



OPEN Disrupted sense of agency-related ownership and disownership increase in the Rubber Hand Illusion

János Kállai¹✉, Orsolya Vincze², Rita Hargitai², Bea Ehmann³, Zsófia Bacsaki⁴, Virág Pulai⁵, András Norbert Zsidó² & Tibor Szolcsányi¹

Empirical evidence suggests that body ownership and the sense of agency operate as an interactive system correlated with the level of consciousness during tasks involving modifications in body representation. This study sought to elucidate the nature of this association by documenting the verbal manifestations of this interaction. Specifically, the study aimed to reveal the role of a sense of agency in the individual sensitivity to the Rubber Hand Illusion (RHI). The sense of agency was measured through a post hoc interview wherein participants could verbally express their rubber hand ownership and real hand disownership experiences following the RHI examination. The RHI was induced in 49 healthy, right-handed college volunteers, including 28 males (mean age 28.6) and 21 females (mean age 26.6). Three main scores - ownership, disownership, and proprioceptive drift - were defined to measure individual sensitivity to Rubber Hand Illusion. Verbal reports related to the RHI were analyzed utilizing an automated narrative content analysis toolkit which explored the deeper content of words and stories to identify situation-driven cognitive processes, specifically focusing on the rate of sense of agency and other cognitive variables. The findings indicated that a greater disruption in the sense of agency predicts increased sensitivity to the Rubber Hand Illusion. Therefore, individuals with a lower rate sense of agency exhibit increased malleability in body representation when a rubber hand illusion is induced.

Rubber Hand Illusion Task¹ is an effective method to induce body and body parts misidentification. The induced alteration in body representation can be achieved by manipulating multimodal stimuli including visual, proprioceptive, and tactile inputs. The human body is considered a multisensory integration system of perception and action. This integration is crucial in self-representation, specifically in body schema and image^{2,3}. The body schema has a longer personal developmental history and is dominated by space and time-organized proprioceptive, and somatosensory inputs. These cognitive constructions operate at a lower level of consciousness. In contrast, body image (BI) has a shorter developmental trajectory and is dominated by visual stimuli. It is changeable, relatively unstable, and rapidly adjusts to current events⁴. The body schema and body image together form an interactive reference system with four distinct components: (1) the experience of being a body (body ownership); (2) that has a defined location in the space, where the inner sensations align with the perceived location of one's body (self - location); (3) taking a first-person perspective on the environment, using egocentric representation of distal and proximal space (perspective)⁵ and (4) experience of being an active and salient participant in the current socio-cognitive context (sense of agency)⁶. The reliability of perceiving body schema and body image depends on the configuration of the reference frame in which stimuli are presented. This variability is associated with the coherence of multimodal stimuli and the available neural organization in healthy individuals and patients with psychiatric or neuropsychological deficits. One illustrative instance of a deficit in recognizing one's body and its constituent parts is the autotopagnosia syndrome⁷. Autotopagnosia entails an injured awareness of the spatial positioning of one's body or body parts, resulting in disruptions in self-representation, body identity, ownership, and disownership⁸. For instance, consider a patient with autotopagnosia who was unable to point to his hand or other body parts when directly asked to do so. However,

¹Institute of Behavioral Sciences, Medical School, University of Pécs, 7625 Pécs Szigeti Street, 12. H, Pécs, Hungary.

²Institute of Psychology, Faculty of Humanities and Social Sciences, University of Pécs, Pécs, Hungary. ³Institute of Cognitive Neuroscience and Psychology, Research Centre for Natural Sciences, Hungarian Academy of Sciences, Budapest, Hungary. ⁴Department of Paediatrics, Medical School, University of Pécs, Pécs, Hungary. ⁵Department of Addictology and Rehabilitation, Szigetvár Hospital, Szigetvár, Hungary. ✉email: janos.kallai@aok.pte.hu

this inability changed when the examiner placed a small cube on the patient's hand and inquired, 'Where has the cube been placed?' The patient correctly responded, 'You put it on my hand.' This case study highlights the origin of ownership and disownership, the role of body image and body schema in body-part representation, the significance of the perceptual reference frame and the sense of agency, and points to their distinct neural mechanisms in the brain⁹.

Sense of agency

The perception of one's body involves diverse representational forms. The semantic level encompasses concepts that describe the entire body, the names of specific body parts, and notions that express their spatial and temporal relationships^{10,11}. The representation of the body manifests through lexical and semantic categories and is closely linked to feelings of ownership and disownership. Clinical observations and empirical data suggest that the body representations are intricately connected to several cognitive processes: goal-directed voluntary actions; personal engagement or embodiment; higher consciousness in executed movements; awareness of bodily states and actions; self-involved responsibility; and agency over internal and external events^{12–14}. The sense of agency depends on the control rate of perceptual input and motor outcomes. The mentally generated efferent copies predict the expected sensory and motor consequences of the intended action. Furthermore, the sense of agency has social-psychological prerequisites, such as self-mastery, and stable social status, which facilitate problem-solving in personal and environmental contexts. However, the absence of an efferent copy or the lack of necessary cognitive control disrupts the sense of agency¹³. The sense of agency can be measured in complex social environments in congruent and incongruent experimental situations and different narrative content. The sense of agency can be achieved through behavioral observations, virtual reality paradigms¹⁴, questionnaires, and situation-dependent structural interview methods^{15,16}. However, disruptions in the sense of agency, multisensory integration, or neural lesions can lead to dissociative experiences, thought disorders¹⁷, and uncertainty in body part identification^{18,19}. Furthermore, the coherence in multimodal stimuli integration, the stability of the action context, and individual personal beliefs and task requirements influence the dynamic interaction of different components of the sense of agency and are associated with bottom-up and top-down cognitive processes^{2,13}. The sense of agency is a general phenomenological response to complex tasks and environments mentioned above. In these tasks, the conscious top-down guided judgments and the unconscious bottom-up guided inferences interplay in the task resolution and the emerging sense of agency appearance. These collaborating cognitive steps have a hierarchic structure, but their weight in the sense of agency is context-dependent and at present its direct measure is vague. Analyzing the dual nature of the sense of agency Synofzik et al.²⁷ introduced a theory that covers the interplays between the top-down and bottom-up processes defining two-step functions for the judgmental agency (JoA) and feeling of agency (FOA) exploring the origin of the sense of agency functions. The feeling of agency is mainly associated with automatic interferences and striving to maintain body representation stability and with a low level of conscious control. However, judgmental agency is related to a higher conscious control over the possible decision where the object and the subject of the problems can be defined and conceptualized. The sense of agency and its origin play a role in developing human body representation and are closely related to self-identity and body part ownership¹⁴. We hypothesize that studying the relationship between the sense of agency and body-related ownership opens a way to understand the deeper structure of the sense of agency components and its influences on the construction of the body-part representation. An illustrative example examining body part representation is the rubber hand illusion, which can induce body ownership and disownership experiences in healthy individuals and patients without adverse effects.

Rubber Hand Illusion (RHI)

The fundamental configuration for inducing the RHI¹ involves the following elements: participants sit in front of a desk; their left hand and right hand assume normal positions on the desk; a folding screen is located beside the left real hand and to the other side of the folding screen a rubber hand is placed. Consequently, the participant's left hand is invisible to the participant, but physically, proprioceptively is present. This position can impact the role of the body schema in the coherent representation of the body. However, the rubber hand is visible, but proprioceptively unfelt. This position accentuates the role of body image in body representation. The rubber hand, which closely matches the form, color, and spatial position of the invisible left hand, is positioned in front of the participant's peripersonal space. Specifically, it is close to the midline but slightly closer to the folding screen^{20,21}. During the initial phase of the RHI induction, the right hand, located in the periphery of the field of vision, does not actively participate in the completion of the task (detailed configuration of the RHI in Fig. 1).

RHI examination: instruction and setting

Within the framework of the RHI paradigm, participants' bodies serve as relatively passive subjects for experimental manipulation. The assistant examiner controls the participants' movements, directing their cognitive activity toward specific goals while introducing various mental and physical constraints. Therefore, in this task, the sense of agency and the participant's level of engagement depend on individual characteristics (trait effect) and their responses to the current task requirements (state effect)²². Previous RHI studies have revealed diverse participant reactions. While most individuals passively accept the induced modification in body image and schema, others resist body representation alterations. Verbal remarks such as "This is impossible," "I understand what you want," "It was awful," or "It was absurd" frequently arise during the induction of the Rubber Hand Illusion (RHI) and often persist beyond the experimental sessions. The comments provide insights into how participants respond to constraints and alterations in body representation and the incorporation of body parts. Their verbally articulated attitude may correspond to passive or active mental approaches^{23,24}.

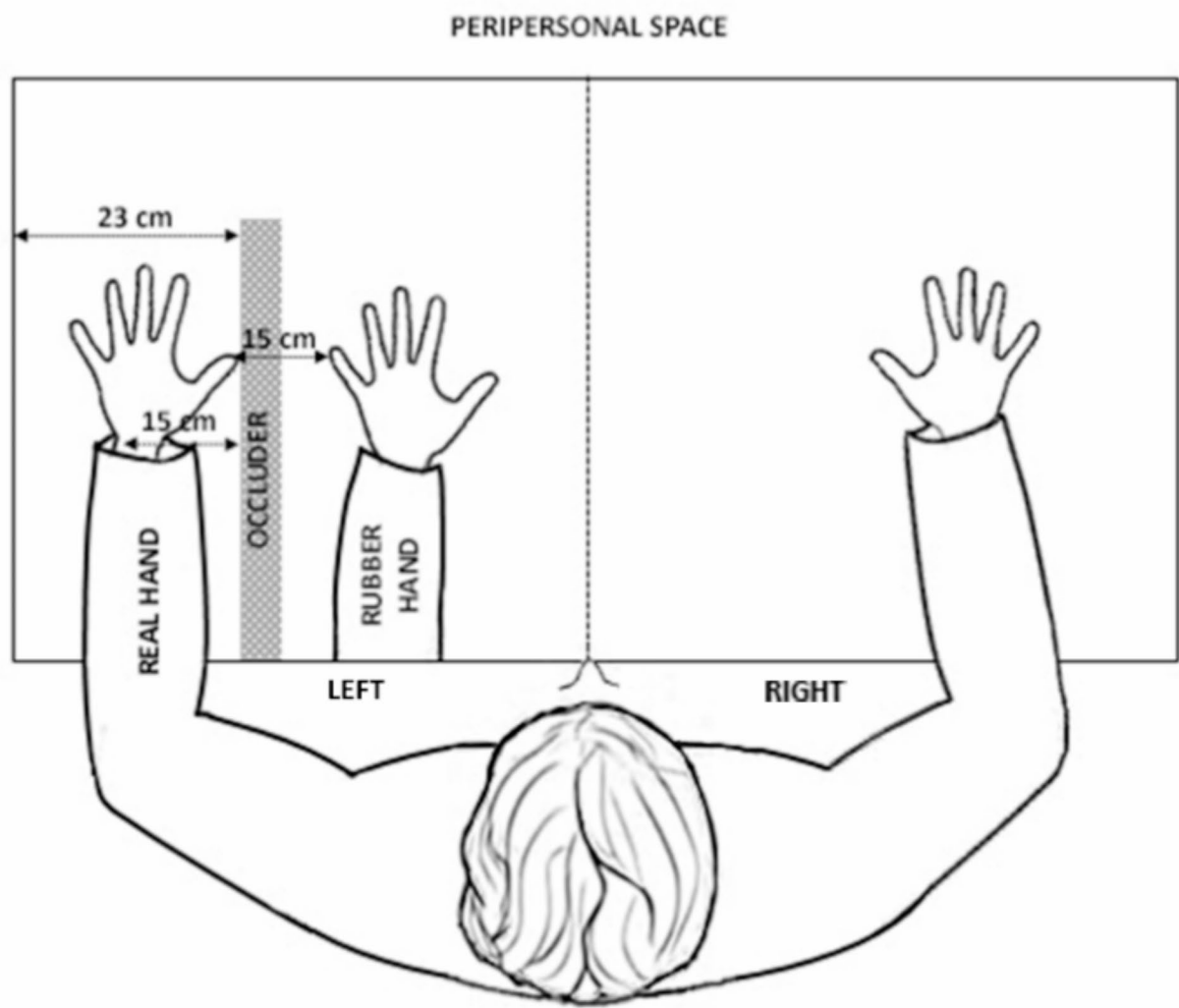


Fig. 1. The standard Rubber hand Illusion examination setting with a folding screen (occluder) between the left real hand and the left real hand-like rubber hand.

The RHI rating scales.	
RUBBER HAND OWNERSHIP scale.	
1.	It seemed like I was feeling the touch of the paintbrush in the location where I saw the rubber hand being touched. (spatial localization item)
2.	It seemed like the touch I felt was caused by the paintbrush touching the rubber hand. (spatial localization item)
3.	It seemed like the rubber hand belonged to me. (embodiment item)
4.	It seemed like the rubber hand was my hand. (embodiment item)
REAL HAND DISOWNERSHIP scale.	
5.	It seemed like I was unable to move my hand. (self-regulation dysfunction item)
6.	It seemed like my hand was out of my control. (self-regulation dysfunction item)
7.	It seemed like I couldn't really tell where my hand was. (autotopagnosia item)
8.	It seemed like I could have moved the rubber hand if I had wanted. (autotopagnosia item)

Table 1. Rubber Hand Illusion rating scales from a psychometrically tested list³³.

The investigation of verbally expressed linguistic content plays a role in examining body representation, particularly within ambiguous and conflicting contexts. Changes in body representation can be detected through verbal expressions involving passive and active voices, cognitive processes, and psychological interpretations within the current context. These verbal expression forms exhibit relative uniformity across diverse languages²⁵. The linguistic system, designed to structure linguistic behavior, ensures a valuable starting point for studying individual differences. The RHI provides a potential context for a participant confronting body-part representation difficulties. Notably, assessing personal linguistic expression characteristics may be an adequate method to reveal cognitive strategies, unexpected bodily experiences, and passive or active participation in the RHI experimental setting and parallel involved a sense of agency experience^{10,26}.

Hypothesis

The Sense of Agency (SoA) primarily depends on an individual's subjective awareness. When the actors interpret the current social and physical environments, they actively seek to control events. Crucially, this occurs when their personal goals align with the behavioral possibilities in the current environments. The individuals perceive that the unfolding events and the outcome of their actions are contingent upon their capability and activity^{27,28}. Researchers have revealed that verbal expressions contribute to reflecting this evaluative function. These expressions can be methodically classified and used in automated content analysis software^{12,29}. By examining these verbal expression forms we acquire valuable insights into how individuals integrate incongruent multimodal information during an RHI induction.

Previous research^{3,13,30} has shown that individuals with heightened RHI sensitivity are prone to substituting their body representation with an external body or an object resembling a human body or body parts. The current study assumes that verbal expressions recorded after the RHI experiment can reveal an individual's cognitive processes influencing their sensitivity to the illusion. The RHI induction ensures options to sustain the awareness of personal thoughts, feelings, and body-related sensations. Additionally, it allows for an alternative perspective accepting these uncommon mental experiences without evaluating their reality^{23,24,31}.

Individuals' task-specific cognitive strategies and the rate of sense of agency experiences influence RHI sensitivity. We assume that the rate of this sensitivity manifests during interviews where participants describe their experiences immediately after the RHI experiment in a post hoc session. Referring to the dual nature of the sense of agency, (dynamic interplay of the bottom-up and top-down effects in the RHI setting) we test via two contradictory hypotheses.

First (Hy1), we suppose that participants, in the first step, respond to the RHI-induced multimodally constructed environment by an automatic low-level, nonconceptual bottom-up driven body representation modification using an open and passive intake perceptual attitude. In instances, the participant thinks that the source of his or her body representation changing originates from the experimental setting and the experimenter's maneuvers. The participant adapting to this condition partly discards cognitive control over events and uses low-level sensory and motor control. Considering the inhibited motor responses in the RHI setting, this mental activity can be characterized as a disruptive sense of agency (DSOA) that can be measured in post hoc interviews.

Second (Hy2), in the second step it can be supposed that participants depending on their personal bias actively focus on the constructed environment, interpret the context of the experimental conditions and changes in their body representation, and strive with conscious efforts to analyze the content and response option. The result of the analysis may be standing against or accepting the body-related unusual sensations. Consequently, a participant in this context can defend himself or herself against body representation modification. The observed multimodal incongruence, and the intention to solve that, triggers enhanced cognitive processing and top-down attentional control, leading to diminished sensitivity to RHI induction. This function manifests in increased cognitive and psychological reference-taking scores and can be measured in post hoc interviews.

Methods

Participants

Forty-nine healthy, right-handed volunteers (twenty-eight males with a mean age of 28.7 years, SD = 5.2, and twenty-one females with a mean age of 26.6 years, SD = 3.4) were recruited from a local university student pool. Handedness was assessed using the Edinburgh Handedness Inventory³², and all recruited participants had Handedness Laterality Quotients exceeding 70%. None of the participants had a history of psychiatric illness or prior experience with the Rubber Hand Illusion. They were unaware of the specific hypothesis being tested in the study. Informed consent was obtained from all subjects, and participants received a nominal fee for their participation. The study adhered to the principles outlined in the Declaration of Helsinki and received approval from the Medical Research Council, Ministry of Interior, Budapest, Hungary (ETT TUKEB # BM/16388-1/2023)."

Rubber hand Illusion: questionnaire and behavioral measures

The sensitivity of the RHI is defined using three measures: ownership, disownership, and proprioceptive drift^{1,33}. The vividness of ownership and disownership scores exhibits a close relationship, whereas proprioceptive drift demonstrates a weaker association with the illusion experience. Measurement of the RHI sensitivity contains an induction condition with synchronous tactile burst stimulation on both a real hand and a rubber hand. In contrast, the control condition utilizes asynchronous bursts in real and rubber hands. Both synchronous and asynchronous inductions lead to illusory ownership and disownership, albeit to varying degrees. Considering the rate of difference between the synchronous and asynchronous conditions, the RHI sensitivity is significantly stronger during synchronous inductions. This finding suggests that over the state effect of the RHI, a personal bias is also present in reaction to the RHI^{19,23,34,35}.

Measure 1 Synchronous	Measure 2 Asynchronous	t	df	p	Mean drift.	SE diff.	SE cohen's d
Ownership	Ownership	8.65	48	<0.001	16.3	1.9	0.24
Spatial localization	Spatial localization	9.06	48	<0.001	9.0	0.99	0.24
Embodiment	Embodiment	6.66	48	<0.001	7.0	1.05	0.22
Disownership	Disownership	4.96	48	<0.001	8.3	1.68	0.20
Self-regula. dysfunction	Self-regula. dysfunction	7.91	48	<0.001	4.6	0.93	0.21
Autotopagnosia	Autotopagnosia	4.51	48	<0.001	3.7	0.84	0.18
Proprioceptive drift	Proprioceptive drift	2.10	48	<0.040	1.5	0.73	0.13

Table 2. Differences between synchronous and asynchronous conditions in ownership (in spatial localization of touch and embodiment sensation scales); disownership (self-regulation dysfunction and autotopagnosia scales), and proprioceptive drift.

	2	3	4	5	6	7	8
1. Ownership sum	0.943**	0.930**	0.680**	0.693**	0.598**	0.371*	0.914**
2. spatial localization		0.803**	0.609**	0.616**	0.540**	0.340*	0.845**
3. embodiment			0.682**	0.698**	0.597**	0.362*	0.877**
4. Disownership sum				0.958**	0.948**	0.322*	0.886**
5. self-regulation dysf.					0.815**	0.357*	0.880**
6. autotopagnosia						0.252	0.804**
7. Proprioceptive drift							0.545**
8. RHI Sensitivity Index							

Table 3. Sex-controlled partial correlation matrix for the validity scores for the Rubber Hand Illusion: Phenomenologically registered ownership, disownership; the behaviorally measured proprioceptive drift; and the aggregate RHI Sensitivity Index. $p < 0.05$; $p < 0.01$.

The reception of the rubber hand in the body image and body schema was measured by the sense of ownership and disownership questionnaire. The items of the questionnaires contain ownership and disownership scales (Table 1.). Participants answered each statement by choosing a number from an 11-point scale ranging from 0 (“strongly disagree”) to 10 (“strongly agree”). The ownership involves a localization (LOC) scale, and an embodiment scale (EM). Cronbach’s alpha coefficients reported in the present sample - specifically, 0.950 and 0.921- indicate excellent internal consistency. The sense of localization (LOC) indicates that rubber hand-related visible stroking is not only perceived visually but also detected as an associated touching stimulus on the surface of the rubber hand. The sense of embodiment (EM) involves conscious experiences when the participants feel the rubber hand is a physically real part of their body. The sense of disownership was also measured by two subscales namely, self-regulation dysfunction (SFD) and autotopagnosia-like (AUA) experiences scales. In the present sample, Cronbach alpha=0. 601 and 0.708) is adequate. The higher scores on the SFD scale indicate limited decision-making and inhibited executive function for the invisible real hand. The AUA scale assesses the rate of mislocalization of the invisible real hand, inhibited proprioceptive stimulation, and decreased body part identification experiences. The third main component of the RHI, the proprioceptive drift, is related to the rate of ownership and disownership scores and is measured behaviorally. The phenomenological and behavioral measures of the RHI scores show only limited associations. However, in the studies of a comprehensive analysis of the RHI, the proprioceptive drift as a part of the additional RHI score is considered in several investigations as an aggregate score for RHI sensitivity^{35–37}.

Proprioceptive drift.
The perceived position of the participants’ left hand was assessed by a procedure known from previous experiments involving the non-visual variant of the RHI³⁸. First, a ruler was placed in an angular position in front of the participants, who were asked to put their right index finger somewhere on the front part of the ruler. After the participants were asked to close their eyes, the experimenter removed the folding screen and positioned the ruler closely up the table. Finally, the participants were asked to indicate the perceived position of their left index finger by drawing their right index finger on the ruler to the location where they felt it was exactly above the tip of their left index finger. The outcome of the proprioceptive drift was defined by the difference between the experimental and the control condition proprioceptive drift scores. The higher scores indicated that the felt spatial position of the participant’s real hand drifted toward the spatial localization of the rubber hand.
The effect of the RHI induction, both phenomenological and behavioral scores, was adequately manifested and gratified the validity requirements. In synchronous conditions, the values of ownership and disownership were higher compared with asynchronous conditions (see Tables 2, and 3). The difference between synchronous and asynchronous conditions in the proprioceptive drift is also considerable but low. The elevated difference scores observed under synchronous conditions, compared to asynchronous conditions, indicate increased sensitivity to the induction of the rubber hand illusion.

Procedure

The conflict in multisensory integration between the body schema and body image is an essential prerequisite for the RHI induction. This challenge is achieved through synchronous tactile stimulation to the real and the rubber hand. An assistant, positioned in front of the seated participant simultaneously stimulates the visible rubber hand and the invisible real hand using brushes. This dual incongruence in multimodal stimulation elicits three distinct responses. The mismatch between visual and tactile cues results in an illusory sense of ownership over the rubber hand, and simultaneously, participants experience a sense of disownership in their invisible real hand. The RHI-induced disownership leads to a localization drift in the spatial perception of the real hand. This proprioceptive-related perceptual deficit decreases the awareness of the hand's position and results in a localization error within the body schema system. Previous research has established associations between RHI-related ownership, disownership, and proprioceptive drift scores. These scores are linked to body awareness and body representation disruption that engage distinct neural processes within the brain^{13,21}. The experimental phase consisted of two blocks corresponding to the two experimental conditions synchronous stroking, and asynchronous stroking. The stroking was touched to each finger and dorsum manus, except the thumb in both conditions. The pattern and the frequency (0.9 Hz) of stroking were predetermined using a metronome that guided the experimenter over an earphone. The synchronous and the asynchronous blocks started with a 2-minute stroking period respectively. Five-minute pauses were installed between the experimental blocks. After the synchronous tactile stimulation by brush participants were asked to complete a rating scale that involved the rubber hand illusion-related ownership and disownership feelings (Table 1). A similar rating scale was completed after the asynchronous stimulation blocks. The rate of the RHI was calculated as the score difference between the synchronous and asynchronous stimulation blocks. After the “stroking period” the proprioceptive drift was assessed. The RHI Sensitivity Index is defined by aggregating the values of ownership, disownership, and proprioceptive drift scores. After the RHI experiment, participants were escorted to an interview room where a semi-structured interview was administered. During this session, they were prompted to articulate their subjective experiences related to their involvement in the laboratory study.

Content analysis

The linguistic analysis of verbal expressions is suitable for exploring the deeper content of situation-driven attitudes and cognitive processes¹². In the present case, content analyses can provide an adequate opportunity to reveal cognitive processes that play a role in the manifestation of ownership and disownership experiences during induction of the RHI. After the RHI examination session, a semi-structured interview was administered, asking participants to respond to the following questions: “Please describe the sensations you experienced in your body during the examination, and elaborate on your feelings related to the experimental context” Forty-nine interviews were recorded and analyzed by an automatized artificial intelligence-controlled content analyzer program called NarrCat (Narrative Categorical Content Analyzer toolkit)²⁶. NarrCat is a content analyzer algorithm composed of different thematic modules, that search texts for specific words and phrases and enable researchers to quantitatively analyze narrative composition about psychological processes like agency or cognitive elaboration and psychological perspective taking. Examples: typical phraseologies for cognition “I opened my eyes, and there was the fake hand; suddenly, I thought it was mine” I realized it wasn't mine after all.” Example for psychological perspective-taking “Well, at first, I was scared, what happened to my hand (laughs)!? I felt like it belonged to me.” An example of a disrupted sense of agency involving passivity, obsessions, and passive voice: “I had to look at the prosthetic hand, and my brain got a little bit tricked”. Consequently, examining the syntactical and semantical composition of an individual's verbal act might provide an empirically based knowledge of behavioral adaptation³⁹.

The concept of agency pertains to the mental processes through which individuals influence the events they participate in⁴⁰. Agency encompasses various psychological attributes, including activity, effectiveness, authority, capability, resilience, autonomy, regulation, or competent movement control⁴¹, that systematically manifest while an individual moves in real or virtual peripersonal or extrapersonal places¹⁴. At the core of these attributes lies individuals' confidence in their capacity to attain their objectives and control the events in their events. The agency can manifest through various narrative styles, with one such mode involving the use of voice. Active and passive voices denote whether the subject or the object of the sentence acts as the verb. Active voice signifies our engagement and capacity to impact the current situation, however passive voice, especially agentless passive, diminishes agency by shifting the focus from the actor to the object, thus obscuring the agent's role⁴¹. The agency was measured by using the activity, and passivity modules of NarrCat^{42,43}, which automatically detect verbs of active and passive overt behaviors (e.g., achieve, go, take) and various intentional words forms (e.g., aim, plan, want, will, deliberately) and modal words of constraint (e.g., must, need) in the texts. After a word count normalization process, the present study - considering the (hy1) hypothesis - used the difference between passive and active word counts as the index of the disrupting sense of agency.

Cognitive activity and psychological reference-taking (conceptualization), focus on using inner-state words or phrases to indicate the speakers' speaking on the underlying meaning of the topic and their trials to understand and elaborate on the event^{38,44}. The module on psychological perspective in NarrCat summarizes the matches from cognition module⁴⁵ that identify various mental states and processes of actors. These include mental verbs (e.g., think, belief, sob, wonder, hope, hurt), nouns (e.g., inference, decision, fear, fury), adjectives (e.g., happy, proud, grateful), and idioms (e.g., draw lesson, keen on). Focusing on the hypothesis (hy2) the cognitive activity module and psychological perspective submodules were used to define the assumed internal or trait agency-based activity to maintain the integrity of body representation. The individual with higher scores in these modules strives to cope via conceptualization with incongruent multimodal environments while the RHI is induced.

The study aimed to control two RHI sensitivity-related hypotheses. The study selected RHI-relevant narrative categories, - psychological perspective and cognition, and disrupted sense of agency - from a large pool using the NarrCat system. Disrupted Sense of Agency Index (DSI)^{26,45,46} was derived by quantifying the difference between passive and active word counts. Additionally, the cognition (COG) score represents the aggregate of the cognition module, while the psychological perspective (PS) score reflects the aggregate score of psychological aspects. See Fig. 2 for detailed descriptive statistics of the variables in the present study sample. The analysis considered the semantical, morphological, and syntactical features in verbal descriptions of the RHI-related sensations in a post hoc structured interview. The NarrCat system automatically clustered words and idioms. On average, text files contained 788 words (with a range of 243 to 2169), depending on participants' verbal activity. The individual differences in the produced word counts are normalized and COG, PS, and DSI activity are expressed in percent of word counts.

Statistical analysis

First, to confirm the success of the RHI manipulation, we analyzed the differences between the synchronous and asynchronous manipulations in terms of illusory ownership, disownership, and proprioceptive drift scores using paired samples t-tests. In addition, we analyzed the associations between illusory ownership, disownership, proprioceptive drift difference scores, and RHI using partial correlations controlling for participant gender. The assumptions for these statistical analyses were met; the distribution of the variables did not violate normality, as evidenced by skewness and kurtosis values less than |2|.

To test our hypotheses, we employed linear regression analysis, designating the RHI Sensitivity Index as the dependent variable, while the Disrupted Sense of Agency Index, along with Cognitive and Psycho-perspective scores, served as independent predictors, with gender as a control variable. We then used a multiple indicator multiple cause model (MIMIC) for a more fine-grained analysis. Here, the indicators forming the latent outcome variable were the difference between synchronous and asynchronous possession, dispossession, and proprioceptive drift scores, while the independent predictors were the Disrupted Sense of Agency Index, Cognitive, and Psycho-perspective scores as independent predictors. We also controlled for participant gender. To evaluate the model fit, we used the comparative fit index (CFI), Tucker–Lewis index (TLI), root mean square error of approximation (RMSEA), and the standardized root mean squared residual index (SRMR). The cutoffs for good model fit were CFI and TFI values of 0.95 or greater⁴⁷ RMSEA, and SRMR values of 0.08 or lower⁴⁸. All assumptions for the models were met, and multicollinearity was not a concern (VIF values were less than 4). Statistical results are presented in tables for clarity. Detailed descriptive statistics for all variables used in the present study can be found in Supplementary Material 1. Data are in a repository, including hyperlinks and persistent identifiers for the data where available. <https://osf.io/tnwpa/>.

Results

Results indicate that the RHI-induced sensitivity is elevated for both ownership and disownership, and it tends to be higher for proprioceptive drift scores under synchronous conditions compared to asynchronous multimodal stimulation. Statistical results are presented in Table 2, and descriptive statistics are presented in Fig. 3.

Correlation analysis revealed a robust positive relationship between ownership and disownership. However, when proprioceptive drift was considered, the association between ownership and disownership remained, albeit to a lesser degree. The behavioral score is solely associated with real hand disownership, self-regulation dysfunction, and rubber hand ownership experiences (Table 3). The autotopagnosia score did not exhibit a significant association with the rate of proprioceptive drift. The results are consistent with previous findings^{17,34} and indicate a difference between phenomenological and behavioral components of the RHI induction. Nevertheless, the aggregate value of the three scores is a valid index for estimating individual sensitivity to the RHI.

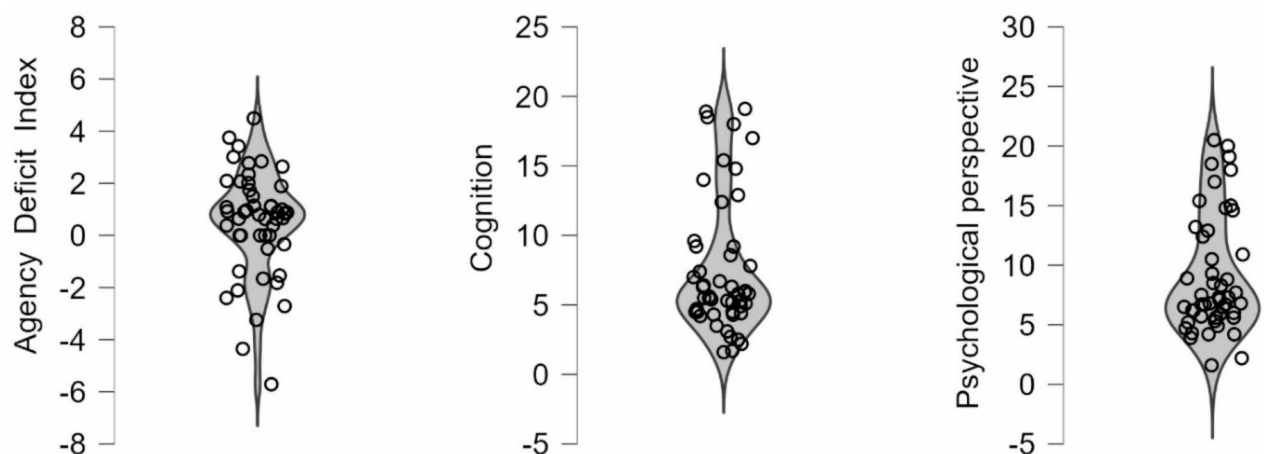


Fig. 2. Violin plots and individual data points show the descriptives of the three narrative categories.

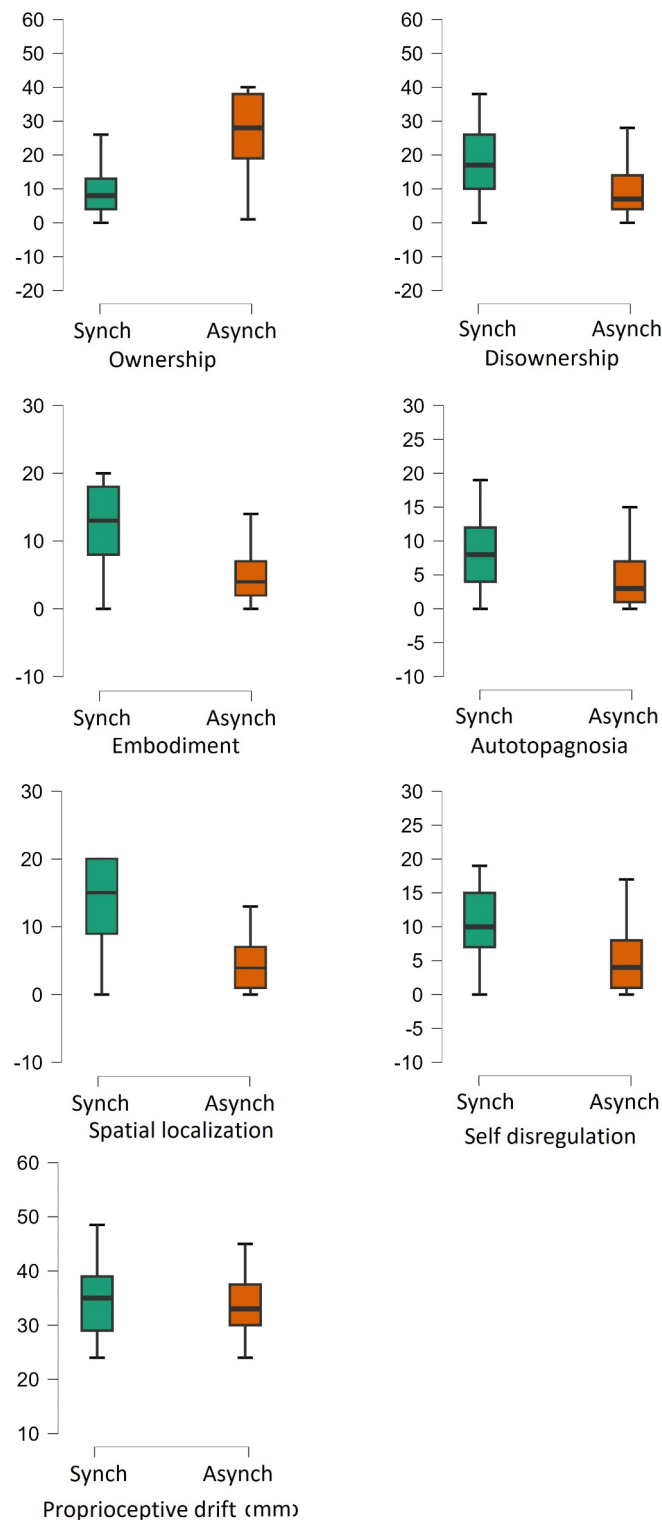


Fig. 3. Box plots showing the differences and descriptives for synchronous (green) and asynchronous (orange) conditions in ownership (in the spatial localization of touch and embodiment sensation scales), disownership (in the self-regulation and autotopagnosia scales), and proprioceptive drift.

The linear regression model was significant ($F(4,44)=3.206$, $p=0.021$, adjusted $R^2=0.155$). Disrupted Sense of Agency Index was a significant positive predictor of the RHI sensitivity index, while Cognitive and Psychoperspective scores were nonsignificant. Table 4 shows the exact statistical results with point estimates and standardized coefficients.

	b	SE	β^a	t	p
Disrupted Agency Index	5.340	1.706	0.428	3.129	0.003
Cognitive	1.771	1.369	0.339	1.294	0.202
Psycho-perspective	-1.571	1.335	-0.306	-1.177	0.245
Sex	-4.125	6.878		-0.600	0.552

Table 4. The results of the linear regression model. ^aStandardized coefficients can only be computed for continuous predictors.

Predictor	b	SE	z-value	p	95% Confidence Interval		β
					Lower	Upper	
Disrupted Agency	0.250	0.096	2.605	0.009	0.062	0.438	0.214
Cognitive	-0.100	0.064	-1.559	0.119	-0.226	0.026	-0.085
Psycho-perspective	0.122	0.068	1.790	0.073	-0.012	0.255	0.104
Sex	-0.099	0.339	-0.293	0.769	-0.763	0.564	-0.085

Table 5. Statistical results of the MIMIC model.

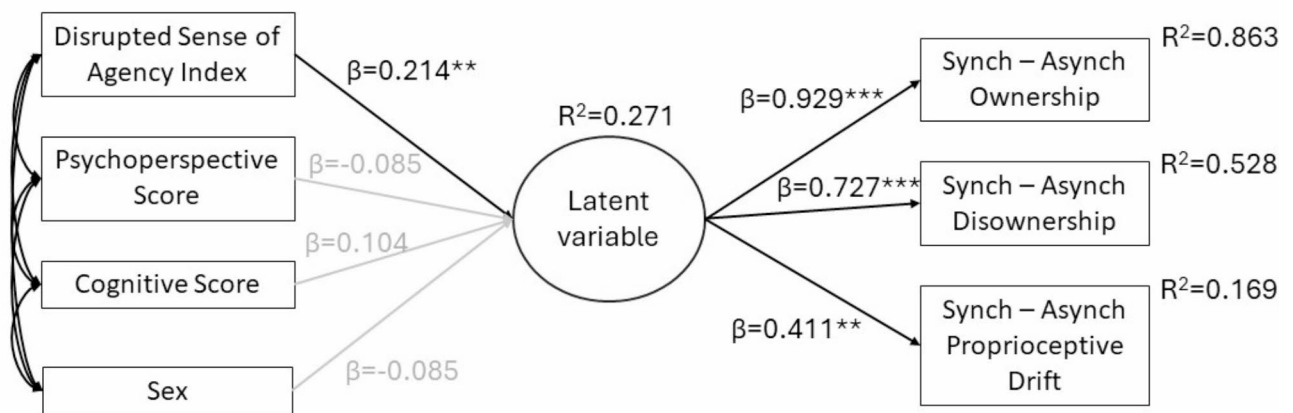


Fig. 4. The graphical presentation of the MIMIC model tested in the present study. Note: ** $p < 0.01$, *** $p < 0.001$. Nonsignificant results appear in gray.

The results concerning the MIMIC model were similar. The model showed a good fit ($\chi^2(8) = 5.608$, $p = 0.691$, CFI = 1.00, TLI = 1.00, RMSEA = 0.00 [90%CI = 0.00–0.13], SRMR = 0.032). Again, the Disrupted Agency Index emerged as a significant positive predictor of the latent variable (adjusted $R^2 = 0.271$), while Cognitive and Psycho-perspective scores were nonsignificant. See Table 5 for the exact statistical results regarding the predictor variables.

The latent variable involving the three main components of the RHI sensitivity indicates that higher ownership, disownership, and proprioceptive drift are associated with a higher sense of agency deficiency. However, higher cognitive control, and the conscious elaboration of the experimental setting, have not played an essential role in manifesting RHI sensitivity (see Fig. 4).

Discussion

The susceptibility to changes in body representation elicited by the Rubber Hand Illusion (RHI) is associated with reduced conscious regulation of multisensory integration. In addition, individuals exhibiting perceptual openness can process disorganized environmental stimuli without necessitating increased cognitive control^{49–52}. Our study hypothesized that this instability in body and body part representation would be reflected in questionnaire scores and verbal content during post hoc structured interviews. The interview focused on three main content categories: cognitive processes, psychological reference taking, and disrupted sense of agency. Our hypothesis posited that employed cognitive strategies and assessed agency activity play a critical role in rubber hand ownership, real hand disownership, and overall sensitivity to the RHI induction.

First, we validated previous findings on the Rubber Hand Illusion (RHI), showing that synchronous tactile stimulation of the hidden real hand and a visible rubber hand enhances the sense of embodiment of the rubber hand

and induces a feeling of disembodiment in the real hand, especially in contrast to asynchronous stimulation^{1,33}. The results support the view that RHI does not evoke but enhances sensitivity to the RHI-induced malleability of body representation⁵⁶. Furthermore, our findings are consonant with earlier results on the function of proprioceptive drift in the RHI induction. Notably, higher ownership and disownership are associated with real hand proprioceptive drift however, the rate of the associations is relatively low. These results indicate differences in the underlying functions of questionnaire-based experiences and behaviorally measured proprioceptive drift data^{17,34,35}. In line with previous findings³³ from the questionnaire items of ownership and disownership, four valid and reliable subscales have been selected; for ownership (spatial localization, embodiment); and disownership (self-regulation dysfunction, autotopagnosia). The designation of the subscales refers to the dual nature of the RHI scores that involve top-down and bottom-up cognitive processes. Our findings are consistent with those reported in references⁵³ and⁵⁴, suggesting that these scales and subscales are pivotal in determining sensitivity to the rubber hand illusion. Furthermore, our study confirms that body perception differs between RHI-sensitive and non-sensitive individuals. The sensitive persons view their body representation as an open system, wherein the body is considered a multimodal cognitive integration system with perceptual and motor functions and shows individually different stability and permeable mental representation boundaries⁵⁵. This incorporation intensifies when ownership is catalyzed by synchronous visuotactile stimulation, which increases the gap between body image and body schema incongruency. In participants, the RHI-induced unexplained sensations provoke feelings of uncertainty and generate spontaneous verbal and nonverbal reactions during and after RHI examination^{22–24}.

We hypothesized that individuals with reduced cognitive control engagement, involving bottom-up processes, exhibit a heightened disrupted sense of agency (DSOA) and are more susceptible to experiencing the RHI. On the other hand, the discomfort in body representation induced by the RHI triggers increased cognitive processing and top-down attention control, leading to reduced personal sensitivity to RHI induction.

Assessing the rate of SoA, two relevant score groups were selected for NarrCat. Considering the first step, participants with DSOA showed higher sensitivity to the RHI induction involving enhanced rubber hand ownership and real hand disownership. The MIMIC model supported these results. Moreover, the DSOA is associated with higher rubber hand ownership-related scales specifically spatial localization of tactile stimulation and feeling of embodiment. Furthermore, the DSOA is linked to higher real hand disembodiment-related scales specifically self-regulation dysfunction and autotopagnosia. The predictive impact of DSOA is also observable in proprioceptive drift measurements. The behavioral test for the location of the invisible real hand in the peripersonal space showed that in participants with DSOA the distance between the rubber and the real hand decreased. The representation of the real hand within the peripersonal space drifted toward the location of the rubber hand.

However, the second step involves top-down cognitive maneuver-related words and phrases to address cognitive factors, and psychological perspective-taking functions and adapt to the current demands of RHI task-induced body representation modifications. These verbal expressions can be utilized to explore how individuals conceptualize the induced changes in body representation. These scores reflect a secondary function of the sense of agency, occurring when individuals defend themselves and seek options to manage the demands of experimental conditions and the unusual changes in body representation. Regression analysis revealed that individuals with elevated conceptualization activity (cognitive maneuvers and psychological perspective-taking) showed no associations with sensitivity to RHI or other parts of rubber hand ownership and real hand disownership. This finding can be interpreted as evidence that the experimental setting of the Rubber Hand Illusion (RHI) contributes to a decline in top-down functions and the activity of the related sense of agency. Consequently, this decline supports the bottom-up processing and manifests in the disrupted sense of agency (DSOA).

The relationship between body ownership experiences and the sense of agency has a long research history and was examined by diverse methods and interpretation frames focusing on conscious and unconscious learning mechanisms, neurocognitive processing, self-representation, the current state-related self-consciousness, and predictive coding models (see in a review by Tsakiris⁵⁰, Braun et al.,⁵⁷, Limanowski & Friston⁵⁸, Rossi Sebastiano et al.,⁵⁹). The object of the present study is a standard version of the rubber hand illusion task where rubber hand ownership and real hand disownership were assessed. Earlier findings indicated that the sense of agency associated with top-down organized goal-directed action, efferent copies, intentions, and competent and conscious control over the goal of action ensures a feedback loop for the predicted outcome^{13,28,57}. When the previously mentioned conditions for the sense of agency (SoA) are not met, the SoA becomes disrupted, resulting in a decrease in top-down processing activity and concurrently facilitating the enhancement of bottom-up functions.

In our data interpretation, three contradictions can be elaborated. First, the rate of real hand disownership is proportional to the rate of rubber hand ownership. Second, body schema and body image are organic parts of the body representation, however, the body image is controlled by visual, and body schema is controlled by proprioceptive stimuli. Third, two mental processes are going on parallel, top-down and bottom-up. The level of these functions is variable and depends on the rate of personal cognitive control that manifests in a typical experience, namely in the senses of agency.

Considering the main elements of the body representations, the increased ownership may be associated with increased malleability in the visually dominated body image. Moreover, real hand disownership may be linked to decreasing proprioceptive sensitivity in the real hand. The higher rate of proprioceptive drift indicates the RHI induces an automated recalibration in the reference frame of the body representation. Therefore, the attention resources between the rubber and the real hand are shared and compensated⁵⁰. This compensation may be a result of a bottom-up automatic inference. Nevertheless, an unresolved question remains open; where can the domain of voluntary action-based agency be located within this recalibration process? Additionally, what cognitive steps are necessary to validate the modifications in body representation? Our data indicated that the

inhibited voluntary actions and the associated disrupted sense of agency facilitate uncontrolled modifications in body representation. However, the uncertainty resulting from recalibration triggers an effort to maintain cognitive control over the body schema and image reality. Conceptualizing this uncertainty may be achievable through heightened cognitive activity and psychological reference-taking. However, the substantial impact of this conceptualization cannot be manifested within the context of the RHI setting.

RHI induction mobilizes fantasies, worries, feelings of control, intentions, and attributions. Most participants focus on the phenomenological response to the RHI^{24,60}. Individuals address cognitive challenges to preserve a clear differentiation between real and unreal experiences. Others aim to form parallel representations to view reality from two perspectives. These strategies work within an integrated frame of reference. Shifting and drifting the unstable focus of attention between first and third-person perspectives is an essential part of the RHI induction^{2,54,61}. The participant's attentional focus is shared between the experimenter or stimulation machine (or assistant) and the participant's personal views of his or her body experiences. The change in body representation during the RHI induction can be interpreted from different perspectives⁵⁷. The body can be conceptualized through the reflective system with high cognitive control and self-awareness⁵⁰. On the other hand, it can be described through the reflexive system with multisensory integration, lower cognitive control, and lower self-awareness^{49,62,63}. The body's frame of reference depends on task demands or individual biases that fluctuate between foreground (reflective) and background (reflexive processes). The changes in body representation depend on personal cognitive and motor involvement, manifested in the rate of agency activity. Both external objects and internal personal sensations are salient agents in an individual peripersonal space^{14,64}. People have the feeling: "When I do something, I perceive that I am doing something". The source of our study is an earlier observation: completing the RHI task, the participant focuses on both their body-related sensations and the social context of the examination, "what" and "where" the experimenter is doing in the current moment. Attention fluctuates between external and internal events. Attention oscillates between external and internal stimuli. The extent of this oscillation is reflected in the sense of agency score when a participant (initiator, donor) is subjected to the event or (endures, adopts) objects to actions.

Consequently, participants must ask themselves: "Who is the main actor in this state?" "Am I the agent or another person?" On the other hand, the experimental setup and instructions limit participants' voluntary motor activity during RHI induction. We assumed the attentional fluctuation between external and internal events and the limitations of motor activity trigger an individual response to understand and solve the task in this specific environment. The response to this requirement is manifested in experimental settings that relate to both conceptualization and the sense of agency. Our results showed that the conceptualization of the RHI setting did not provide any predictive effect on the RHI sensitivity. However, the sense of agency plays a role in increasing or decreasing RHI sensitivity. A disrupted sense of agency predicts heightened sensitivity, whereas an elevated sense of agency predicts reduced sensitivity to the induction of the rubber hand illusion.

Considering previous findings, three main theoretical models can account for interpreting the role of a sense of agency in the RHI. The comparator model^{27,28,65} emphasizes that the intention of a designed action, the efferent copy, is a prerequisite for developing an experience of self-integrity and predictability of the consequence of an action and the associated sense of agency. In our current experimental condition, the RHI setting does not provide any motor action for the participant, so the ability to develop an efferent copy and design a goal-directed behavioral outcome cannot be expected. Consequently, control over the incoherent multimodal stimuli remains outside of competent control and the associated sense of agency experience. This disruption in the sense of agency opens a clear path for bottom-up cognitive processing and reduces the stable presence of the body representation. Simultaneously, visually dominant multimodal stimulation enhances the perceptual weighting of the rubber hand's position within peripersonal space, thereby facilitating its embodiment.

Another interpretation approach, the apparent mental causality model^{28,66,67} focuses on the priority of the cause, which relates to the goal of mental or physical action. Fitting this model to the RHI shows that the visually dominated position of the rubber hand, located in the peripersonal space of the RHI setting, cueing the dominant target is a relevant object when the rubber hand and the real hand receive consistent synchronous tactile stimulation. The time scale of stimulation is visually congruent but the felt tactile stimulation is spatially incongruent. Eliminating this incongruence between body image (visible rubber hand) and body schema (tactile perception in the real hand) leads to a double solution. The target (rubber hand) remained in the focus of perception as a detached body part. Conversely, the proprioceptive signals of the invisible real hand and their perception are suppressed. This is a typical psychological defense mechanism called driftage or displacement. These mechanisms are commonly identified in healthy and clinical populations in the case of anxiety and schizophrenia spectrum disorder, or problems accepting transplanted organ donation^{6,7,62,68–70}.

The two-step model posits two integrated types of sense of agency^{27,70}. When considering mental processing it involves bottom-up and top-down processes, however, depending on its examination context and the individual biases in different weighting. The Feeling of Agency (FoA) is contingent upon an individual's state and is predominantly shaped by a bottom-up cognitive approach linked to non-conceptual processes. It also encompasses unconscious inferences. On the other hand, the Judgment of Agency (JoA) is trait-dependent and activated by personally salient conditions, leading to higher-level conceptual and interpretative judgments about one's actions or control over events in the environment^{27,28}. The expression of FoA and JoA depends on task demands and the type of mental control involved in achieving behavioral outcomes. Our research indicates that the RHI setting and instructions inhibit the expression of effective mental control and the emergence of JoA. Additionally, thought to be conceptualization functions (including cognitive activity and psychological reference-making) are linked to higher-order control processes. However, despite their role, they cannot sufficiently mobilize mental resources to prevent the alterations in an individual's body representation induced by the RHI. Consequently, the cognitive control of the RHI setting is decreased and simultaneously the Feeling of agency is regressed. Subsequently, the automatic recalibration of body image and schema representations

occurs, and alongside the elicited uncertainty, the sensitivity to the RHI induction increases. In the second stage of the sense of agency, the Judgment of Agency-related function strives to mitigate the effect of the incongruent condition on body representation. However, the judgmental action-related functions result in only limited success. Conversely, a decrease in RHI sensitivity may be observed in individuals who exhibit a strong cognitive control bias towards managing congruent and incongruent environments, coupled with extensive training in decision-making under ambiguous conditions.

In summary, the content analysis of the RHI post hoc interview indicates that incoherent multimodal stimulation results in a disrupted sense of agency for most of the participants. The presented data support the view that verbal expression of this disruption in the sense of agency points to a dissociation between the feeling of agency, and judgment of agency. The stages of two dynamic components coexist to evoke body representation instability and enhance the sensitivity to the RHI induction. When these components of the sense of agency are disrupted, the capacity for top-down conceptualization is constrained, and the likelihood of instability in body representation and self-integrity is increased^{50,68}. This cognitive and psychophysiological uncertainty may also be manifested in cognitive symptoms of schizophrenia spectrum disorders^{24,69,70}. This possibility has been reported in several studies^{24,58,67}. However, in those cases when the top-down processing remains adequate the shorter or longer disruption of the agency may result in a creative outcome^{70–72}.

Conclusion

The present research demonstrated a comprehensive approach to analyzing the linguistic aspects of responses to the rubber hand illusion. The results showed that sensitivity to changes in body representation induced by rubber hand illusions depends on the rate of different components of the sense of agency. The study supports the previous suggestion that understanding the cognitive mechanism in the rubber hand embodiment necessitates a detailed analysis of both the feeling of agency and the judgment agency. In research on social adaptation, the agency is a fundamental factor in investigations in experimental conditions, natural environments, and computer-generated environments. Higher or lower agency is a valid method to assess the effect of incoherent and coherent stimulus patterns on self-integration capabilities. The type of coping depends on the individual's bias in dealing with undesirable and unpredictable environments. The presented result can be interpreted within the framework of the current sense of agency theories and describes a dynamic process that may be used in healthy individuals, during the therapeutic care of psychiatric patients, patients with transplanted organs after surgical procedures, and maladaptive use of digitally constructed media effects and environments.

Limitation

In this study, the assessment of the sense of agency was based exclusively on the ratio of passive to active words and phrases. The other components of a sense of agency—intention, goal-directed behavior, consciousness, and activation of efferent copy—were not evaluated, as the standard RHI paradigm used limits proper voluntary motor actions. Consequently, these agency elements were not considered. Numerous neuropsychological studies have elucidated the structural underpinnings of the sense of agency, ownership, and disownership experiences. Neural networks are implicated in these phenomena and contextually linked additional components, or closely integrated systems^{73,74}. This study does not utilize neuroscience methodologies; consequently, it does not address debates concerning the functional integrity or autonomy mechanisms underlying the sense of agency and ownership experiences.

Data availability

Data are in a repository, include hyperlinks and persistent identifiers for the data where available. <https://osf.io/tnwpa/>.

Received: 28 June 2024; Accepted: 4 November 2024

Published online: 20 November 2024

References

1. Botvinick, M. & Cohen, J. Rubber hand's 'feel' touch that the eyes see. *Nature*. **391**, 756 (1998).
2. Gallagher, S. *How the body Shapes the mind* (Oxford University Press Oxford UK, 2005).
3. de Vignemont, F. Bodily feelings: Presence, agency, and ownership. In (ed Kriegel, U.) *The Oxford Handbook of the Philosophy of Consciousness* (82–101). Oxford University Press. (2020).
4. Dijkerman, H. C. & Haan, E. H. F. Somatosensory processes subserving perception and action. *Behav. Brain Sci.* **30**, 189–239. <https://doi.org/10.1017/S0140525X07001392> (2007).
5. Blanke, O. & Metzinger, T. Full-body illusion and minimal phenomenal selfhood. *Trends Cogn. Sci.* **13**, 7–13 (2009).
6. David, N., Newen, A. & Vogeley, K. The "sense of agency and its underlying cognitive and neural mechanisms. *Conscious. Cogn.* **17**, 523–534 (2008).
7. Sattin, D. et al. An overview of the body schema and body image: Theoretical models, methodological settings and pitfalls for rehabilitating persons with neurological disorders. *Brain Sci.* **13**, 1410. <https://doi.org/10.3390/brainsci13101410> (2023).
8. Gerstmann, J. The problem of imperception of disease of impaired body territories with organic lesions. Relation to body scheme and its disorders. *Arch. Neurol. Psychiatry.* **48**, 890–913 (1942).
9. Paillard, J. Vectorial versus configural encoding of body space a neural basis for a distinction between body schema and body image. In (eds Knockaert, V. & Prester, D.) *Body Image and body schema. Interdisciplinary Perspectives.* (89–109). John Benjamin, Amsterdam. (2005).
10. Hargitai, R. et al. Linguistic markers of depressive dynamics in self-narratives: Negation and self-reference. *Empir. Text. Cult. Res.* **3**, 26–38 (2007).
11. von Elk, M. & Blanke, O. The relationship between body semantics and spatial body representations. *Acta. Psychol.* **138**, 347–358 (2011).

12. P McAdams, D. Narrative identity: what is it? What does it do? How do you measure it? *Imagination Cognit. Personal. Conscious. Theory Res. Clin. Pract.* **37**(3), 359–372 (2018).
13. Haggard, P. Sense of agency in the human brain. *Nat. Rev. Neurosci.* **18**(4), 196–207. <https://doi.org/10.1038/nrn.2017.14> (2017).
14. D'Angelo, M. et al. The sense of agency shapes body schema and peripersonal space. *Sci. Rep.* **8**, 13847. <https://doi.org/10.1038/s41598-018-32238-z> (2018).
15. Aaltonen, S. Trying to push things through: forms and bounds of agency in transitions of school-age young people. *J. Young Stud.* **16**, 375–390 (2013).
16. Konopasky, A. W. & Sheridan, K. M. Towards a diagnostic toolkit for the Language of Agency. *Mind Cult. Activity.* **23**(2), 108–123. <https://doi.org/10.1080/10749039.2015.1128952> (2016).
17. Krugwasser, A. R., Stern, Y., Faivre, N., Harel, E. V. & Salomon, R. Impaired sense of agency and associated confidence in psychosis. *Schizophrenia (Heidelb.)* **2**, 8(1), 32. (2022). <https://doi.org/10.1038/s41537-022-00212-4>
18. Schwoebel, J. & Coslett, H. B. Evidence for multiple, distinct representations of the human body. *J. Cogn. Neurosci.* **17**, 543–553 (2005).
19. Petkova, V. I., Khoshnevis, M. & Ehrsson, H. H. The perspective matters! Multisensory integration in ego-centric reference frames determines full-body ownership. *Front. Psychol.* **2**(35), 1–7 (2011).
20. Lewis, E. & Lloyd, D. M. Embodied experience: a first-person investigation of the rubber hand illusion. *Phenomenol. Cogn. Sci.* **9**(3), 317–339. <https://doi.org/10.1007/s11097-010-9154-2> (2010).
21. Matuz-Budai, T. et al. Individual differences in the experience of body ownership are related to cortical thickness. *Sci. Rep.* **12**, 808. <https://doi.org/10.1038/s41598-021-04720-8> (2022).
22. Roseboom, W. & Lush, P. Serious problems with interpreting Rubber Hand Illusion experiences. *Collabra Psychol.* **8**(1). <https://doi.org/10.1525/Collabra.32274> (2022).
23. Moguillansky, C. V., O'Regan, J. K. & Petitmengin, C. Exploring the subjective experience of the rubber hand illusion. *Front. Hum. Neurosci.* **23** (2013).
24. Kállai, J. et al. Temperament and psychopathological syndrome specific susceptibility for rubber hand illusion. *Psychiatry Res.* **229**, 410–419 (2015).
25. Pléh & Cs A tér és a nyelv világa. (Space and the language). MTA Kiadó Budapest. ISBN 978-963-508-723-5 (2014).
26. László, J. et al. Narrative language as an expression of individual and group identity: the narrative categorical content analysis. *SAGE Open* **3** <https://doi.org/10.1177/2158244013492084> (2013).
27. Synofzik, M., Voss, G. & Vosgerau, & The experience of agency: an interplay between prediction and postdiction. *Front. Psychol.* **4**, 127. <https://doi.org/10.3389/fpsyg.2013.00127> (2013).
28. Moore, J. W. What is the sense of agency and why does it matter? *Front. Psychol.* **7**, 3. <https://doi.org/10.3389/fpsyg> (2016).
29. Ehmann, B., Garami, V., Naszódi, B., Kis, B. & László, J. Subjective time experience: Identifying psychological correlations by narrative psychological content analysis. *Empir. Cult. Text. Res.* **3**, 14–25 (2007).
30. Lenggenhager, B., Mouthon, M. & Blanke, O. Spatial aspects of bodily self-consciousness. *Consciousness and Cognition*, 18 110–117. (2009).
31. Burin, D. et al. Relationships between personality features and the Rubber Hand Illusion: an exploratory study. *Front. Psychol.* **10**, 2762. <https://doi.org/10.3389/fpsyg.2019.0276> (2019).
32. Oldfield, R. C. The assessment and analysis of handedness: the Edinburgh Inventory. *Neuropsychologia* **9**, 97–113 (1971).
33. Longo, M. R., Schur, F., Kammers, M. O., Tsakiris, M., Haggard, P. & What is embodiment? A psychometric approach. *Cognition* **107**, 978–998 (2008).
34. Jsselsteijn, W. A., de Kort, Y. A. W. & Haans, A. Is this my hand I see before me? The rubber hand illusion, in reality, virtual reality, and mixed reality. *Presence* **15**(4), 455–464 (2006).
35. Rohde, M., Di Luca, M. & Ernst, M. O. The Rubber Hand Illusion: feeling of ownership and proprioceptive drift do not go hand in hand. *PLoS One* **6**(6), e21659. <https://doi.org/10.1371/journal.pone.0021659> (2011).
36. Chancel, M. & Ehrsson, H. H. Proprioceptive uncertainty promotes the rubber hand illusion. *Cortex* **165**, 70–85 (2023).
37. Lanfranco, R. C., Chancel, M. & Ehrsson, H. H. Quantifying body ownership information processing and perceptual bias in the rubber hand illusion. *Cognition* **238**, 105491 (2023).
38. Lopez, C., Bieri, C. P., Preuss, N. & Mast, F. W. Tactile and vestibular mechanisms underlying ownership for body parts: A non-visual variant of the rubber hand illusion. *Neurosci. Lett.* **511**(2), 120–124. <https://doi.org/10.1016/j.neulet.2012.01.055> (2012).
39. Pennebaker, J. W. *The Secret life of Pronouns: How our Words Reflect who we are* (Bloomsbury, 2012).
40. Jenkins, A. H. Psychological agency: A necessarily human concept. In: (ed Frie, R.) *Psychological Agency: Theory, Practice, and Culture*. MIT Press. (2008).
41. Yamaguchi, S. Culture and control orientations. In: (ed Matsumoto, D.) In: *The Handbook of Culture and Psychology*. 223–243. Oxford University Press, Oxford. (2001).
42. Penelope, J. *Speaking Freely* (Pergamon, 1990).
43. Szalai, K. & László, J. Activity as a linguistic marker of agency: Measuring in-group versus out-group activity in Hungarian historical narratives. *Empir. Text. Cult. Res.* **4**, 50–58 (2010).
44. Pólya, T., Kengyel, G. J. & Budai, T. Narrative construction of product reviews reveals the level of post-decisional cognitive dissonance. *Information* **12**, 46. <https://doi.org/10.3390/info12010046> (2021).
45. László, J., Ehmann, B., Pólya, T. & Péley, B. Narrative psychology as a science. *Empir. Text. Cult. Res.* **3**, 1–13 (2007).
46. Balconi, M. Disruption of the sense of agency: From perception to self-knowledge. In M. Balconi (ed.), *Neuropsychology of the sense of agency: From consciousness to action* (pp. 125–143). Springer-Verlag Publishing/Springer Nature. (2010). https://doi.org/10.1007/978-88-470-1587-6_7
47. Hu, L. & Bentler, P. M. Fit indices in covariance structure modeling: sensitivity to under-parameterized model misspecification. *Psychol. Methods* **3**(4), 424–453. <https://doi.org/10.1037/1082-989X.3.4.424> (1998).
48. Browne, M. W. & Cudeck, R. Alternative ways of assessing model fit. *Sociol. Methods Res.* **21**(2), 230–258. <https://doi.org/10.1177/0049124192021002005> (1992).
49. Ehrsson, H. H., Holmes, N. P. & Passingham, R. E. Touching a rubber hand: feeling of body ownership is associated with activity in multisensory brain areas. *J. Neurosci.* **25**, 10564–10573. <https://doi.org/10.1523/JNEUROSCI.0800-05.2005> (2005).
50. Tsakiris, M. My body in the brain: a neurocognitive model of body-ownership. *Neuropsychologia* **48**, 703–712 (2010).
51. Thakkar, K. N., Nichols, H. S., McIntosh, L. G. & Park, S. Disturbances in body ownership in schizophrenia: evidence from the Rubber Hand Illusion and case study of a spontaneous out of body experience. *PLOS ONE* **6**(10), e270891–e270899 (2011).
52. Holmes, N. P., Snijders, H. J. & Spence, C. Reaching with alien limbs: visual exposure to prosthetic hands in a mirror biases proprioception without accompanying illusions of ownership. *Percept. Psychophys.* **68**, 685–701 (2006).
53. Albrecht, M. A., Graham, K., Martin-Iverson, M. T. & Waters, F. The rubber hand illusion: manipulating our sense of body experience. In (eds Cavanna, A. E. & Nani, A.) *Consciousness: States, Mechanisms and Disorders* (139–162). Nova Science. (2012).
54. Thériault, R., Landry, M. & Raz, A. The Rubber Hand Illusion: top-down attention modulates embodiment. *Q. J. Experimental Psychol.* **75**, 2129–2148 (2022).
55. Paladino, M. P., Mazzurega, M., Pavani, F. & Schubert, T. W. Synchronous multisensory stimulation blurs self-other boundaries. *Psychol. Sci.* **21**(9), 1202–1207 (2010).
56. Farmer, H. & Tsakiris, M. The bodily social self: a link between phenomenal and narrative selfhood. *Rev. Phil Psych.* **3**, 125–144. <https://doi.org/10.1007/s13164-012-0092-5> (2012).

57. Braun, N. et al. The senses of Agency and Ownership: a review. *Front Psychol.* **16**(9), 535 (2018). <https://doi.org/10.3389/fpsyg.2018.00535>
58. Limanowski, J. & Friston, K. J. Attention modulation of vision versus proprioception during action. *Cereb. Cortex*, **30**, 1637–1648.
59. Rossi Sebastiano, A. R. et al. Balancing the senses: electrophysiological responses reveal the interplay between somatosensory and visual processing during the body-related multisensory conflict. *The Journal of Neuroscience*, **44**(19):e1397232024 (2024). <https://doi.org/10.1523/jneurosci.1397-23.2024>.
60. Asai, T., Mao, Z., Sugimori, E. & Tanno, Y. Rubber hand illusion, empathy, and schizotypal experiences in terms of self-other representation. *Conscious. Cogn.* **20**, 1744–1750 (2011).
61. Fiorio, M., Modenese, M. & Cesari The rubber hand illusion in hypnosis provides new insights into the sense of body ownership. *Sci. Rep.* **10**, 5706 (2020).
62. Kahneman, D. *Thinking, fast and slow* (Farrar, Straus and Giroux, 2011).
63. Evans, J. B. T. & Stanovich, K. E. Dual-process theories of higher cognition: advancing the debate. *Perspect. Psychol. Sci.* **8**(3), 223–241. <https://doi.org/10.1177/1745691612460685> (2013).
64. Smit, M. et al. Changes in perceived peripersonal space following the rubber hand illusion. *Sci. Rep.* **13**, 7713. <https://doi.org/10.1038/s41598-023-34620-y> (2023).
65. Frith, C. The self in action: lessons from delusions of control. *Conscious. Cogn.* **14**, 752–770. <https://doi.org/10.1016/j.concog.2005.04.002> (2005).
66. Wegner, D. M. & Wheatley, T. Apparent mental causation. Sources of the experience of will. *Am. Psychol.* **54**, 480–492 (1999).
67. Chambon, V., Sidarus, N. & Haggard, P. From action intentions to action effects: how does the sense of agency come about? *Front. Hum. Neurosci. Rev.* <https://doi.org/10.3389/fnhum.2014.00320> (2014).
68. Braun, N., Thorne, J. D., Hildebrandt, H. & Debener, S. Interplay of agency and ownership: the intentional binding and Rubber Hand Illusion paradigm combined. *PlosOne*. **9**(11), e111967. <https://doi.org/10.1371/journal.pone.0111967> (2014).
69. Graham, K. T., Martin-Iverson, M. T., Holmes, M. P., Jablensky, A. & Waters, F. Deficits in agency in schizophrenia and additional deficits in body image and body schema, internal timing in passivity symptoms. *Front. Psychiatry*. **5**, 126. <https://doi.org/10.3389/fpsyg.2014> (2014).
70. Moccia, L. et al. Sense of agency and its disturbances: A systematic review targeting the intentional binding effect in neuropsychiatric disorders. *PCN Psychiatry Clin. Neurosciences*. **78**, 3–18 (2024).
71. Blakemore, S.-J., Wolpert, D. M. & Tith, C. D. Abnormalities in the awareness of action. *Trends Cogn. Sci.* **686**, 237–242 (2002).
72. Romano, D., Maravita, A. & Perugini, M. Psychometric properties of the embodiment scale for the rubber hand illusion and its relation with individual differences. *Sci. Rep.* **11**, 5029. <https://doi.org/10.1038/s41598-021-84595-x> (2021).
73. Seghezzi, S., Giannini, G. & Zapparoli, L. Neurofunctional correlates of body-ownership and sense of agency: a meta-analytical account of self-consciousness. *Cortex*. **121**, 169–178. <https://doi.org/10.1016/j.cortex.2019.08.018> (2019).
74. Pyasik, M., Burin, D. & Pia, L. On the relation between body ownership and sense of agency: a link at the level of sensory-related signals. *Acta. Psychol.* **185**, 219–228. <https://doi.org/10.1016/j.actpsy.2018.03.001> (2018).

Acknowledgements

This research project was funded by the National Research, Development, and Innovation Office under grant number NKFI K – 120334. OTKA FK 146604, and János Bolyai Research Scholarship provided by the Hungarian Academy of Sciences.

Author contributions

J.K. and T.S. and O.V. experimental design, conceptualization, wrote the main manuscript text. A.N.Z. prepared figures and conducted statistical analyses. B.E. and R.H. content analysis. Z.B. and V.P. collected interview data. All authors reviewed the manuscript.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1038/s41598-024-78822-4>.

Correspondence and requests for materials should be addressed to J.K.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by-nc-nd/4.0/>.

© The Author(s) 2024