and proprioceptive sensations) or on external visual information (i.e., the sight of the rubber hand; "exteroception"). Given that interoceptive and exteroceptive cues appear antagonistic (Tsakiris, 2017), this experimental procedure should modulate the illusion such that participants will report a stronger illusion with somatosensory versus visual instructions.

As a case in point, providing instructions to attend to different sensory information suffice to interfere with the otherwise automatic sensory predominance of vision during the McGurk effect (Buchan & Munhall, 2011b). Thus, participants experience a stronger McGurk illusion when receiving instructions to attend to visual information rather than to auditory information. This research suggests that this effect emerge due to the selective attention to one sensory modality over the others. Other findings show that the suggestion to prioritize auditory input leads to a weaker McGurk illusion in highly hypnotizable individuals (Déry et al., 2014; Lifshitz et al., 2013). Similarly, attentional instructions modulate the multisensory perception of emotions: when a voice expresses an emotion that differs from an accompanying face, selectively attending to either modality changes which one tends to dominate (Takagi et al., 2015). In contrast to these previous findings, however, deliberate and automatic attention hardly affect the ventriloquist illusion—another multisensory illusion where sound appears to arise from the moving lips of a puppet rather than from the actual source of the sound (Bertelson et al., 2000; Vroomen et al., 2001). Nonetheless, as both the McGurk effect and the RHI share an analogous pattern of dominance of visual processing, we aimed to replicate these findings in the RHI. Consequently, we expected that instructions to attend to the visual stimulation of the fake hand would produce a stronger RHI than instructions to attend to the felt somatosensory stimulation (by prioritizing the exteroceptive versus interoceptive system).

Hypotheses

Two hypotheses guided our research: first, with respect to exposing the influence of cognitive factors in the RHI, we posited that a cognitive load would decrease the magnitude of the effects of the illusion; second, because prevalent views on perception emphasize the centrality of visual processing, we also submitted that the magnitude of the effect will be greater when subjects attend to the visual signal.

Factor Analysis

In the current study, we first carry out a factor analysis rather than using the pre-established dimensions of body-ownership identified by Longo et al. (2008). Several reasons motivate this approach. First, independent researchers have yet to validate the questionnaire of Longo et al. (2008), providing an opportunity to corroborate the proposed structure of body-ownership in a different sample. Second, there were known limitations to the Longo et al. (2008) methodology (cf. Fabrigar et al., 1999). For instance, Longo et al. (2008) used Principal Component Analysis, while it would have been more appropriate to use Exploratory Factor Analysis due to the implicit goal of generalizing the findings to the population level rather than restraining the interpretation to the sample level (Fabrigar et al., 1999; Field et al., 2012). Similarly, given the intercorrelation between the factors, the factor rotation should have been oblique, as opposed to orthogonal (Fabrigar et al., 1999; Field et al., 2012). Therefore, carrying out our own factor analyses improves the validity of the psychometric dimensions used in this study and provides stronger theoretical value. Furthermore, this approach yields factor scores that are relevant to our experimental conditions, instead of using dimensions developed within a different context. Lastly, we include additional items used in more recent RHI studies that are not part of the questionnaire developed by Longo et al. (2008), making it that much more critical to conduct new factor analyses and therefore validate the relevant constructs.

Methodology

Participants

We recruited 38 undergraduate students through the Psychology participant pool system at BLINDED University (convenience sample); data collection stopped at the end of the semester. Each participant gave informed consent and received two credits for their participation. We excluded five participants due to requests from participants to stop the experiment, excessive knowledge about the goals of the experiment, or experimenter error. For purposes of analysis, we kept data from 33 participants. We provide the factor score data and analyses on the Open Science Framework (https://osf.io/qc2hm/). The BLINDED Ethics Board approved this study (REB File #: BLINDED).

Materials

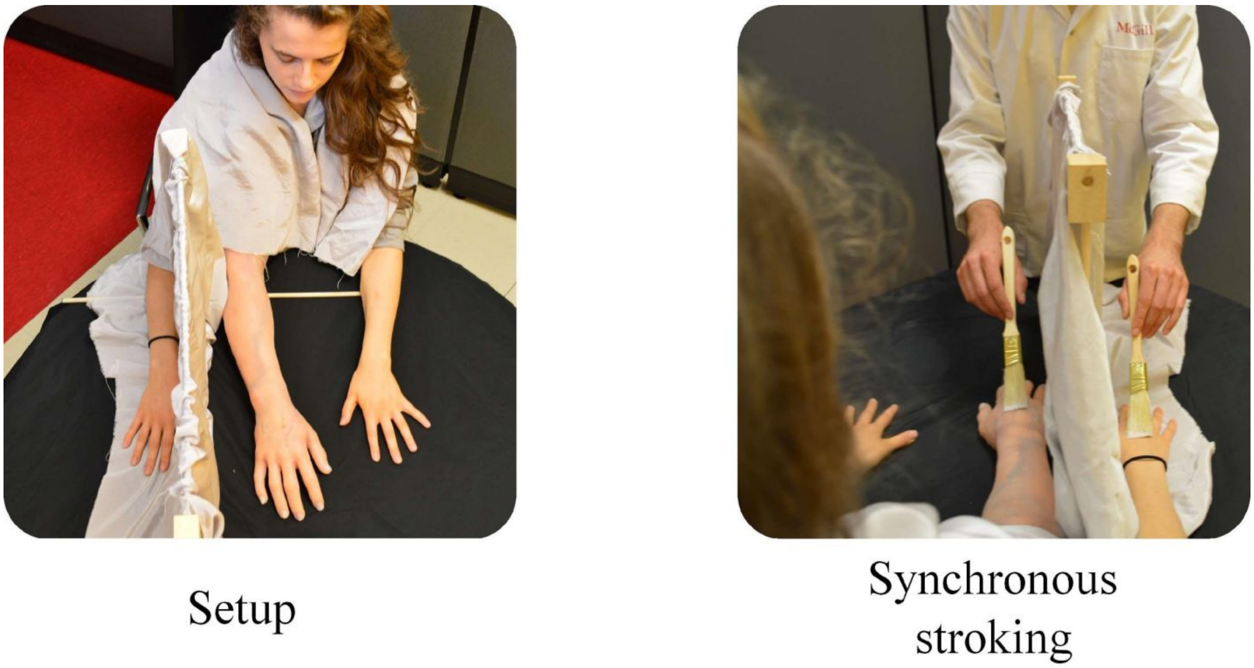
The fake hand consists of a realistic silicon anatomical prosthesis including the right hand, forearm, arm, and shoulder (produced by Milsuite FX Inc.). A self-made separator wrapped with a silver-pink cloth occluded the real right hand of participants from their view. Participants 1 to 15 indicated their responses to a questionnaire on an eight-item visual analogue ranging from 0 (“I do not agree at all”) to 7 (“I agree completely”) following statements such as, “I felt as if the hand I saw was my hand.” Participants 16 to 38 indicated their responses on the computer by typing a number from 0 to 7 in a similar fashion, but without a visual analogue. In brief, the questionnaire assesses changes in phenomenological experience as a function of our experimental conditions. To design it, we adapted 35 questions from other researchers adopting the RHI methodology (Farmer et al., 2012; Gonzalez-Franco et al., 2014; Guterstam et al., 2011; Longo et al., 2008; Rohde et al., 2011; Tsakiris et al., 2011).

Procedure

The experimenter explained the general goals of the study to participants, who then signed a consent form before the experiment began. We noted down the age, sex, skin color, and handedness of each participant, after which participants entered the testing room. Participants then sat on a chair in front of a table supporting the experimental apparatus and we positioned their right arm on the table on the right of an occluding partition so that their hand and arm were out of sight. They similarly positioned their left hand on the table, but in a clearly visible fashion in their left field of view. We then placed a fake silicon arm on the left of the occluder so that the shoulder section of the fake arm leaned against the frontal part of the right shoulder of participants. The angle of the fake arm differed from the natural position of the real arm by about five centimeters—the width of the partition. We then put a sheet to cover their shoulders to visually mask the distinction between their real arm and the fake arm. After giving proper instructions about the procedure, we synchronously stimulated both the real and fake arms with small paintbrushes for approximately two minutes to induce the illusion (Figure 1).

Figure 1

Rubber Hand Illusion Setup



Note. Left: experimental setup with fake silicon arm between the two real hands and the occluder. Right: participant view during synchronous stroking.

Participants underwent the illusion across four counter-balanced experimental conditions: (a) Cognitive Load and Attend Visual Signal; (b) No Load and Attend Visual Signal; (c) Cognitive Load and Attend Tactile Sensation; and (d) No Load and Attend Tactile Sensation. During cognitive load, we exposed participants to a string of characters composed of six random digits and letters (e.g., A7D3X2) that appeared for approximately one second on a computer screen. They had to remember this character string until after the stimulation was over, after which they had to spell out the character string they had received (i.e., about 2 min). In the no load condition, participants merely had to remember a string of characters composed of the same random number or letter (e.g., EEEEEE). Regarding the attended sensory signal condition, we instructed participants to attend to their visual perception of the stroking of the hand in front of them in the visual signal condition: "*Please attend to the sight of the hand in front of you while it* *is being stroke until further instructions. Please do not attend to your real hand or to its tactile sensations. Attend to the hand you see.*" In the tactile signal condition, we instructed participants to focus on the tactile sensation of the paintbrush touching their real hand while keeping their gaze focused on the fake hand: "*Please attend to the tactile sensation of your real hand while it is being stroke until further instructions. Continue to gaze at the fake hand but do not focus on it. Attend to the sense of touch on your real hand.*"

After the stimulation, participants filled out a self-administered questionnaire concerning their experience for each of the four conditions, so that each participant filled out four questionnaires in total. This questionnaire assessed various dimensions relating to the phenomenology associated with the RHI. At the end, we debriefed each participant. In total, the experiment took approximately 45 minutes.

Factor Analysis

We initially followed the same analytical procedure as Longo et al. (2008) in an attempt to replicate their psychometric findings: a Principal Component Analysis (PCA) with orthogonal varimax rotation[1]. Pooling data from repeated measures can be "'akin' to having twice as many subjects" and so "should improve the identification of factors" (Schopflocher & Ulrich, 2005). Accordingly, given our small sample size to perform this analysis for each of our four conditions, we pooled participant data from the four conditions, "as-if" each condition represented a different participant, which provided a total of 132 observations. Monte Carlo simulations suggest that when items communalities are rather high (.60 or higher), samples containing as few as 60-100 observations are considered adequate, whereas when communalities

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[1] Here, we note that an oblique rotation should be used instead given the expected inter-factor correlations (Field et al., 2012).

are lower (around .50), adequate samples will contain 100-200 observations (de Winter et al., 2009; Fabrigar et al., 1999; MacCallum et al., 2001; MacCallum et al., 1999; Mundfrom et al., 2005; Russell, 2002). These predictions hold when the ratio of items to factors is medium to high (3.3-6.7), though the higher the ratio the better. Given our 35-item average communalities of .60 and our high item:factor ratio of 8.75, 132 observations make for an adequate sample size.

Our PCA results for the most part replicated those of Longo et al. (2008), we thus followed up with a Confirmatory Factor Analysis (CFA) to validate the latent structure of the questionnaire developed by Longo et al. (2008). We hypothesized a four-factor structure based on the PCA findings from Longo et al. (2008) and excluded items that loaded less than .5 or that were not included in the original analysis. Overall, this CFA included 21 of the questions from Longo et al. (2008) and assumed four factors based on their four-factor model (for synchronous stroking only): (a) embodiment of rubber hand, (b) loss of own hand, (c) movement, and (d) affect. We specified the model as follows: (a) embodiment → items 1-8, 15-16; (b) loss of hand → items 14, 19, 28-30; (c) movement → items 12, 17, 34; and (d) affect → items 20-22 (average communalities of these 21 items = .68; item:factor ratio = 5.25).

Since the various indices indicated that the model fitted the data poorly (but see van Prooijen & van der Kloot, 2001, for a discussion on the relationship between CFA fit and factor structures obtained through factor analysis), we opted to follow up with an Exploratory Factor Analysis (EFA) to clarify the structure underlying this specific data set. We performed EFA using the Minimal Residual method to extract the factors as well as an oblique (i.e., "oblimin") rotation due to the intercorrelation between our factors. Again, we pooled the conditions to yield 132 observations. We obtained the weighted standardized factor scores using Bartlett's method (as suggested by DiStefano et al., 2009, for oblique rotation). These analyses were done in R version 3.4.2.

Experimental Analyses

Using the weighted standardized factor scores obtained from the EFA, we relied on hierarchical linear regression models to determine whether the four factors identified by the EFA—that is, *embodiment of rubber hand*, *loss of own hand*, *feeling of having two right hands*, and *affect*—varied as a function of instructions and cognitive load (Gelman & Hill, 2006). Within this framework, the *embodiment* component refers to feelings of ownership and control over the fake hand; the *loss of own hand* component indexes loss of control and feelings of numbness over the real hand; the *feeling of having two right hands* component corresponds to the impression of feeling both the rubber hand and the real hand simultaneously; and finally, the *affective* dimension follows from questions pertaining to the pleasantness of the experience. Here, instructions (i.e., visual versus tactile) and cognitive load (i.e., no load versus load) were included in a stepwise fashion as fixed factors, while participants were included as random factors. We selected the best fitting model based on likelihood-ratio chi-squared test and the Bayes Information Criterion (BIC). Moreover, we relied on Bayes Factors to evaluate how evidence weights in favor of the null hypothesis versus the alternative one (Wagenmakers, 2007). We estimated Bayes Factors via the BIC through the following equation: $BF_{01} = e^{\Delta BIC_{10}/2}$. We fitted the hierarchical linear regression models using the MATLAB (MathWorks inc., version R2020a) fitglme function.

Results

Principal Component Analysis

Ten of the 27 items used by Longo et al. (2008) did not load on the same factor in our PCA results (our items no 14, 17, 19, 21, 23, 24-26, 32, 34; Longo's items 11, 14, 15, 17, 18, 21, 23-25, 26). See Table S1 for complete loadings and comparison with Longo et al. (2008).

Confirmatory Factor Analysis

The data did not meet the assumption of multivariate normality for CFA (i.e., the variables were not normally distributed). We accordingly used a robust maximum likelihood estimator with Huber-White standard errors and a scaled test statistic (asymptotically equal to the Yuan-Bentler test statistic) using the *lavaan* package (Rosseel, 2012). The results of the confirmatory factor analysis are available in Table 1. Overall, none of the indices meet the commonly accepted minimum criteria and revealed poor fit of the data (Schreiber et al., 2006).

Table 1

Confirmatory Factor Analysis Results

	χ^2	*df*	χ^2/df	*p*	CFI	TLI	RMSEA	SRMR
Reference Value[1]	**Ratio of χ^2 to *df* < 2 or 3**			**> .05**	**≥ .95**	**≥ .95**	**< .06 to .08**	**≤ .08**
Current study [a]	600.08	183	3.28	< .001	.79	.76	.13	.11

[1]As proposed by Schreiber et al. (2006).

[a] Excludes items not used by Longo et al. (2008) as well as those that loaded less than .5 in their study. Includes 21 of the questions from Longo et al. (2008) and four factors based on their four-factor model (for synchronous stroking): (a) embodiment of rubber hand, (b) loss of own hand, (c) movement, and (d) affect.

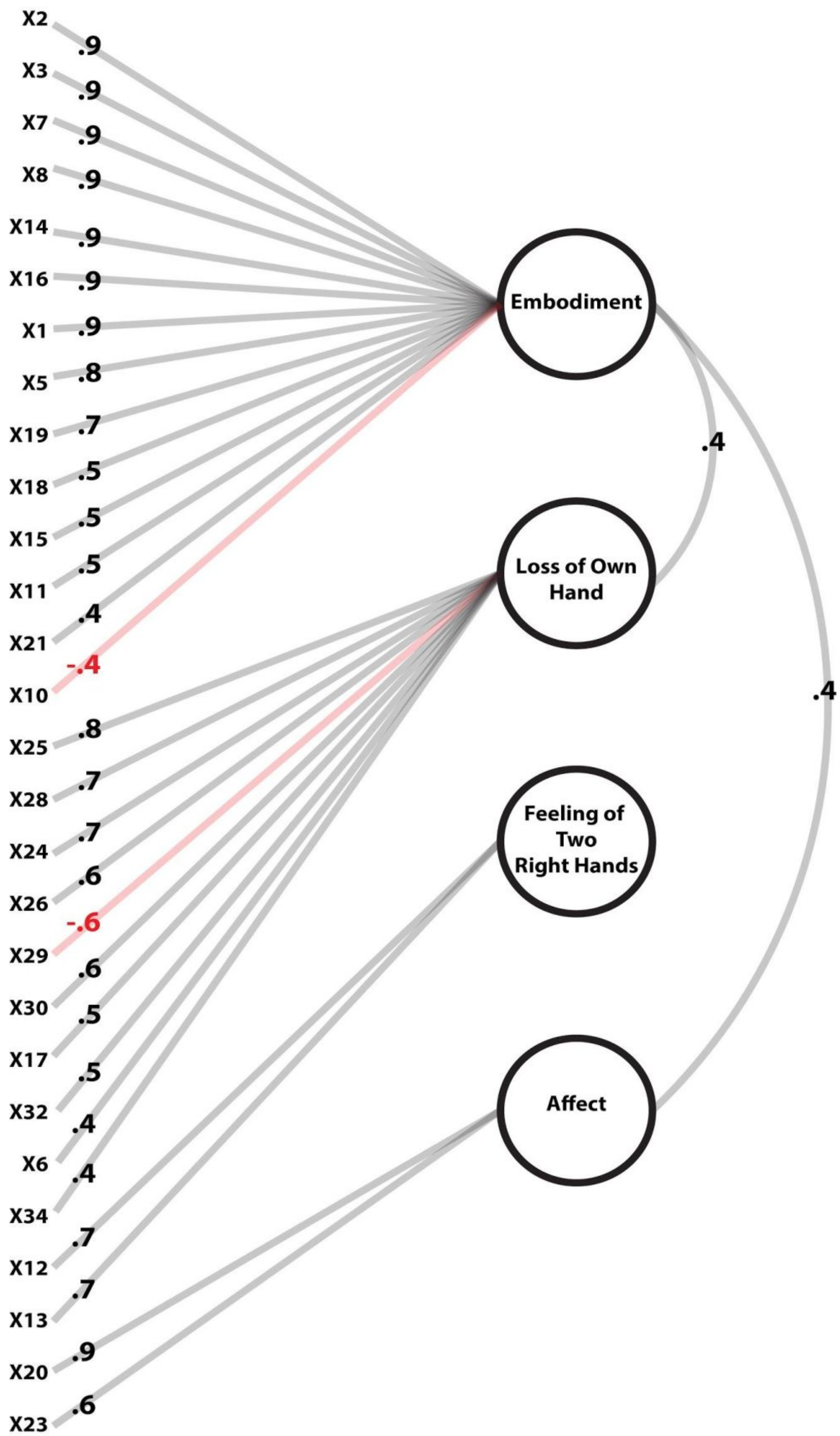
Exploratory Factor Analysis

Following the poor fit of the CFA, we opted for an EFA. We verified the sampling adequacy of the individual items with the Kaiser–Meyer–Olkin (KMO) measure. We removed three items with KMO values smaller than .7 (considered mediocre by Kaiser, 1974): items 22, 27, and 35. All other values were greater or equal to .7. We also removed an additional three items with fewer than five correlations greater than .3 (items 9, 31, and 33). To obtain a determinant of the correlation matrix greater than 1e-5 (a common rule of thumb, Field et al., 2012), we would have needed to drop an additional 13 items with correlations greater than .7 (items no 1, 2, 3, 4, 5, 6, 7, 8, 14, 16, 18, 19, and 30). Since we deemed this solution impracticable (this represents close to 50% of our questions), we decided to simply drop one extra item: question 4, since it had almost identical wording to item 2 and correlated with it at .9 (indicating the question may have been redundant). Overall, this resulted in the exclusion of seven items (4, 9, 22, 27, 31, 33, and 35), leaving us with 28 items (average communalities of these 28 items = .65; item:factor ratio = 7). This procedure leaves us with a suboptimal correlation matrix determinant of 6.87e-12, although the overall KMO measure of sampling adequacy was a hair over .9 ("marvelous", according to Kaiser, 1974). This solution entails that the high multicollinearity of the data set represents a limitation of the current factor analysis. Bartlett's test of sphericity, x^2 (378) = 3,105.945, $p < .001$, confirmed the inter-item correlations were large enough for the analysis. Five components had eigenvalues over Kaiser's criterion of 1 and together explained 70.92% of the variance, although the point of inflexion on a scree plot justified keeping three components that explained 62.37% of the variance. We decided to retain four components explaining 66.70% of the variance in light of both Kaiser's criterion and the scree plot, as well as of previous findings by Longo et al. (2008).

A four-factor solution revealed that although residuals distributed normally, more than 50% of residuals (85.71%) were larger than .05, and that the root-mean-square residual (.21) was over .08, putting these values above the commonly accepted limits. Field et al. (2012) suggests that such results encourage extracting more factors; however, extracting more factors only worsened both issues, and extracting fewer factors did little to help reach the acceptable values. These values may be due to our low sample size. Figure 2 graphically displays the model. This EFA model provided a much better BIC fit (-691.09) than the CFA model (10,351.36). Yet the EFA scale overall had poor internal consistency (Cronbach's alpha = .47 [.32, .62]).

Figure 2

Exploratory Factor Analysis



Note. Numbers on the left represent item numbers; numbers on the lines represent item loadings on their primary factor or intercorrelation between factors. The red lines represent negative loadings.

See Table S2 for the table of loadings/pattern matrix (and Table S3 for the equivalent without excluded items, for those interested in where those would have loaded), Table S4 for the table of correlations, and Table S5 for the structure matrix. The table of loadings suggests the four components represent (a) Embodiment of rubber hand (Table 2), (b), Loss of own hand (Table 3), (c) Feeling of having two right hands (Table 4), and (d) Affect (Table 5).

Table 2

Factor 1: Embodiment of rubber hand

Item	Question	Theoretical Dimension	Loading
1	I felt the touch of the brush on the hand I saw.	Ownership[a]	0.853
2	I felt as if the hand I saw was my hand.	Ownership[b]	0.931
3	It seemed like the hand I saw was part of my body.	Embodiment of rubber hand[c] (Ownership[d])	0.907
5	It seemed like the hand I saw belonged to me.	Embodiment of rubber hand[c] (Ownership[d])	0.821
7	It seemed like I could have moved the hand I saw if I had wanted.	Loss of own hand[c]	0.893
8	It seemed like I was in control of the hand I saw.	Embodiment of rubber hand[c]	0.877
11	It no longer felt like my (real) hand belonged to my body.	Disownership of the real hand[a]	0.509
14	It seemed like the touch I felt was caused by the brush touching the hand I saw.	Embodiment of rubber hand[c]	0.857

15	It seemed like the hand I saw was in the location where my hand was.	Embodiment of rubber hand[c] (Location[d])	0.523
16	It seemed like my hand was in the location where the hand I saw was.	Embodiment of rubber hand[c] (Location[d])	0.855
18	It seemed like I couldn't really tell where my (real) hand was.	Loss of own hand[c]	0.546
19	It seemed like my (real) hand had disappeared.	Loss of own hand[c]	0.568

Note. Adapted from: [a]Guterstam et al. (2011), [b]Gonzalez-Franco et al. (2014), [c]Longo et al. (2008), and [d]Tsakiris et al. (2011).

As we can see, the "Embodiment of rubber hand" factor came back up again, encompassing most items from previous studies, except that 1) according to the PCA by Longo et al. (2008), items 7, 18 and 19 should have loaded on the "Loss of own hand" factor, and item 11 should have loaded on "Loss of own hand" as well according to theorization by Guterstam et al. (2011).

Table 3

Factor 2: Loss of own hand

Item	Question	Theoretical Dimension	Loading
17	I felt as if my (real) hand were drifting towards the left (towards the fake hand).	Movement[c,e]	0.528
24	I had the sensation of pins and needles in my hand.	Deafference[c] (only with asynchronous condition)	0.701

25	I had the sensation that my hand was numb.	Deafference[c] (only with asynchronous condition)	0.784
26	It seemed like the experience of my hands was less vivid than normal.	Deafference[c] (only with asynchronous condition)	0.635
28	It seemed like I was unable to move my hand.	Loss of own hand[c]	0.710
29	It seemed like I could have moved my hand if I had wanted.	Loss of own hand[c]	-0.633
30	It seemed like my hand was out of my control.	Embodiment of rubber hand[c]	0.613

Note. Adapted from: [e]Rohde et al. (2011) and [c]Longo et al. (2008).

"Loss of own hand" came back as well, including many items from previous studies, except that according to the PCA by Longo et al. (2008), item 30 should have loaded on the "Embodiment" factor, item 17 should have loaded on the "Movement" factor, and items 24, 25, and 26 should not have loaded anywhere (as in their study it only loaded on a "Deafference" component that only emerged in asynchronous stroking conditions).

Table 4

Factor 3: Feeling of having two right hands

Item	Question	Theoretical Dimension	Loading
12	It felt as if I had two right hands.	Feeling of having two right hands[a]	0.673

13	I felt the touch of the brush on both hands at the same time.	Feeling of having two right hands[a]	0.667

Note. Adapted from: [a]Guterstam et al. (2011).

The structure emerging from this factor does not seem to reflect the third factor identified by Longo et al. (2008), “Movement”. In fact, these two questions were not used by Longo, but according to Guterstam et al. (2011), items 12 and 13 should belong to a dimension they coined “Feeling of having two right hands”. It seems like this dimension replaced the “Movement” dimension. Only three items previously loaded on the “Movement” dimension (items 12, 17, and 34). It seems that item 17 now load on the “Loss of own hand” dimension, associating the drift to losing own’s hand. Note that we did not include the question: “… it seemed like I had three hands”, which previously loaded on “Movement”, since we thought it was similar enough to our item 12 (feeling like having two right hands). Furthermore, item 34 previously loaded on “Movement” as well, whereas now it did not load anywhere, perhaps because we used the modified wording by Guterstam et al. (2011), which added the specification that the rubber hand was “visually” drifting towards the real hand.

Table 5

Factor 4: Affect

Item	Question	Theoretical Dimension	Loading
20	I found the experience enjoyable.	Affect[c]	0.857
23	I found myself liking the hand I saw.	No loading[c]	0.567

Note. Adapted from: [c]Longo et al. (2008).

Although we had to remove item 22, the "Affect" factor came up again, with the difference that item 23 had previously not loaded on any factor in the PCA by Longo et al. (2008).

Table 6

Items with no loadings greater or equal to .5

Item	Question	Theoretical Category
6	It seemed like the hand I saw began to resemble my real hand.	Embodiment of rubber hand[c] (Ownership[d])
10	I felt the touch of the brush on my (real) hand.	Disownership of the real hand[a]
21	I found the experience interesting.	Affect[c]
32	It felt as if my (real) hand were turning 'rubbery'.	Control statement[a,c,e]
34	It appeared (visually) as if the fake hand was drifting to the right (towards my real hand).	Control statement[a,e], Movement[c]

Note. Adapted from: [a]Guterstam, Petkova, and Ehrsson (2011), [c]Longo, Schüür, Kammers, Tsakiris, and Haggard (2008), [d]Tsakiris, Tajadura-Jiménez, and Costantini (2011), and [e]Rohde, Di Luca, and Ernst (2011).

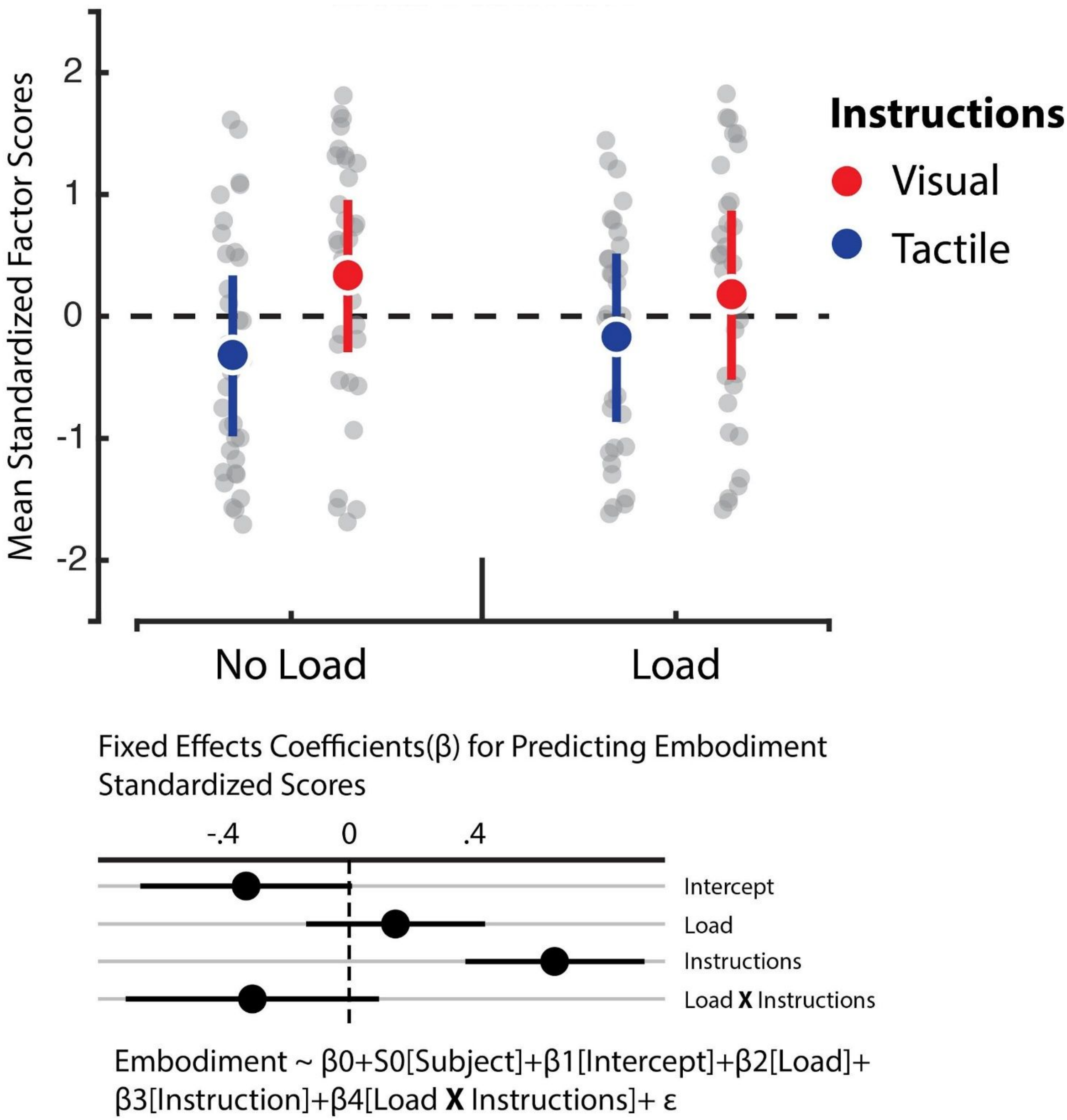
Here, according to the PCA by Longo et al. (2008), item 6 should have loaded on the "Embodiment" factor. Item 10 may have been expected to load on "Loss of own hand" in light of the theorization by Guterstam et al. (2011). In the study by Longo et al. (2008), item 21 loaded on the Affect dimension. Item 34 may have also been expected to load on the "Movement" factor according to them; however, we used a modified wording version (Guterstam et al., 2011; Rohde et al., 2011) that was classified as a control statement (perhaps because of the emphasis on a "visual" drift).

Experimental Condition

We relied on hierarchical linear regression models to determine whether the instructions and load manipulations influenced feelings of embodiment, increased feelings of having two right hands, affective components of the RHI, and reduced feelings of one's own hand (see Figures 3, 4, 5, and 6). The best fitting model for predicting feelings of embodiment revealed that instructions were a statistically reliable predictor ($\beta = .5$, SE = .1, 95% CI [.29, .7]; see Tables S6 and S7). This outcome indicates how the difference between tactile and visual instructions on feelings of embodiment of the rubber hand was greater during the no load condition compared to the load one. Hence, the load manipulation hindered the effect of instruction. In turn, however, the regression models revealed no influence of instructions and load on the feeling of having two right hands and loss of feeling towards one's own hand. In both cases, the data was best fitted by the baseline model which solely comprised the intercept (see Tables S8 and S9). Bayes factor confirmed this assessment. Evidence largely supported the null model for the feeling of having two right hands against the load ($BF_{01} = 9.9$) and instruction ($BF_{01} = 10.02$) manipulations. Likewise, evidence also supported the null model for losing feeling in one's own hand with respect to the load manipulation ($BF_{01} = 11.13$); though evidence was ambiguous regarding the instruction manipulation ($BF_{01} = 2.11$). Lastly, we observed that the best fitting model for predicting the affective component solely included load as a reliable predictor ($\beta = -.17$, SE = .09, 95% CI [-.35, -.009]; see Tables S10 and S11). This outcome shows that cognitive load reduces this dimension of the RHI.

Figure 3

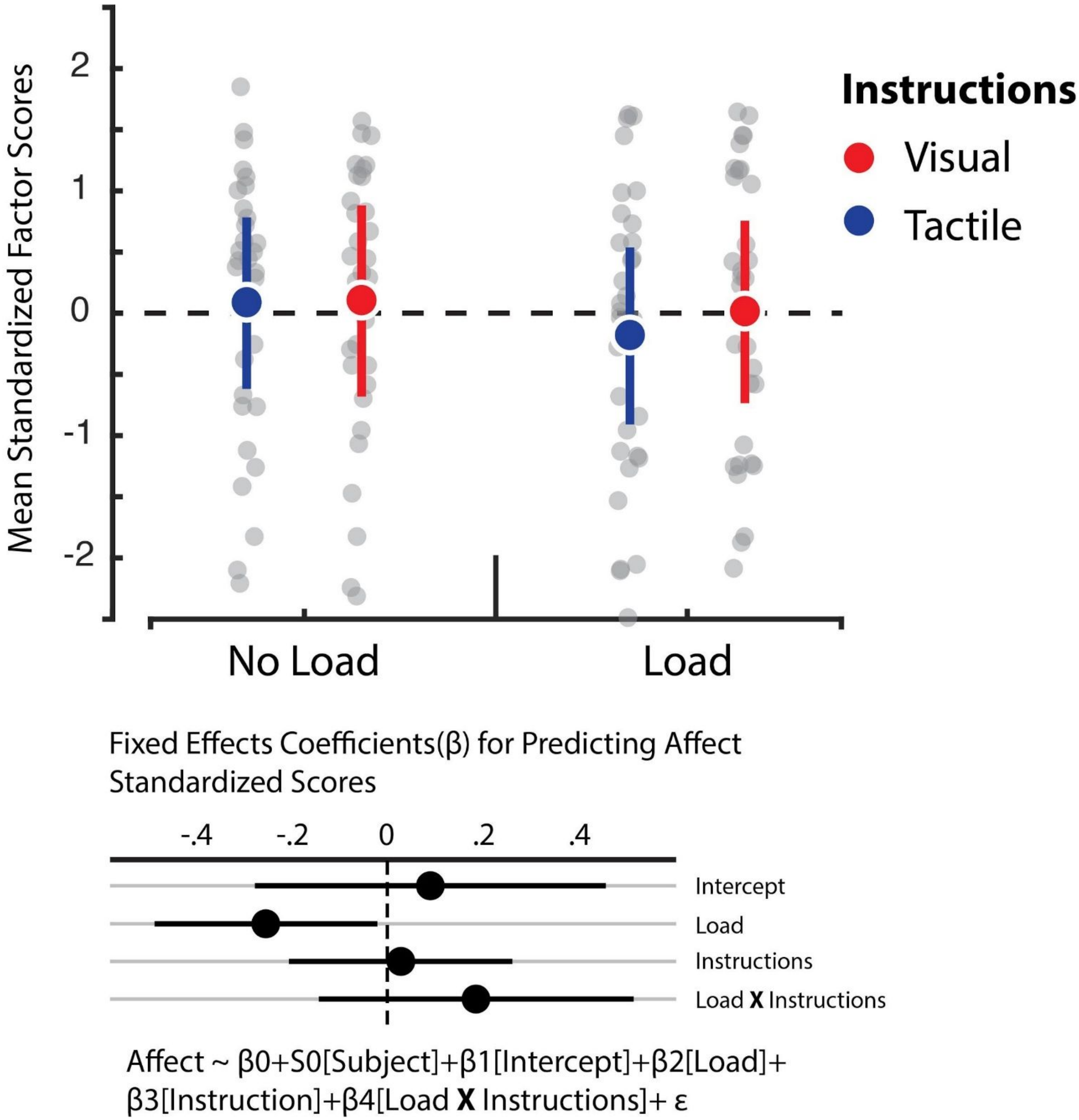
Embodiment Factor



Note. Averaged standardized factor scores for the “Embodiment of rubber hand” dimension (*y-axis*). In the original scale, participants could choose between 0 (“I do not agree at all) to 7 (I agree completely). Regression analyses revealed that *Instructions* were a statistically reliable predictor of embodiment, ($\beta = .5$, $SE = .1$, 95% CI [.29, .7]. Error bars represent 95% bootstrapped confidence intervals.

Figure 4

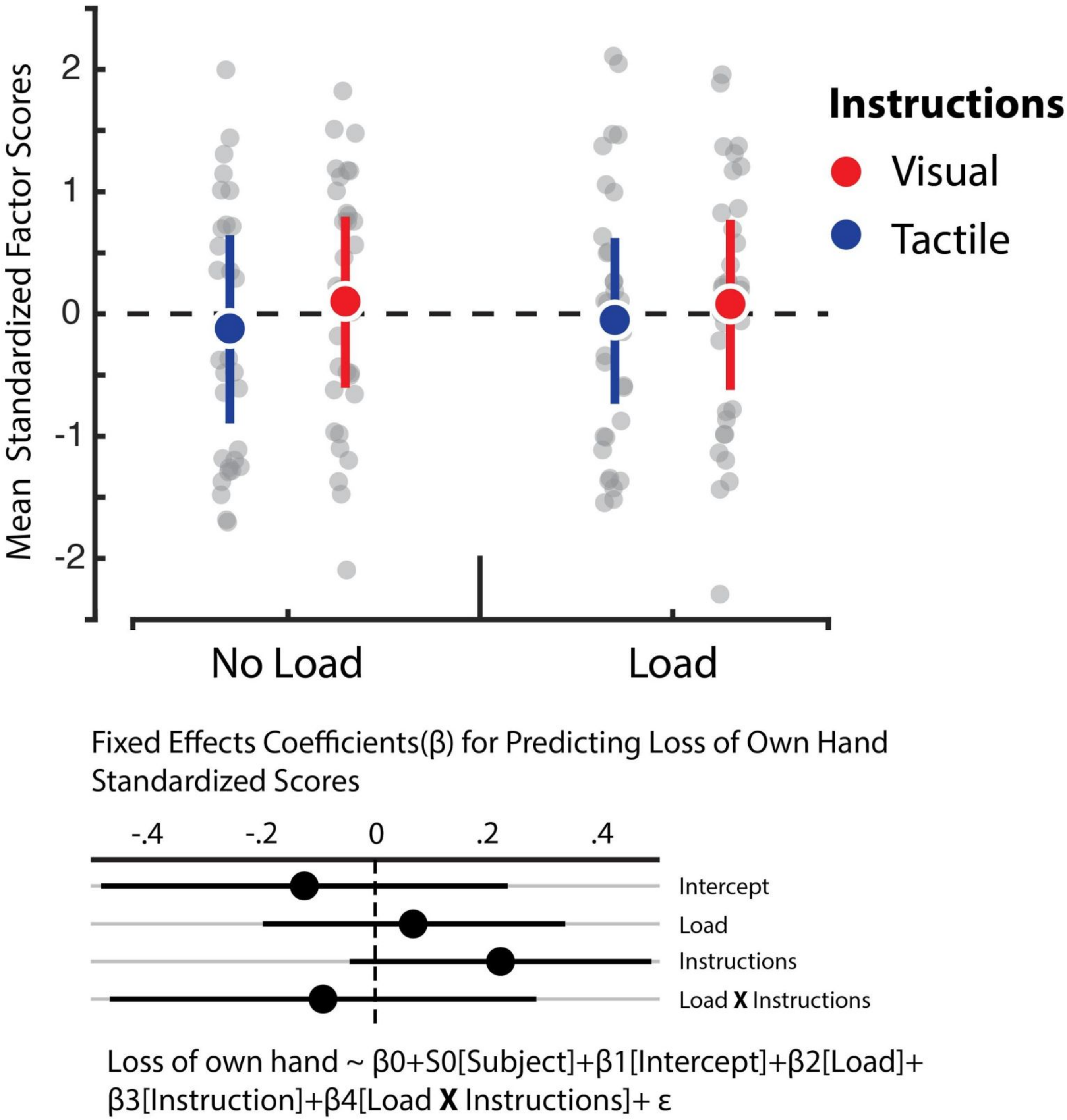
Affect Factor



Note. Averaged standardized factor scores for the "Affect" dimension (*y-axis*). In the original scale, participants could choose between 0 ("I do not agree at all) to 7 (I agree completely). Regression analyses revealed that *Load* was a statistically reliable predictor of affect, ($\beta = -.17$, $SE = .09$, 95% CI [-.35, -.009]). Error bars represent 95% bootstrapped confidence intervals.

Figure 5

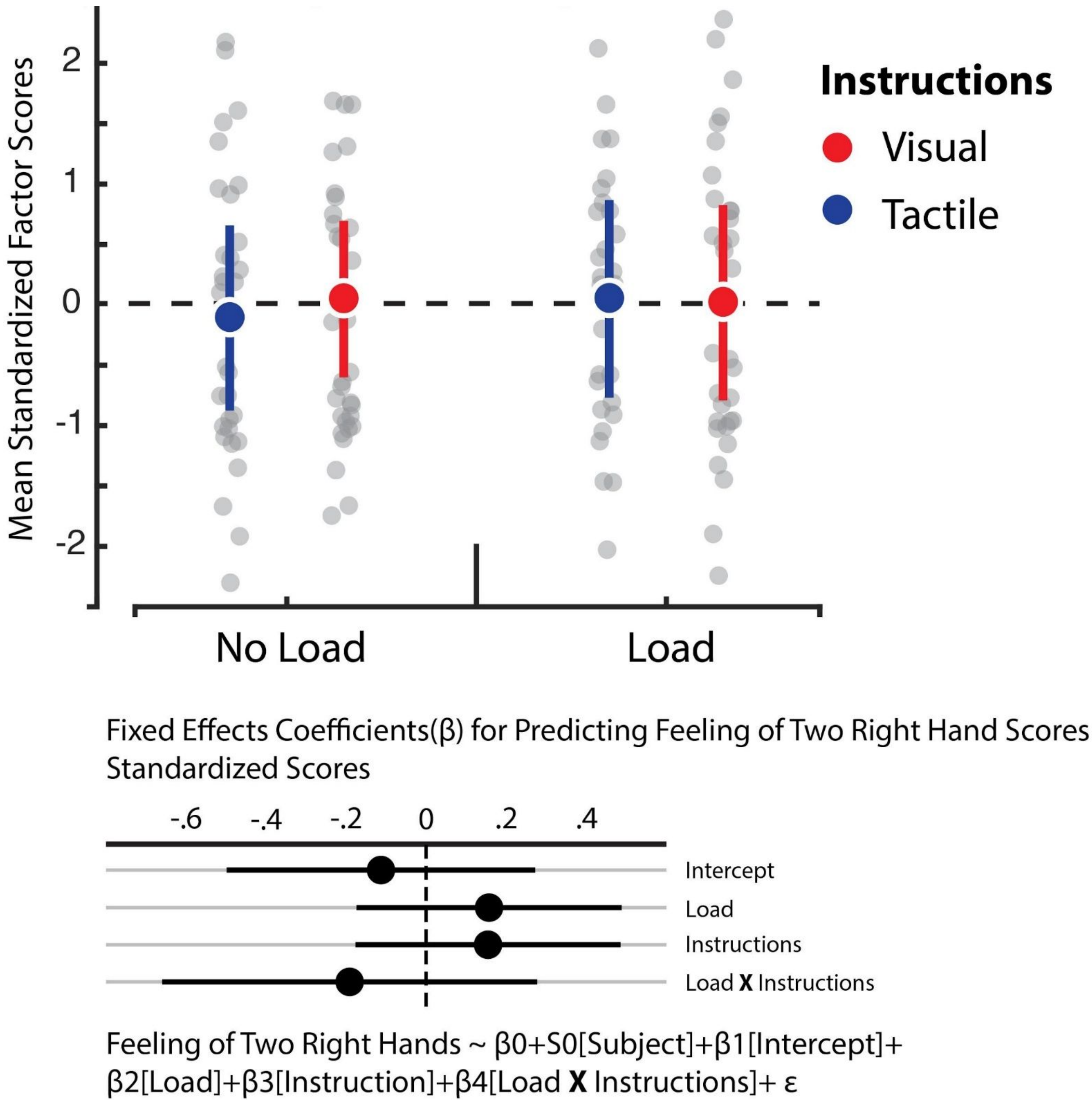
Loss of One's Own Hand Factor



Note. Averaged standardized factor scores for the "Loss of own hand" dimension (*y-axis*). In the original scale, participants could choose between 0 ("I do not agree at all) to 7 (I agree completely). There were no significant effects. Error bars represent 95% bootstrapped confidence intervals.

Figure 6

Feeling of Having Two Right Hands Factor



Note. Averaged standardized factor scores for the "Feeling of having two right hands" dimension (*y-axis*). In the original scale, participants could choose between 0 ("I do not agree at all) to 7 (I agree completely). There were no significant effects. Error bars represent 95% bootstrapped confidence intervals.

Discussion

The present study aimed to explore the influence of top-down components, such as attention and working memory, on the RHI. To this end, we investigated whether the illusion is vulnerable to the availability of working memory resources by manipulating a cognitive load, and by varying task instructions with regards to the attended sensory event. Our approach aligned with previous work in this field, as we relied and built on a questionnaire developed for investigating the phenomenology of this body illusion (Longo et al., 2008). Using a factorial approach, we predicted that reducing the availability of cognitive resources and instructing participants to attend to somatosensory sensations would lessen the magnitude of the RHI. Our results partly support these predictions as task instructions influenced the central RHI dimension of embodiment. Here, we observe that visual instructions correspond to stronger feelings of embodiment over the fake hand relative to instructions that emphasize tactile/proprioceptive inputs. In this fashion, our results demonstrate how top-down processes such as attention shape body representations by weighting inputs differently. Furthermore, our findings also indicate that cognitive load reduces the pleasantness of the experience—an unexpected outcome that potentially highlights the influence of working memory over the interpretation of the RHI phenomenology. Indeed, limited working resources during the RHI may reduce one's ability to assess their own experience. The experimental design failed to impact other dimensions, namely, feelings of having two right hands and of losing one's own hand. Null findings are notoriously difficult to interpret (e.g., Wagenmakers, 2007). Here, we resort to Bayesian statistics to evaluate whether evidence supports the null hypothesis (Dienes, 2014). Whereas in most cases, Bayes factors support the null hypothesis, they are inconclusive with respect to feelings of losing one's own hand. In sum, these results contribute to a growing body of evidence suggesting that various higher-order cognitive processes modulate several phenomenological dimensions of the RHI.

Exploring the Effects of Task Instructions

Our findings emphasize the influence of task instructions and attention in shaping the phenomenology of the e*mbodiment of rubber hand* dimension. We speculate that these modulations reflect the putative central role of visual processing in bodily self-consciousness (Deroy et al., 2016; Faivre et al., 2015)[2]. Prevailing views argue that the combination of visual and tactile inputs overwrites prior proprioceptive knowledge, thereby altering body representations during the RHI (Botvinick & Cohen, 1998; Ehrsson et al., 2004; Hagura et al., 2007; Pavani et al., 2000). The current work expands this viewpoint by showing how focusing attention to visual inputs heightens feelings of *embodiment*. This outcome intimates that the emergence of this phenomenon rests on the predominance of sight, such that attentional prioritization of visual information towards the prosthesis facilitates its integration in the body schema and weakens that of the real hand. This interpretation aligns with previous work (Botvinick & Cohen, 1998; Ehrsson et al., 2004; Hagura et al., 2007; Pavani et al., 2000). Conversely, focusing on tactile information decreases the effectiveness of the RHI, which entails that attending to somatosensory information grounds body representations and impedes the ability of visual inputs to alter body representations. This result aligns with previous findings showing that greater awareness of internal bodily signals ("interoception") similarly reduces the RHI (Schauder et al., 2015; Tsakiris et al., 2011). Thus, by improving proprioception and awareness of the true body position, enhanced somatosensory processing may have consolidated

[2] We also refer the reader to discussions of demands characteristics, phenomenological control, and imaginative suggestion in the RHI (Dienes et al., 2020; Lush, 2020; Lush et al., 2019; Roseboom & Lush, 2020).

a firmer and clearer body representation—less prone to distortions—thus leading to attenuated feelings of embodiment of the fake hand yet to stronger embodiment of the real hand. Our findings highlight the predominance of visual processing over the weaker role of somatosensory perceptions on core phenomenological dimensions of self-awareness and body ownership, despite the fact that both elements represent fundamental components of the illusion.

Attention likely plays a key role in shaping our phenomenology of the RHI. As sensory signals compete to reach higher order processes, attending to a specific sensory modality reduces the efficacy of unattended ones, a phenomenon known as cross-modal *deactivation* (Knudsen, 2007; Laurienti et al., 2002; Mozolic, Hugenschmidt, et al., 2008; Mozolic, Joyner, et al., 2008). Relative to our findings, cross-modal deactivation represents a likely mechanism by which selective attention interferes with multisensory integration and alters phenomenological components of the RHI as a function of the attended sensory signal. Thus, whereas attending to visual inputs entails that visual information supersedes somatosensory inputs, resulting in a stronger illusion, attending to somatosensory sensations may have prioritized the processing and the integration of somatosensory signals at the expense of the otherwise dominating visual sensory input (Sinnett et al., 2007). Accordingly, given the centrality of visual information in self-consciousness, incomplete integration of visual information could lead to a partial breakdown of the illusion—that is, if visual information cannot prevail over prior body signals and representations.

The Influence of Cognitive Load

In contrast to our predictions and studies following the McGurk Effect (Alsius et al., 2014; Alsius et al., 2005; Alsius et al., 2007; Buchan & Munhall, 2011a, 2012), cognitive load hardly affected the phenomenological components under investigation. One could argue that our cognitive load insufficiently taxed cognitive resources. Our failure to find effects of load across these dimensions may also follow from a lack of statistical power, as the effects of cognitive load over multisensory integration appears modest (Buchan & Munhall, 2011a, 2012). Note, however, that Bayes Factor analysis favored the null hypothesis. Finally, whereas attention may be necessary to determine which information will be processed, it is possible that, in the RHI at least, working memory resources play a negligible role in the actual integration of visuotactile information. Nevertheless, our cognitive load task was reliable in altering affective components of the RHI, leading to lower ratings of pleasantness. This marginal effect may be due to the fact that the cognitive load interferes with the capacity to appraise the effect, thus leading participants to report lower pleasantness of the experience.

Summary of Results and Implications of Findings

Instructions modulate phenomenological dimensions of the RHI. Cognitive load modulates the pleasantness of the procedure for participants. Consistent with past findings regarding the role of visual processing, our findings demonstrate that shifting attention to non-visual modalities tends to diminish the RHI. Specifically, our results show that attending to somatosensory sensory input, brings about an overall weakening of the illusion. Moreover, reduced cognitive resources likely impacted the ability of participants to enjoy the experience.

One potential mechanism, although speculative, may explain how instructions influence the RHI. This explanation involves selective attention and cross-modal deactivation—for example, by facilitating the neural processing of the attended sensory signal and simultaneously down-regulating other unattended sensory pathways. By doing so, this dynamic will have disrupted the normal multisensory integration process (Mozolic, Hugenschmidt, et al., 2008; Mozolic, Joyner, et al., 2008).

By highlighting the central influence of attention processing in the RHI, our results entail theoretical and methodological implications. From a theoretical perspective, our present findings are consistent with, and extend, previous RHI studies (Kilteni et al., 2015; Tsakiris, 2017). We also replicate past research efforts concerned with the role of attentional processes in cross modal sensory integration (Buchan & Munhall, 2011b; Déry et al., 2014; Fernández et al., 2015; Hartcher-O'Brien et al., 2017; Koelewijn et al., 2010; Lifshitz et al., 2013; Mozolic, Hugenschmidt, et al., 2008; Mozolic, Joyner, et al., 2008; Senkowski et al., 2005; Talsma et al., 2007; Talsma et al., 2010; Talsma & Woldorff, 2005). Specifically, this study illustrates the importance for existing models of body ownership to accommodate and integrate attentional factors in developing a more comprehensive understanding of bodily self-consciousness. We also note that bodily self-consciousness differs from other forms of multisensory integration, as it relies, for example, on both internal (interoceptive) and external (exteroceptive) stimuli, rather than on purely exteroceptive stimuli (Blanke et al., 2015). From a methodological perspective, our results further support the commanding influence of task instructions over several phenomenological dimensions involved in the RHI. Subsequently, we encourage researchers to heed the importance of instructions and attention in this experimental approach.

Limitations

Our study has a few limitations. For example: 1. Perhaps our specific load task insufficiently taxed cognitive resources to result in interference with the illusion; 2. The experimenter manually controlled exposure to experimental visual character strings, introducing variation in latency exposure across participants; 3. Questions from the body ownership questionnaire followed a non-random order, and may have introduced a response bias to the answers; 4. Although our experimental design follows typical RHI studies, it lacks a baseline, control condition of asynchronous (versus synchronous) stroking.

Other limitations apply to our factor analysis procedures as well. For example: 1. We draw on a modest sample size (however, our average communalities and item:factor ratio were high); 2. Pooling data from the different conditions potentially limits the interpretability and generalizability of our conclusions; 3. Factor scores distributed pseudo-normally; 4. The determinant of the correlation matrix, the proportion of residuals greater than .05, and the root-mean-square residual fell outside recommended value ranges. In this regard, this research effort primarily serves as a preliminary exploration.

Conclusion

Unlike focusing on tactile sensations, attending to visual aspects of the rubber hand elicits a stronger illusion. Furthermore, increased cognitive load makes the RHI less enjoyable. Our study confirms that attention plays a central role in the RHI. Indeed, we found that task instructions regarding the attended modality influenced several phenomenological aspects. Specifically, emphasis on somatosensory sensations tends to weaken the overall experience compared to emphasis on visual sensations, because instructions seem to decrease feelings of embodiment relative to the fake hand.

Our current findings have important implications for future research on multisensory integration and for studies employing RHI-like methodologies. First, these results contribute to our understanding of the role of attention in multisensory processes. Second, attention to particular features (e.g., visual versus tactile aspects) may introduce considerable variation in body ownership. Thus, researchers should attempt to more fully account for attentional factors in existing models of body-ownership. Third, and more specifically, participants may focus on one feature of the experience at the expense of another (e.g., the proprioceptive feeling of their real hand). Thus, it would behoove researchers to provide explicit instructions emphasizing visual representation, in order to maximize the illusory effect. In conclusion, our findings contribute to the debate over the role of top-down, higher-order cognitive factors in illusions of body ownership and multisensory integration.

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