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Community series in body representation and interoceptive awareness: Cognitive, affective, and social implications

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Community series in body representation and interoceptive awareness: Cognitive, affective, and social implications

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Editorial: Community series in body representation and interoceptive awareness: cognitive, affective, and social implications

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Editorial on the Research Topic
Community series in body representation and interoceptive awareness: cognitive, affective, and social implications

Introduction

The integration of multisensory signals from inside and outside the body is pivotal for building functional higher-order own body representations (BR) across the life span (Raimo et al., 2021a,b; Sorrentino et al., 2021; Boccia et al., 2023) and for self-consciousness (Park and Blanke, 2019; Quigley et al., 2021). However, exteroceptive and interoceptive bodily signals and their integrated neural representation can also influence other aspects of cognition spanning from understanding others' emotional experience (Canino et al., 2022; Raimo et al., 2023) to memory skills (Ianì, 2019; Messina et al., 2022). This point highlights the need to expand previous findings across the lifespan, providing empirical support to a specific interpretation of embodiment, according to which mental representations in bodily formats have an important role in cognitive, affective, and social processes (Goldman and de Vignemont, 2009).

Following a previous Research Topic titled "Body Representation and Interoceptive Awareness: Cognitive, Affective, and Social Implications" (Raimo et al., 2022), this Community Series features nine new articles that delve deeper into the relationship between BR, interoception, and cognitive and social processes both in childhood and adulthood.

Interoceptive processing, self-image, and higher-order cognitive and social processes

To address the role of interoceptive ability in cognition during childhood, Pollatos et al. investigate the association between interoceptive accuracy, measured by cardiac-perception, and decision-making in a large sample of 1,454 children (6–11 years). The authors observed a correlation between interoceptive accuracy and decision-making abilities in situations of varying complexity. In line with the somatic-marker hypothesis (Damasio, 1994), these findings suggest that a better access to somatic feedback, in terms of higher interoceptive accuracy, could be positively associated with the ability to forgo short-term benefit for long-term profit already in middle childhood.

Along the same lines, Zhou et al. propose a novel model exploring how interoception promotes action understanding in children. During early infancy, infants would understand others' actions through automatic interoceptive processing and feedback. Then, in infancy, the rapid development of proprioception would provide internal reference information for imitating others' actions. Finally, in early childhood, the development of the ability to combine multiple interoceptive information would facilitate integration of different kinds of internal and external information, which is pivotal for the mentalizing level of action understanding. The involved neural mechanisms are also discussed.

In adults, sex-related individual differences in interoceptive processing are explored by Alfano et al., who investigate functional connectivity of networks involved in interoceptive sensibility in male and female participants. Behaviorally, female participants showed a stronger attitude in self-perceiving their internal sensations. An association between levels of interoceptive sensibility and functional connectivity in the salience network and in fronto-temporo-parietal brain areas is also present, more marked in female participants.

Da Costa Silva et al. validate two self-report measures of body awareness in a non-clinical adult French-speaking sample: the Postural Awareness Scale and the Multidimensional Assessment of Interoceptive Awareness (version 2). The satisfactory internal consistency, construct validity, and reliability over time suggest that they are reliable tools for assessing proprioception and interoceptive sensibility.

Kim et al. explore the relationship between mental representations of self and social evaluation, examining the usefulness of visual proxies of self-image. The authors report that a visual proxy of mental representation of self (a classification image of self) could add independent information in predicting social evaluation and suggest a new computational scoring method to objectively assess classification image of self.

Finally, Wang et al. explore the effect of transcutaneous stimulation of the vagal nerve (central in relaying visceral signals to the brain and intrinsically involved in interoception) on cognition. Vagal nerve stimulation is combined with inhibitory control training for obtaining an "exogenous" online neuromodulatory effect and an "endogenous" activation of brain regions involved in inhibitory control. The results show a synergistic ameliorative effect on inhibitory control, thus providing a novel approach to be applied in healthcare contexts.

Higher-order functional BR and sense of body ownership

Cruz et al. present a study on the development of higher-order BR, exploring the role of body schema and body structural description (BSD) in the healthy and pathological development of children's *body image*, defined as body-related semantic-lexical knowledge (e.g., names of body parts). Using semantic word fluency tasks and graph analysis, the authors suggest that children's body image would be influenced by body schema, which is related to the sensorimotor experience, and BSD, which mainly derives from the visual experience. Also, children with cerebral palsy had poorer lexical-semantic knowledge of body parts, likely due to reduced sensorimotor and visuoperceptual experiences of the affected body parts.

Biran et al. examine BSD impairment in adults with complex regional pain syndrome (CRPS) and the consequent severe distress associated with body misrepresentation. Individuals with CRPS and healthy controls are given visual puzzles related to the human body or to non-human body objects. The participants with pain syndrome perform lower than controls only in the human body puzzle, showing a significant impairment of the topographical continuity of body parts.

Finally, Ruijia et al. focus on how individuals feel about their own deformed bodies, proposing an experimental setup called "monkey's hand", in which the participants take a posture that creates the illusion that one has only four fingers. The results reveal an ambiguous feeling of body ownership, since participants feel that the thumb is functionally absent but structurally present. The authors suggest that this does not imply a simple lack of ownership of the thumb but implies disownership, thus proposing that disownership is different from the mere absence of ownership.

In summary, the articles included in this Community Series provide new insight on BR and interoceptive dimensions, also highlighting their importance in shaping social and cognitive processes. Despite the newfound interest in embodied perspective of higher-order cognition and the evidence collected here, a unique model of how the sensorimotor, perceptual, and interoceptive BR affect various social-cognitive activities is still lacking, highlighting the need for further research in this field.

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Action Understanding Promoted by Interoception in Children: A Developmental Model

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Action understanding of children develops from simple associative learning to mentalizing. With the rise of embodied cognition, the role of interoception in action observation and action understanding has received more attention. From a developmental perspective, this study proposes a novel developmental model that explores how interoception promotes action understanding of children across ages. In early infancy, most actions observed in infants come from interactions with their caregivers. Babies learn about action effects through automatic interoceptive processing and interoceptive feedback. Interoception in early infancy is not fully developed, such as the not fully developed gastrointestinal tract and intestinal nervous system. Therefore, in early infancy, action understanding is based on low-level and original interoceptive information. At this stage, after observing the actions of others, infants can create mental representations or even imitate actions without external visual feedback, which requires interoception to provide internal reference information. By early childhood, children begin to infer action intentions of other people by integrating various types of information to reach the mentalizing level. Interoception processing requires the integration of multiple internal signals, which promotes the information integration ability of children. Interoception also provides inner information for reasoning about action intention. This review also discussed the neural mechanisms of interoception and possible ways by which it could promote action understanding of children. In early infancy, the central autonomic neural network (CAN) automatically processes and responds to the actions of caregivers on infants, providing interoceptive information for action understanding of infants. In infancy, the growth of the somatomotor system provides important internal reference information for observing and imitating the actions of infants. In early childhood, the development of interoception of children facilitates the integration of internal and external information, which promotes the mentalization of action understanding of children. According to the proposed developmental model of action understanding of children promoted by interoception, there are multilevel and stage-dependent characteristics that impact the role of interoception in action understanding of children.

Keywords: action, interoception, action understanding, children, development

INTRODUCTION

Understanding actionP is an important aspect of development of children. The multilevel model of action understanding proposed by Casartelli and Molteni (2014) explains that there are different and non-competitive types of action understanding, ranging from lower-level associative mechanisms to higher-level "mentalizing" abilities. Action understanding starts from simple stimulus-response association to understanding the action intention through mental processes such as cognitive reasoning. The development of action understanding of children is in line with the process of associative learning and mentalizing. For example, infants are able to automatically imitate mouth opening of someone (Meltzoff and Moore, 1977), and, by early childhood, children can speculate on the action intention of an executor (Meltzoff, 1995; Galilee and McCleery, 2016).

Interoception may play a cohesive role between action observation and understanding. Previous studies have emphasized the association between visual observation and actions of children but underestimated the role of interoception. For example, de Klerk et al. (2019) suggested that action imitation of children is formed through the coupling between perception and action. However, the disparity between the weak action ability and understanding of infants makes it difficult for simple perception-motor associations to explain the development of action understanding of children (Fotopoulou and Tsakiris, 2017). Meltzoff (2007) proposed that infants monitor their bodily acts and understand the actions of others *via* proprioception. In addition to proprioception, embodied simulation theory holds that there is a close relationship between interoception, action observation, and action understanding (Meltzoff and Moore, 1997; Freedberg and Gallese, 2007).

Interoception refers to the sense of the physiological condition of own body of an individual, such as hunger, satiety, and thirst. It includes visceroception of the heart, stomach, lung, and other viscera and proprioception of the skin, muscles, and bones (Garfinkel et al., 2015a). Interoception is present since the early years, developing rapidly during infancy (Quattrocki and Friston, 2014; Brewer et al., 2015). Although the metacognitive component of interoception continues to develop well into adolescence, other aspects (e.g., objective interoceptive sensitivity) reach maturity in childhood (Murphy et al., 2017). Indeed, interoception growth of children is a prerequisite for understanding their actions (Bowman et al., 2017; Nicholson et al., 2019). For example, the polyvagal theory suggests that there are distinct autonomic subsystems in mammals. These subsystems are related to social communication (such as facial expression) and responsive behavior (such as fight-flight behaviors and behavioral shutdown). Compared with the polyvagal theory, this study considers that the interoception processing involves not only the autonomic nervous system but also the joint processing of multiple brain regions. Action understanding of children changes with age, and thus, the role of interoception on action understanding of children may undergo changes as well.

Therefore, this study established a developmental model of action understanding of children as promoted by interoception. We argued that interoception is the main driver of action understanding in development. As shown in **Figure 1**, the model suggests that action understanding of children develops with age, going through different stages, including simple act association in early infancy, action observation and imitation in late infancy, and action mentalizing in early childhood. At different stages, the role of interoception in promoting the development of action understanding of children is different. This study discusses in detail how interoception promotes action understanding of children at different developmental stages.

INTEROCEPTION PROMOTES THE DEVELOPMENT OF CHILDREN'S ACTION UNDERSTANDING

Action Association Originates From Interoception

Interoception has inheritable traits and develops in early infancy (Klabunde et al., 2019). Although not mature, infant interoception allows infants to interact with the external environment and others. Initial action understanding is based on interoceptive feedback about what is necessary for survival. Consider thirst as an example. At first, infants only perceive the bodily signal of thirst, but they have not experienced drinking water and receiving feedback afterward. Therefore, infants do not understand why caregivers give them water at first. Only after experiencing drinking water for some time are infants able to associate the interoception of thirst and the action of drinking water, thereby understanding the feeding action of caregivers (Harshaw, 2008). Human newborns can establish classical conditioned reflex by associating sensory stimuli with simultaneous stimuli. The simple association also is adaptive according to the feedback (Lipsitt, 1990). The classical or operant conditionings also support early association learning of infants between interoception and action. Quattrocki and Friston (2014) proposed that infants associate the interoceptive signals of warmth or fullness with caregivers, thus promoting the interaction between infants and caregivers and social development.

The actions observed by early infants are mainly directed at themselves, which allows them to understand actions through interoceptive feedback. Newborns are unable to perform most actions required for survival (e.g., eating, drinking water, and going to the toilet), thus, relying on their caregivers (Reddy and Uithol, 2016). Therefore, in early infancy, because infants do not actually experience these actions, it is difficult for them to understand actions through sensorimotor associations (Cañal-Bruland et al., 2010). Instead, when infants perceive the actions of other people, interoceptive information feedback facilitates their understanding of and responses to actions. For example, Fairhurst et al. (2014) found that infants can understand and respond to different stroking actions. When a caregiver caresses a 9-month-old baby at a moderate speed, the heart rate of the baby slows down and becomes quiet. Infants younger than 6 months of age provide feedback to their mothers if they are

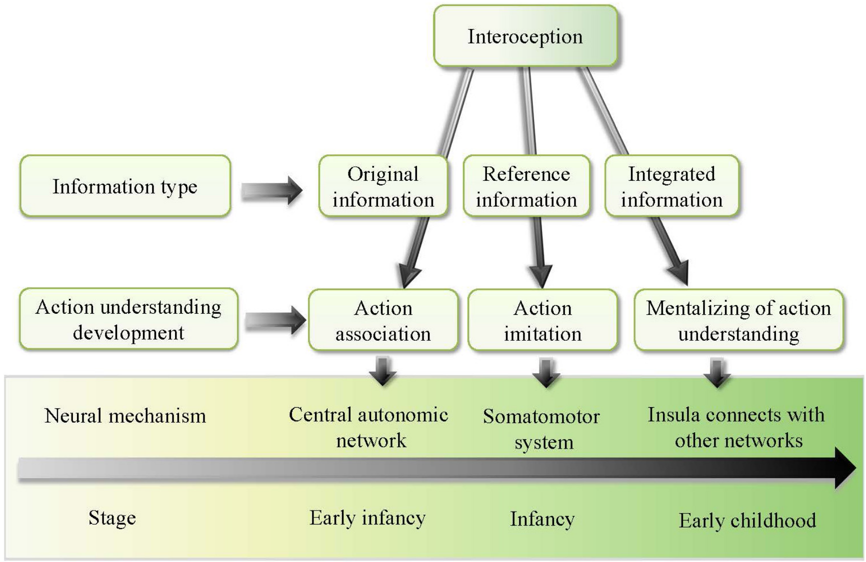

FIGURE 1 | Developmental model of action understanding of children promoted by interoception.

in an uncomfortable holding posture through crying and other behaviors (Esposito et al., 2013).

Through bottom-up interoceptive feedback, infants can even have predictive responses to the actions of others (Murphy et al., 2017). Infants as young as 2 or 3 months can respond predictably to their actions of caregivers. For example, proprioception from being held up by adults allows 2-month-old babies to adjust the stiffness of their bodies as adults reach for them (Reddy et al., 2013). An electroencephalography (EEG) study of infant somatosensation found a significant bilateral mu desynchronization over the frontocentral cortex of an infant before somatosensory stimulation. The finding suggests infant prediction of somatosensory stimulation (Shen et al., 2021). Visceroception from the stomach allows infants to open their mouths in advance in response to the sight of the caregiver with a spoon (Brisson et al., 2012). Moreover, predicting actions can further regulate interoception and promote interpersonal interactions. For instance, the gastrointestinal tract and intestinal nervous system are not fully developed at birth (Gershon, 1999), and different feeding methods (e.g., breastfeeding vs. bottle feeding) determine the feeding actions of mothers, to which infants adjust their internal state (Bramhagen et al., 2006).

In sum, during early infancy, infants observe the actions of others and understand them through interoceptive feedback. However, due to the immaturity of interoception of infants based on internal scattered physiological signals and direct association learning, action understanding of children is still limited at this stage.

Action Imitation Based on Proprioception

Around 1–3 years of age, toddlers observe actions that not only orient them but also point to other targets. At this developmental stage, children consciously imitate an action after observing it (Subiaul et al., 2016); thus, interoception like the sense of body agency and ownership plays an important role in both action observation and imitation (Gao et al., 2019). In action observation, the mirror mapping of actions requires internal body representation (Freedberg and Gallese, 2007). The theory of embodied simulation holds that internal representation provides the processing mechanism of action observation and understanding (Cañal-Bruland, 2017). The observer establishes the corresponding relationship between the observed action and the corresponding internal representation in the brain (Rizzolatti and Sinigaglia, 2010). For example, young children correct their imitative facial responses, which suggests a visual-proprioceptive cross-modal matching process (Meltzoff and Moore, 1997; Marshall and Meltzoff, 2014). Studies have shown that action observation is robustly associated with the activation of the primary somatosensory cortex (Caspers et al., 2010), demonstrating the connection between proprioceptive and external senses, such as visual perception. The observed actions are imitated and coordinated through the ventral anterior motor cortex to understand the motion components of actions (Gazzola and Keysers, 2009).

Interoception processing of children develops from the scattered internal bodily information to its integration into a whole and unified internal representation and from unconscious interoceptive processing to conscious control (Murphy et al., 2017). This development allows action representation of children. Infants form their own body schema in the first 6 months of life, which develops rapidly during the next 2 years (Keromnes et al., 2019). Proprioception improvement provides an internal reference for children to understand the observed actions and imitate them without looking at their bodies. According to the AIM (active intermodal mapping) model of Meltzoff and Moore, infant imitation is affected by three components, namely, the body part used, the action performed, and the goal achieved (Meltzoff and Moore, 1997). Body representation is indispensable in infant imitation. For example, in an EEG study of 14-month-old infants, those who observed actions that involved the hand or foot had stronger desynchronization of the mu rhythm in the corresponding areas of the sensorimotor cortex (Saby et al., 2013).

Due to the immaturity of proprioception, it is still challenging for infants within 1 year of age to imitate and understand actions through internal representation. Infants younger than 6 months mainly focus on action production from different body parts (Reddy et al., 2013; Reddy, 2015). For 9-month-olds, it is still difficult to imitate contralateral actions because of poor contralateral representation (Boyer and Bertenthal, 2016). However, from 2 years of age, with the improvement of proprioception, children can better imitate the observed actions based on a unified internal representation. For example, Yoo et al. (2016) investigated the EEG activity of 9- and 12-month-old infants when they observed purposeful actions and performed the same actions. The results showed that 1-year-olds showed activation in their own sensorimotor regions when they observed actions, and they were able to establish a corresponding relationship between the observed actions and their own actions. At the age of 3 years, children are more proficient in proprioception and body control (Rochat and Morgan, 1995). Well-developed proprioception can help children to observe and imitate actions without being limited by specific action effectors (Caspers et al., 2010) as well as to form a holistic action understanding in the brain through internal representation.

In infancy, the rapid development of proprioception of children provides an internal reference for observing and imitating the actions of others. According to the AIM model, when observing and producing actions, children need to pay attention to the body part used in the action, performance of actions, and goals (Meltzoff and Moore, 1997). The dual attention system (Corbetta and Shulman, 2002) proposes two different attention systems. The goal-driven (i.e., top-down) attention system, which includes parts of the intraparietal cortex and superior frontal cortex, is involved in goal-directed selection for stimuli and responses. The stimulus-driven (i.e., bottom-up) attention system, which includes the temporoparietal cortex and inferior frontal cortex, is more sensitive to behaviorally relevant detailed stimuli. In the process of observing and producing actions, when children spend less of their internal resources on the action details, they will pay more attention to inferring the intention or purpose of the actions of others (Arnold et al., 2019).

Integrated Processing of Interoception Promotes Mentalizing of Action Understanding

Interoception regulates and maintains the balance of the internal environment of the body (Sterling, 2012; Craig, 2015). It integrates multimodal sensory information, including bottom-up input signals from the body and top-down regulatory instructions from the central nervous system (Sterling, 2012; Arnold et al., 2019). Internal signals such as temperature, pain, and heart rate need to be transmitted to the central nervous system through internal sensory afferent receptors such as thermoreceptors, chemoreceptors, mechanoreceptors, and baroreceptors (Berntson and Khalsa, 2021). These interoceptive afferent nerves are widely distributed, unmyelinated, and thin nerve fibers that innervate internal sensors. Interoceptive signals are not definite, single signals (Quigley et al., 2021). For example, cardiovascular information is signaled by different sensors that encode the occurrence, intensity, blood pressure, and neurovascular afferent signals of the heartbeat (Zeng et al., 2018). Therefore, unlike visual or auditory perception, interoceptive signals conveyed by multiple sensors in a non-synchronous way need to be integrated (Petzschner et al., 2021).

Therefore, interoception processing requires the interaction between the brain and body to achieve a dynamic balance by integrating multisensory information (Bonaz et al., 2021). Interoception is controlled not only by the central autonomic neural network (CAN) (Berntson and Khalsa, 2021) but also by high-order neural networks such as the insula (Craig and Craig, 2009). The regulation of the internal state of the body by the brain needs to integrate a variety of information for recognition and inference. Taking breathing as an example, the respiratory rhythm is produced in the brainstem, usually in an unconscious state, but also through the top-down cognitive function to identify and infer the interoceptive signal, and through the emotional control network to change the internal state (Weng et al., 2021). In interoception inference, the central nervous system estimates the internal state using an approximate Bayesian inference. The central nervous system uses sensory data with various uncertainties and noises to verify the prediction model based on *a priori* in real time to estimate the internal state (Barrett and Simmons, 2015; Barrett et al., 2016).

The interoceptive processing mode has an important influence on mentalizing, such as action understanding and intention reasoning (Murphy et al., 2017). Infancy is an important stage of interoception. Numerous interoceptive signal processes, such as hunger, satiety, thirst, and muscle tension, are mainly formed during infancy (Harshaw, 2008). However, at this early stage, babies are not proficient at processing or regulating interoceptive signals and often process them in an implicit way (Murphy et al., 2017). With the improvement of interoception in children, including continuous attention and cognitive monitoring, their interoception awareness is also enhanced (Garfinkel et al., 2015b; Weng et al., 2021), allowing them to control and regulate interoception processing in a top-down manner (Klabunde et al., 2019). At the age of 4 years, interoceptive processing of children affects their reasoning and ability to predict action intentions of people.

At the age of 4 years, children are able to understand action intentions, and their action understanding reaches the mentalizing level (Ansuini et al., 2015). Inferring an action intention is challenging for children because the relationship between action and intention is not a one-to-one mapping (Csibra, 2007; Jacob, 2013), that is, the same actions may have different intentions. For example, if someone suddenly waves their hand when walking on the street, their intention may be to take a taxi or drive a wasp away (Kilner et al., 2007a). Thus, to understand action intentions of others, we made inferences based on multiple information (e.g., actions and situation). For example, through situation information, such as a taxi near the street, we can speculate the intention of a waving action (Kilner et al., 2007a); through the expression or kinematic information of an action, such as a gesture holding a cup, we can guess whether a friend wants to drink. Therefore, integrating multiple information to make inferences plays an important role in action understanding. Indeed, the predictive coding model assumes that action understanding requires the establishment of multiple prediction models based on the integration of internal and external information as well as choosing the priority model based on the principle of minimizing the prediction error (Kilner et al., 2007b; Kilner, 2011; Clark, 2013).

Action understanding, which is based on the integration and processing of various types of information, creates a model for reasoning and predicting similar to the interoception processing model. In that sense, the interoception processing model developed in the early years promotes action understanding mentalizing. Interoceptive information is also integrated into action understanding processing, providing internal information for action reasoning. For example, a study on 3–5-year-olds showed that their internal representation is closely related to their action development, having a significant predictive effect on individual differences of 3–5-year-olds in mentalizing (Meltzoff, 2013). Studies further found that only when the action external information and internal representation are fully integrated can advances in action understanding promote mentalizing of children (Bowman et al., 2017).

The Neural Mechanisms Involved in Interoception and Action Understanding

The Central Autonomic Network in Action Association

Within 1 year of age, the direct feedback of low-level interoceptive information promotes the establishment of action associations of children. Low-level interoceptive information is controlled mainly by the CAN. Similar to the brainstem, the nucleus tractus solitaries (NTS) receives afferent interoceptive information from the spinal cord or vagus nerve (Berntson and Khalsa, 2021). The CAN includes the anterior cingulate forebrain, amygdala, hypothalamus, and brainstem, and it is an internal regulatory system that controls visceral movement, neuroendocrine activity, and other vital internal signals for survival (Benarroch, 1993). The CAN receives the down-up interoceptive signals and reflects automatically, allowing the individual to adapt to the changing internal or external environment and be in a stable state (Beissner et al., 2013).

Interoception is often unconscious (Bonaz et al., 2021). For example, visceral regulation is considered to be mainly composed of low-level reflexive mechanisms, which are autonomous processes (de Groat and Tai, 2015). The NTS is a typical visceral information-receiving area (Berntson and Khalsa, 2021). Although interoception is also regulated by the cerebral cortex and affects high-level information processing, studies have shown that visceral signals affect higher neurobehavioral processes (Berntson et al., 2003). However, interoception awareness in early childhood is not fully developed (Klabunde et al., 2019). Therefore, during infancy and childhood, unconscious rather than conscious interoception processing mainly promotes understanding of action associations by children.

Moreover, interoception of infants is closely associated with their behavioral interactions of caregivers. For example, when the hypothalamus of an infant detects lower-than-baseline blood glucose levels, a crying response will be elicited, prompting the caregiver to feed the infant and balance his/her internal needs (Pezzulo et al., 2015). The CAN controls and regulates interoceptive information, which is associated with the responsive actions of caregivers to promote adaptation and action understanding.

Somatomotor System in Action Imitation

In interoception, the sense of body agency and representation are closely related to the somatomotor system (Murata et al., 2016). Proprioception is a kind of subjective consciousness in which acts are executed by themselves. When the action is recognized as the result of own body of an individual, it produces a sense of agency (Keromnes et al., 2019). The somatomotor system in the brain not only controls itself to produce complex actions, but it is also related to the internal representation of the body. Brain imaging studies have confirmed that in healthy people, the parietal cortex is involved in action detection and proprioceptive generation (Chambon et al., 2013). When the inferior parietal cortex is damaged, the sense of agency and body representation of individuals are impaired (Keromnes et al., 2019).

Action observation and production can activate motor systems, such as the ventral premotor cortex, inferior parietal lobule, primary motor cortex (Dushanova and Donoghue, 2010), dorsal premotor cortex (Tkach et al., 2007), inferior parietal cortex (Chong et al., 2008), and other brain regions. The ventral anterior motor cortex and inferior parietal lobule are the classical mirror neuron regions for action observation (Buccino et al., 2004; Aziz-Zadeh et al., 2006). Based on proprioception, people can mirror and imitate observed actions without having to see their bodies. Therefore, researchers suggest that the mirror reaction of action observation is based on the association between observed action and proprioception (Cook et al., 2014). For example, selectively observing different finger acts can activate the potential amplitude of the area corresponding to the fingers in the motor cortex (Catmur et al., 2011).

During development, 7-month-old infants already have a rich neural representation of the body. For instance, tactile stimulation of different body parts in the infant results in similar activation patterns as adults (Saby et al., 2015; Meltzoff et al., 2018). Well-developed body representations facilitate action observation and imitation of children. Even if they cannot see their own body parts, children match their own body to bodies of others to produce imitative actions. For example, when 14-month-old infants see a head-touch act, they can imitate the act even if they cannot see their own head (Meltzoff and Marshall, 2020). After observing adult mouth action, a child automatically imitates the action without observing his/her mouth (Heyes, 2011). By establishing an association, the superior temporal sulcus (STS), which processes the visual characteristics of the act (Oram and Perrett, 1996), the parietal cortex (Gallese et al., 2002), and the ventral premotor cortex (Rizzolatti et al., 2002; Umesawa et al., 2020) integrate visual action information with the internal representation of the body to imitate and understand actions (Rizzolatti and Sinigaglia, 2010).

Therefore, it is essential for the somatomotor system to develop representation and the sense of body agency of children. The somatomotor system actively participates in the processing when observing and imitating the actions of other people.

The Insular Cortex Connects With Other Brain Regions

The insular cortex (IC) is the main cortical region that processes interoceptive information (Hassanpour et al., 2018), including proprioception and visceroception. Studies have shown that the IC may be the key anatomical region that integrates the internal input signals from the body (Karnath and Baier, 2010), form emotional feelings, and provide a sense of body ownership (Craig and Craig, 2009). In a functional magnetic resonance imaging (fMRI) study, participants watched a video in which an individual smelled something in a glass that produced either nausea or pleasure. The results showed that the left anterior insula and the right anterior cingulate cortex were activated to some extent by observing smelling actions of others (Wicker et al., 2003). Interoception is further processed by the IC to produce corresponding emotions and cognition, which promotes socialization and mentalizing of an individual (Devue et al., 2007).

The IC plays an important role in the development of interoception of children. Interoceptive awareness and proprioception of children develop rapidly, and the IC is an important area for interoceptive signal processing (Keromnes et al., 2019). During processing, the IC extensively connects with other subcortical and cortical regions (Gehrlach et al., 2020). After integrating top-down and bottom-up information, interoception can be adjusted or regulated in a timely manner. For example, visceral signals, such as hunger, are processed by the IC and change depending on whether people see food and have expectations (Livneh et al., 2020). For children, their physical needs are affected by the responses of their mothers and have a long-term impact on the ability of children to recognize their own internal state and emotions, which are mainly processed in the insular region (Fotopoulou and Tsakiris, 2017).

In action understanding, interoception processing in the IC not only provides internal information reference for action understanding but also connects with other brain regions to understand action intentions and even mentalizing of other people. For example, if an observer only observes and recognizes actions, an input from the motor cortex and visceral motor center is needed to establish the relationship between actions of other people and his/her own action experience. However, if the observer perceives and imitates social actions, in addition to the motor cortex, it will also activate the insular region (Casartelli and Molteni, 2014), suggesting that, when observing actions and inferring intentions of others, interoceptive signals processed by the IC are indispensable reference information (Jabbi et al., 2008). Although infants are still in the prespeech stage in the first year, they have developed extensive emotion recognition based on internal arousal. Studies have shown that infants aged 7–12 months can distinguish basic emotional categories such as happiness, sadness, anger, fear, and disgust through classic facial expressions and actions (Ruba et al., 2017; Safar and Moulson, 2017). Through interoception, children can understand the emotional actions of other people. When children are less than 2 years of age, they can match emotional actions of others with related events (Ruba et al., 2020). For example, Ruba et al. (2019) used three emotions with the same valence and arousal, namely anger, disgust, and fear, and tested 14- or 18-month-olds to observe specific events and emotional expressions of performers. The results showed that infants could match negative emotions with specific events. However, understanding these different negative emotions may have different developmental trajectories.

The functional connection between the IC and other brain regions, such as the fronto-temporal network, enables children to consciously process interoceptive signals and integrate their feelings and cognition into the understanding the actions of others (Adolfi et al., 2017), so as to provide an internal reference to infer action intentions or goals of others. Interoception of children develops rapidly from early implicit perception to later sub-components such as interoceptive accuracy, awareness, sensitivity, etc. (Palmer and Tsakiris, 2018). According to the suggestion of Garfinkel, interoception components have different neural developmental trajectories (Garfinkel et al., 2015b). Among them, interoceptive awareness is closely related to metacognitive function, which is a high-level "metacognitive" knowledge of interoception and is affected by the neural development of the anterior cingulate cortex, prefrontal cortex, and other brain regions (Garfinkel et al., 2015b). Thus, it matures later and seems to develop during childhood and throughout adolescence (Klabunde et al., 2019; Bonaz et al., 2021).

The Application of Action Understanding and Interoception Model

The current model describes the typical development of action understanding and interoception in children. However, individual differences of children could affect the developmental relationship between action understanding and interoception. For example, temperament discrepancy of infants shows in reactivity to stimuli and self-regulation (Stifter and Jain, 1996). The behavioral response of early infants to stimuli is mainly biologically driven, which is closely related to interoception. So the individual difference in interoception affects the early action development. Porges et al. (1994) measured the relationship between the behavioral reactivity and autonomic state in 9-month-old infants. They found that high cardiac vagal tone was associated with greater behavioral reactivity. In terms of regulation, a longitudinal study of Stifter and Jain (1996) suggested that 5-month-old infants with high vagal tone showed more regulatory behavior at 18 months of age.

Based on the model of action understanding and interoception of children, infants establish a behavioral response association through interoceptive information and feedback in early stage. Infants with more active autonomic nervous system may produce more and possibly conflicting interoceptive cues simultaneously (Porges et al., 1994; Stifter and Jain, 1996; Huffman et al., 1998). When more activated infants understand actions, they need to pair multiple interoceptive stimulus and response signals, so as to slow down learning or confuse action understanding. This may explain that infants with interoception individual differences perform different in behavioral regulation and interaction with caregivers. For example, according to the report of a mother, a 9-month-old infant with high cardiac vagal tone has more difficult in temperament (Porges et al., 1994). Five-month-old more activated infants showed more regulatory behavior at 18 months (Stifter and Jain, 1996). The regulatory behavior affects the interaction between infants and others. For example, 5-month-old highly activated infants have shown the employment of regulatory strategies when interacting with others at 14 months of age (Fox, 1989).

Children with different temperament types have differences in autonomic nervous system stimulation and information feedback, which affect action understanding development of an infant. In addition, congenital aphantasia with abnormal sensory imagery may also affect action understanding of children. Sensory imagery refers to a perceptual representation present in mind, but the stimulus is not actually being perceived (Kosslyn, 2005). Sensory imagery depends on perceptual representation and activates the corresponding cerebral cortex, so as to produce vivid image and experience. For example, action imagery activates the human motor cortex (Porro et al., 1996; Dechent et al., 2004). Without stimulation, aphantasia cannot produce corresponding imagination and representation in mind (Zeman et al., 2015). In approximately 1–3-year-olds, body action representation plays an important role in infant action simulation. After observing the actions of others, children need to mirror actions in mind. However, individuals with multimodal congenital aphantasia cannot imagine sensations that are generated through interoception, such as representations of emotional states or experiences which depend on somatosensory and insular sensations (Wicken et al., 2021). Therefore, the defect of action imagery may delay the children with congenital aphantasia to simulate and understand the actions of others.

The nerve defect of aphantasia involves not only the corresponding sensory region, but also other brain regions. For example, Hassabis et al. (2007) found that sensory imagery involves a wide network, including ventromedial prefrontal cortex, hippocampus, posterior parietal cortex, etc. When children with congenital aphantasia observing action have problem in action representation, the compensatory nervous system may aid to generate good action models. First, in visual imagination of action observation, Keogh and Pearson (2018) found that congenital aphantasia has a defect in low-level visual imagery, mainly in visual details rather than spatial relations. This provides the possibility for children to observe and simulate the spatial information of action. Second, there is no unique mental imagery cortical network (Mellet et al., 1998). Mental imagery has a high degree of interaction with other cognitive functions, such as situational memory and executive function. With the growth of memory and experience of children, retrieving memory information through situational cues can trigger related emotional and physiological experiences (Moulton and Kosslyn, 2009). Top-down processing could further improve perception dependence through enhancing the information exchange between different brain regions (Moulton and Kosslyn, 2009; Dawes et al., 2020). Therefore, children with congenital aphantasia may delay their action understanding development due to the imagination defect, but cognitive functions improvement plays a compensating role.

The current research takes temperament and congenital aphantasia as an example to explore the practical model application of action understanding and interoception of children. The model predicts the impact of temperamental individual differences on the simple association of action understanding and interoception in infants. When observing and simulating action, action imagination defect may cause developmental delay. According to the model of action understanding and interoception of children, on the one hand, through interoception development characteristics, such as interoceptive accuracy or interoceptive sensitivity, we can predict action development of typical children. On the other hand, physiological mechanism deficiency causes the abnormal development of action understanding and interoception. For example, if the nerves controlling muscles and tendons lack PIEZO2 protein, individuals will lose proprioception and perform uncoordinated actions (Dance, 2020). Therefore, when children are found to have abnormal development of interoception, timely intervention and guidance should be taken.

CONCLUSION

This review systematically explored how interoception promotes the development of action understanding of children. At different stages, there are substantial differences in the role that interoception plays in promoting action understanding of children, the neural mechanisms of which provides a physiological basis for development. However, the current model of action understanding and interoception of children needs more support evidence from empirical studies. For example, future research can focus on the internal neural mechanism of observing and simulating actions in children with congenital aphantasia.

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HZ wrote the article. QG provided suggestions and guidance for the article. WC conceived the structure of the article. QW revised the article. All authors contributed to the article and approved the submitted version.

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Body Structural Description Impairment in Complex Regional Pain Syndrome Type I

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Background: Complex Regional Pain Syndrome (CRPS) is a clinical syndrome composed of chronic pain, motor impairment, and autonomic dysfunction, usually affecting a limb. Although CRPS seems to be a peripheral disorder, it is accompanied by parietal alterations leading to body schema impairments (the online representations of the body). Impairments to body structural description (the topographical bodily map) were not assessed systematically in CRPS. A patient we encountered with severe disruption to her bodily structural description led us to study this domain further.

Aims: To document aberrant body structural description in subjects with CRPS using an object assembly task.

Methods: Body Schema Study: 6 subjects with CRPS-I and six age and sex-matched healthy controls completed visual puzzles taken from WAIS-III and WAIS-R. The puzzles were either related to the human body or non-human body objects. Mann–Whitney U-tests were performed to compare groups' performances.

Results: The CRPS group received relatively lower scores compared to controls for human body objects ($u = 3$, $p < 0.05$), whereas the non-human object scoring did not reveal significant differences between groups ($u = 9$, $p > 0.05$).

Conclusion: CRPS subjects suffer from impaired body structural description, taking the form of body parts disassembly and body parts discontinuity. This impairment can serve as a nidus for aberrant psychological representation of the body.

Keywords: complex regional pain disorder, somatic symptom and related disorders, body structural description, Pain, Wechsler adult intelligence scale

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INTRODUCTION

Complex Regional Pain Syndrome (CRPS) is a chronic neuropathic pain syndrome usually involves one limb. In most cases, it occurs after an injury to the affected limb. It is subdivided into two types—Type I, in which there is no significant nerve damage, and type II, which involves nerve damage. The clinical presentation is composed of a triad of (i) Chronic pain, usually burning in its nature, accompanied by increased sensitivity to pain (hyperalgesia); (ii) Motor impairment with a decrease in motor function of the limb leading to contractures and deformations and (iii) Autonomic dysfunction (edema, sweating, change in color and temperature, atrophic changes; Wilson and Serpell, 2007; Ott and Maihofner, 2018). The condition can be devastating to the extent that some patients seek and, at times, get their affected limb amputated (Dielissen et al., 1995).

The pathophysiology of CRPS involves various peripheral mechanisms (i.e., neurogenic inflammation and peripheral sensitization). However, these peripheral mechanisms cannot explain all the signs related to CRPS (Reinersmann et al., 2013). Nonetheless, CRPS seems to be *prima facie* a peripheral disorder. Accordingly, peripheral dysfunction is regarded as the leading etiological and pathogenic factor. However, there is also a role for central nervous system pathology in general and cortical dysfunction in particular, presumably involving the parietal cortices. There are changes in the cortical sensory parietal representations of the affected limb as documented in fMRI and magnetoencephalographic studies. Sensory fields related to the affected limb are diminished and return to their original size upon recovery (Schwoebel et al., 2001; Schwenkreis et al., 2009; Swart et al., 2009; Strauss et al., 2021). However, this was recently debated. For an alternative view, see (Mancini et al., 2019).

CRPS patients often report distortion in body perception in general and in the perception of the impaired limb in particular. Patients report feeling of being detached and dissociated from the affected body part, the loss of specific anatomical parts, and the inability to mentally visualize segments of the affected body parts (Lewis et al., 2007, 2010; Lewis and McCabe, 2010; Lewis and Schweinhardt, 2012). This could be related to the impairment of the neurological apparatus related to body representations. Body representations encompass three major types: (i) Body image, which is the semantic knowledge related to the body (name of body parts, their use, corresponding objects used with these body parts), (ii) Body schema, which entails a dynamic representation of the human body that is based on body localization in space and (iii) Body structural description which is a topographical map of the human body (e.g., the continuity of body parts; which body part is connected to which?; Sirigu et al., 1991; Coslett, 1998; Buxbaum and Coslett, 2001; Di Vita et al., 2020).

Most studies on the deficits of body representations in CRPS looked at body schema. This function can be studied through mental rotation tasks involving the affected limb (handedness tasks). In these tasks, the subject must judge the laterality of a limb presented from different angles, either from its back or its front. Subjects with CRPS have prolonged reaction times in this task correlated with the parietal dysfunction (Schwoebel et al., 2001, 2002). Other studies looked at body schema impairment by studying the sensation of limb position and limb movement (Brun et al., 2019).

To the best of our knowledge, the body structural description was not studied systematically in CRPS (Echalier et al., 2020; Halicka et al., 2020). It is at times documented in patients' narratives as a missing part of a limb or a "void" in a limb (Lewis et al., 2007; Lewis and McCabe, 2010) or as a disconnected body part (Galer et al., 1995). A few studies documented impaired finger recognition which might be related to impaired structural description (Förderreuther et al., 2004; Cohen et al., 2013; Kuttikat et al., 2018).

The above observations can be related to the unclear demarcation between CRPS and conversion disorders at times. While in CRPS, there is usually a clear physical antecedent and clear signs of physical signs, this is not the case with conversion disorder. However, in both diseases, the symptoms and signs are not fully explained by a biological physical mechanism, there is an association with psychiatric comorbidities, such as post-traumatic stress disorder, somatization, and depression, and both can follow a physical trauma (Shiri et al., 2003; Grande et al., 2004).

We encountered a subject with CRPS who presented with severe alterations in her body structural description. This female patient has a long-standing history of verbal and physical abuse and ambivalence toward others. She presented with right leg CRPS following a minor fall and ankle sprain. She was treated with physiotherapy, occupational therapy, and weekly psychoanalytic-oriented psychotherapy. In treatment, she raised what seemed to be an adequate concern with the symptomatic limb describing anxiety related to the pain, the obscure disease process, and the accompanying dysfunction.

On the other hand, following an appearance of a callous bleeding wound on the affected leg, she raised peculiar and bizarre misrepresentations related to the leg. This took the form of a profound distortion of the structural description of her lower body. The bleeding callous became a bleeding vulva dentata with teeth and animals running within (Arlow, 1955). This propagated to the entire leg that became an emblem of a huge penis–vagina–rectum complex resembling a defecating, menstruating cloaca suggesting a regression to primitive sexuality (Freud, 1905). To the best of our knowledge, no similar cases of CRPS with similar sexual cathexis to the affected limb were previously reported. However, a previous report suggested profuse cathexis of emotional substantial feelings and self-parts onto the affected limb (Zarnegar, 2015). In any case, as suggested, patients with CRPS are reluctant to report their bizarre ideations toward the affected body parts. This might lead to similar reports' Sparsity (Lewis and McCabe, 2010).

In this study, we wanted to assess similar body structural fragmentation in CRPS. Our patient's bizarre presentation might have been an outlier of less dramatic and more common presentations related to the impairment of body structural description. We hypothesized that patients with CRPS might show a similar albeit less profound deficit in body structural description and would be more impaired than controls with tasks requiring the assembly of human body parts suggesting a deficit in the body's structural description. This could shed light on the extent of the functional and cognitive anomalies related to the body found in CRPS and contribute to developing specific rehabilitation interventions that address these deficits (i.e., body structural description) specifically. To test this, we administered the object assembly subtest items of the WAIS-III and the WAIS-R (Wechsler, 1981, 1997). These subtests include puzzles of ordinary objects, and participants are required to connect pieces of puzzles into meaningful objects. We compared the performance on human body objects Assembly (HBOA; hand, human profile, and human figure) with that on non-human body objects Assembly (Non-HBOA; house, butterfly, and elephant). As mentioned above, we expected CRPS subjects to be relatively more impaired with the assembly of human body objects than with the assembly of non-human body objects.

MATERIALS AND METHODS

Subjects

Six subjects with CRPS (type I) and six age and sex-matched healthy controls. Subjects with CRPS were recruited from the outpatient rehabilitation service at Chaim Sheba Medical Center. Control subjects were recruited from hospital and university employees. Inclusion criteria for the CRPS subjects were age > 18 years and CRPS of one limb. Criteria for the control group were age > 18 years and matched with the study group according to sex, age, and education. Exclusion criteria for CRPS and control groups comprised having another pain syndrome, having an orthopedic injury, documented head injury, or inability to perform tasks due to language or physical injury limitations. Control subjects with previously recorded psychiatric disorders were excluded.

Subjects completed demographic information questionnaires (age, family status, education, occupation). Subjects also completed the following questionnaires:

1. Mental Health Inventory (MHI; Veit and Ware, 1983; Florian and Drori, 1990) contains 38 self-reported items designated to assess patients' mental health during the previous month. Items can be used to evaluate a total mental health index, made up of two global scales (psychological wellbeing and psychological distress) and six subscales (anxiety, depression, loss of behavioral or emotional control, general positive affect, emotional ties, and life satisfaction). A higher Global MHI score indicates better psychological wellbeing.
2. The MOS 36-item short-form health survey (SF-36; Ware and Sherbourne, 1992). This survey consists of 36 self-reported items designated to assess patients' health status on eight subscales (pain, general health perception, emotional wellbeing, physical function, role limitation due to physical health, role limitation due to emotional health, social function, and fatigue\energy). We used the pain, emotional health, and general health subscales. Scoring was determined by the sum of items. A lower score indicates a more severe disease.
3. The Bath CRPS Body Perception Disturbance Scale comprises seven self-reported items and assesses changes in patients' perception of an affected limb. A higher score denotes more disturbance, with 57 being the maximum total score (Lewis and McCabe, 2010). The Questionnaire was administered only to the CRPS group.
4. Assessment of Pain Severity—Pain on the day of the testing was assessed using a Visual Analog Scale (VAS) of zero to ten taken from the McGill Pain Questionnaire (Waldman, 2009). Pain in the last 4 weeks before testing was assessed using items 22–23 from SF-36 (Ware and Sherbourne, 1992).
5. Assessment of PTSD symptomatology—Patients completed the PTSD Inventory. This 17 items questionnaire assesses the severity of post-traumatic stress disorder symptomatology. A cutoff score of 50 and above is recommended for a probable diagnosis of PTSD (Solomon et al., 1993; Weathers et al., 1993; Ginzburg et al., 2002).

The Experimental Task—Object Assembly Task

Six visual puzzles taken from WAIS-III and WAIS-R (Wechsler, 1981, 1997). The puzzles were human body objects [hand, human profile, and human figure] or non-human body objects [house, butterfly, and elephant]. Scoring for each item was determined by the number of correct connections and performance times according to the WAIS-III and WAIS-R manuals (Wechsler, 1981, 1997). We calculated the average score for each category. The higher the score, the better the performance is (Human Body Objects: 0–10, Non-Human Body Objects: 0–10.6, All objects: 0–10.33).

Ethics

The study was approved by the ethical committee of Chaim Sheba Medical Center and following the Helsinki declaration. All subjects were explained the study protocol and gave written informed consent.

Statistics

Due to the small number of participants and non-normal distribution of both the experimental and demographic data as visualized in histograms, Mann–Whitney U-tests were performed to compare CRPS and control group performances and Spearman Analysis to study correlations. As we calculated three comparisons of the experimental task, we used a Bonferroni post-hoc analysis correction and multiplied the calculated value of p by three. We used IBM SPSS Statistics, version 27. When appropriate, we report the average and standard deviation. We used the "ggridges" R-Package for the rain cloud plots (Jeehyoung, 2022).

RESULTS

Demographic Data

Each group included four women and two men. Between-group comparison was conducted using Mann–Whitney U-tests to assure appropriate matching. There were no significant group differences in age (Controls 31.2 ± 13.40 years, CRPS 31.0 ± 12.41 years, $U = 18$, $p > 0.05$) or education (Controls 14.17 ± 3.54 years, CRPS 14.17 ± 3.13 years, $U = 18$, $p > 0.05$).

Clinical Characteristics

Controls reported better general health compared with CRPS patients (SF-36 General Health: Controls 95.8 ± 5.8, CRPS 55.0 ± 32.0, $U = 4.5$, $p = 0.026$), had less pain (SF-36 Pain: Controls 94.68 ± 9.3, CRPS 26.3 ± 31.3, $U = 1$, $p = 0.006$; Pain-VAS-Controls 0.67 ± 1.6, CRPS 6.2 ± 3.1, $U = 1$, $p = 0.009$), better mental health (Global MHI score: Controls 183.7 ± 23.6, CRPS 119.8 ± 41.0, $U = 2$, $p = 0.010$) and better emotional functioning (SF-36 Emotional: Controls 82.7 ± 9.4, CRPS 46.0 ± 20.4, $U = 2.5$, $p = 0.012$). CRPS patients scored 29.3 ± 14.4 on the BATH scale suggesting a relative impairment in their body perception (Lewis and Schweinhardt, 2012). All CRPS patients scored on the PTSD inventory below the cutoff (18.2 ± 8.4, cutoff = 50; Weathers et al., 1993, see **Tables 1**, **2**).

TABLE 1 | Demographic and Clinical Characteristics of the CRPS Patients.

	Sex	Age range (Years)	Education range (Years)	Body part	Meds	Psychiatric diagnosis	SF-36 general health	SF-36 Pain	SF-36 emotional	Pain (VAS 0–10)	Global MHI score	Bath score	PTSD inventory
1	M	35–50	13–20	LE	P,BDZ	None	65	45	44	5	113	31	30
2	F	20–35	8–12	UE	O,P,S	None	25	0	24	8	67	38	25
3	F	50–65	8–12	LE	TCA,O,CB	None	80	10	44	9	139	51	21
4	M	20–35	13–20	UE	SN,BDZ,CB	DEP	20	0	28	9	81	19	12
5	F	20–35	8–12	LE	P,O	ADHD	40	22.5	80	5	176	10	11
6	F	20–35	13–20	UE	P,CB	None	100	80	56	1	143	27	10
Average (SD)	–	31 (12.41)	14.17 (3.13)	–	–	–	55.0 (32.0)	26.3 (31.3)	82.7 (9.4)	6.2 (3.1)	119.8 (41.0)	29.3 (14.4)	18.2 (8.4)

Body Part: LE, Lower Extremity, UE; Upper Extremity; Meds, Medications; TCA, Tricyclic Anti-Depressants; BDZ, Benzodiazepines; CB, Cannabis; O, Opiates; P, Pregabalin; S, SSRIs; SN, SNRIs; SD, Standard Deviation. Age and education are given in range to mask subjects' identity further.

TABLE 2 | Demographic Data, Clinical Characteristics and Experimental Task Results.

	Controls	CRPS	
Demographics			
No (F/M)	6 (4/2)	6 (4/2)	
Age (SD)	31.2 (13.4)	31.0 (12.4)	$U = 18$, $p = 1$
Education (SD)	14.2 (3.5)	14.2 (3.1)	$U = 18$, $p = 1$
Clinical Characteristics			
SF-36 General Health (SD)	95.8 (5.8)	55.0 (32.0)	$U = 4.5$, $p = 0.027$
SF-36 Pain (SD)	94.6 (9.3)	26.3 (31.3)	$U = 1$, $p = 0.006$
SF-36 Emotional (SD)	82.7 (9.4)	46.0 (20.4)	$U = 2.5$, $p = 0.012$
Global MHI score (SD)	183.7 (23.6)	119.8 (41.0)	$U = 2$, $p = 0.010$
Current Pain Severity (SD)	0.7 (1.6)	6.2 (3.1)	$U = 1$, $p = 0.009$
Bath score (SD)	–	29.3 (14.4)	–
PTSD Inventory (SD)	–	18.2 (8.4)	–
Experimental Task			
All Objects (SD)	5.7 (1.2)	4.0 (0.6)	$U = 4.5$, $p = 0.090$
HBOA (SD)	7.5 (1.4)	5.6 (0.8)	$U = 3$, $p = 0.048$
Non-HBOA (SD)	3.8 (2.1)	2.5 (1.4)	$U = 9$, $p = 0.447$

HBOA, Human Body Object Assembly; Non-HBOA, Non-Human Body Object Assembly. SD, Standard Deviation.

Experimental Task

Mann–Whitney U-tests compared CRPS and control group performance on the object assembly task. We conducted three comparisons. The first comparison was the total score for all six objects; the second compared Human Body Objects Assembly (HBOA), and the third compared Non-Human Body Objects Assembly (Non-HBOA). A significant difference was found only for the HBOA (Controls 7.5 ± 1.45.6 ± 0.8, CRPS 5.6 ± 0.8, u = 3, $p = 0.048$) but not for the total score for all assembly objects (Controls 5.7 ± 1.2, CRPS 4.0 ± 0.6, u = 4.5, $p = 0.090$) and not for the Non-HBOA (Controls 3.8 ± 2.1, CRPS 2.5 ± 1.4, u = 9, $p = 0.447$, see **Table 2**; **Figures 1, 2**).

Spearman correlations were performed to determine the relationship between performance on the object assembly tasks and pain levels, psychological wellbeing, general health, and levels of body perception disturbances (Bath Scale). There were strong and significant correlations between the performance on HBOA and current pain ($r_s = -0.660$, $p = 0.027$), SF-36 Pain ($r_s = 0.707$, $p = 0.010$), and SF-36 General Health ($r_s = 0.582$, $p = 0.047$). There were no significant correlations for Non-HBOA. There were strong and significant correlation between the performance on all objects and SF-36 Pain ($r_s = 0.704$, $p = 0.011$) and SF-36 Emotional ($r_s = 0.617$, $p = 0.032$, see **Table 3**).

DISCUSSION

We compared the performance of 6 subjects with CRPS with that of six age and sex-matched healthy controls in an object assembly task. CRPS subjects were relatively more impaired with HBOA than Non-HBOA compared with controls, suggesting a specific impairment to body structural description. This was further supported by the strong and significant correlations between performance on HBOA and pain severity and impaired health (SF-36 pain, Pain (VAS), SF-36 General Health) and the lack of correlation between performance on Non-HBOA

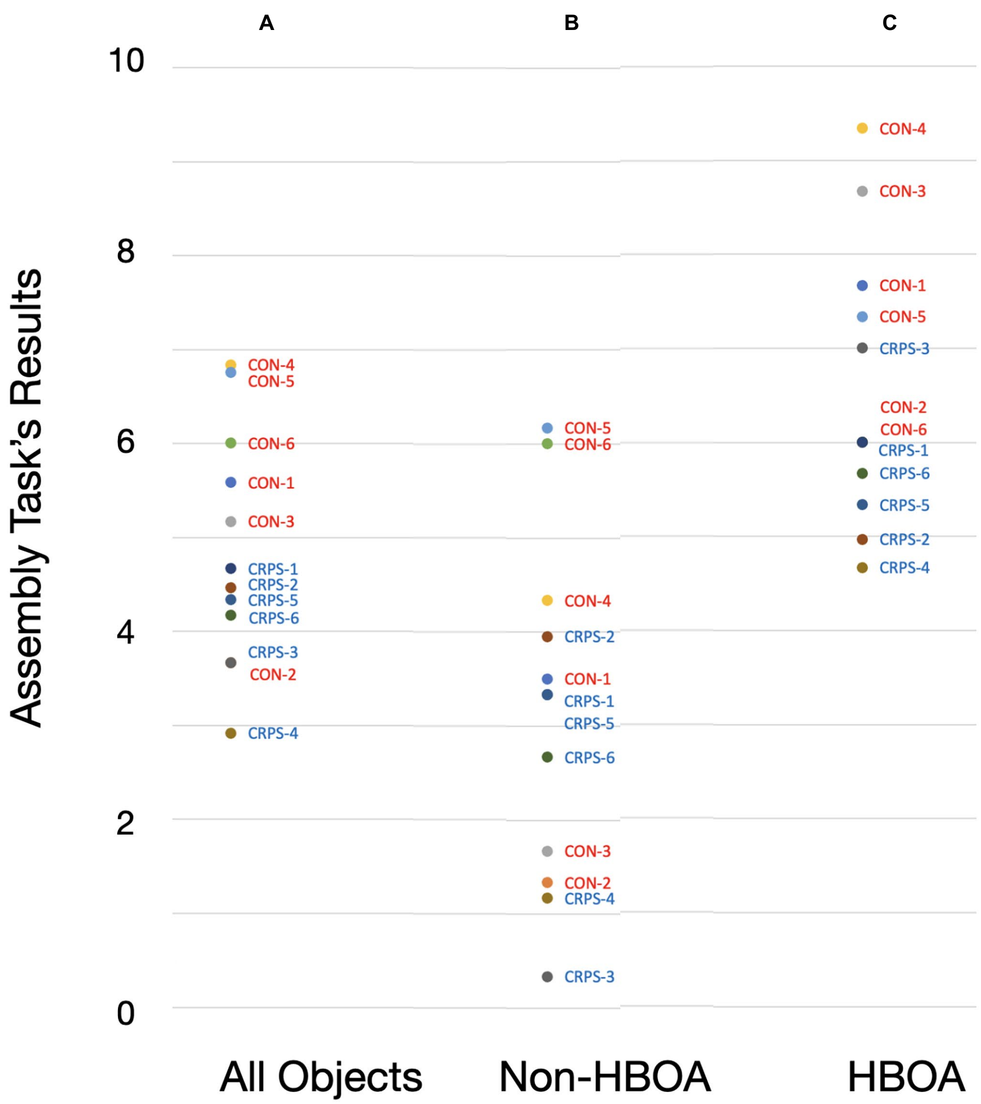

FIGURE 1 | Assembly tasks' resutls by subjects. A—Performance on all stimuli (All Objects); B—Performance on Non-Human Body Object Assembly (Non-HBOA); C—Performance on Human Body Object Assembly (HBOA).

and the clinical measures. These correlations are in accordance with our hypothesis as they suggest that the higher the pain and the health difficulties, the worst the relative impairment to body structural description.

The patients had an aberrant perception of their affected limb, as demonstrated by their score on the Bath scale, similar to what was previously reported in CRPS patients (Lewis and Schweinhardt, 2012).

The performance on the HBO suggests that the impairment is not confined to the patients' own body but is somewhat generalized to the body of others or at least to the representations of others, as in the assembly task. In this regard, the deficit of the CRPS patients could involve one's own body ("Autotopagnosia") or the body of others ("Heterotopagnosia"). Following Gerstmann, this could be called "Somatotopagnosia," denoting an impairment in locating body parts regardless of the body's ownership (one's own or bodies of others; Gerstmann, 1942).

Our findings shed new light on the body representations in CRPS and point to a discrete body structural description deficit. However, they are in line with previous observations of impaired body structural description in other neurological conditions with accompanied impaired body schema, such as phantom limb (Ramachandran, 1998; Ramachandran and Blakeslee, 1998; Ramachandran and Hirstein, 1998) and cerebral palsy (Di Vita et al., 2020).

How can these somatotopagnostic phenomena cause and contribute to the bizarre bodily experiences reported by the illustrative case and the less dramatic reports experienced by other subjects with CRPS? Here we propose two intertwining mechanisms that act together, a bottom-up and a top-down mechanism:

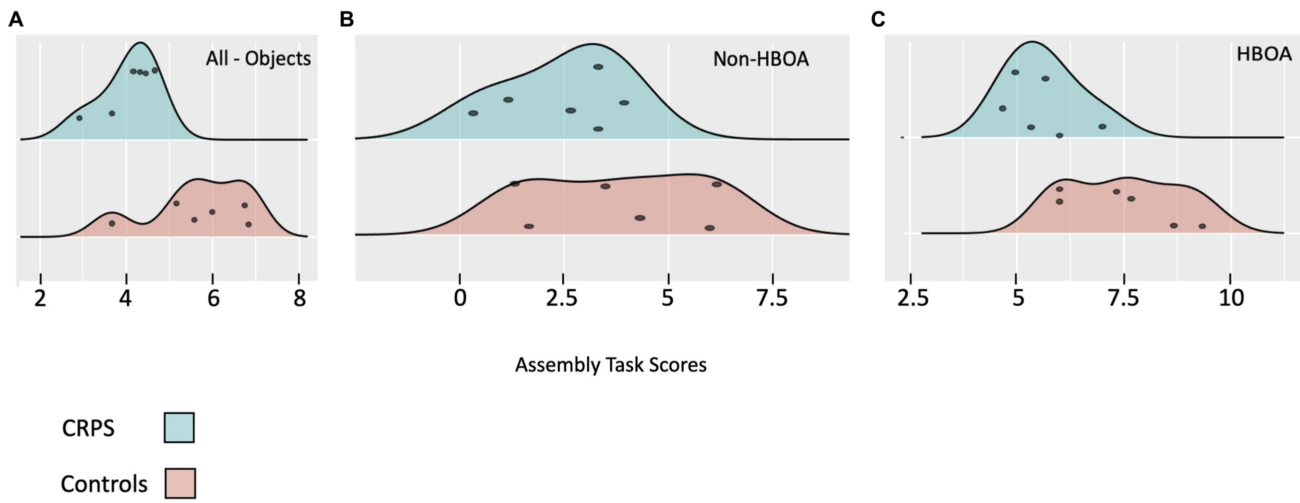

FIGURE 2 | Performance on the Assembly Task presented in a rain cloud plot. **Panel A**—results for all objects; **Panel B**—Results for the Non-Human Body Objects Assembly (Non-HBOA); **Panel C**—Results for the Human Body Objects Assembly (HBOA).

TABLE 3 | Spearman Correlations between The Object Assembly Tasks and The Demographic and Clinical Data.

		Age	Education	MHI total	Pain (VAS)	SF-36 Pain	SF-36 General health	SF-36 Emotional	Bath scale
HBOA	Spearman	0.254	−0.030	0.563	−0.660*	0.707*	0.582*	0.539	0.543
	Sig	0.425	0.926	0.056	0.027	0.010	0.047	0.071	0.266
Non-HBOA	Spearman	−0.037	0.140	0.424	−0.515	0.475	0.150	0.490	−0.116
	p	0.909	0.663	0.170	0.105	0.119	0.642	0.106	0.827
All Objects	Spearman	0.118	0.191	0.571	−0.586	0.704*	0.345	0.617*	0.143
	p	0.716	0.552	0.053	0.058	0.011	0.273	0.032	0.787

*(All Objects, Human Body Object Assembly (HBOA), Non-Human Body Object Assembly (non-HBOA)) and the demographic and clinical data. (Sig. = Significance (2-tailed), * = Correlation is significant at the 0.05 level (2-tailed)).*

The first mechanism, the Bottom-Up Mechanism, is related to peripheral injury. Impairment to sensory afferent information from the limb can cause cortical reorganization of the primary sensory cortex, leading to impaired bodily representations (Swart et al., 2009; Mancini et al., 2019). This mechanism is not unique to CRPS and is observed in other disorders with primary peripheral damage, such as Phantom Limb, where following limb amputation, cortical sensory representation from neighboring areas of cortex related to the affected limb shift to the deafferented cortical representation (MacIver et al., 2008) and these patients perform slower in body schema handedness tasks (Corradi-Dell'Acqua and Tessari, 2010).

This bodily fragmentation can cause severe distress and anxiety, as suggested by the misrepresentation of the body and the impairment of the topographical continuity of body parts. This was described cleverly in Freud's Uncanny:

> "Dismembered limbs, a severed head, a hand cut off at the wrist, as in a fairy tale of Hauff's, feet which dance by themselves, as in the book by Schaeffer which I mentioned above—all these have something peculiarly uncanny about them, especially when, as in the last instance, they prove capable of independent activity in addition. As we already know, this kind of uncanniness springs from its proximity to the castration complex." (Freud, 1919, p. 244)

This description directs us to the more speculative second mechanism based on top-down processes. Although Freud connects this uncanny anxiety to the castration complex, it is plausible to think that the origin of this anxiety could be related to various psychological conflicts and not necessarily limited to sexual oedipal conflicts. The cathexis of psychological conflicts onto the affected body part, whether associated with a sexual theme or any other theme, can be explained through a top-down mechanism leading to the projection of mental, psychological ideation and conflicts onto the affected limb. The cortical reorganization and the impaired representations serve as a nidus around which the mental images are cathected. Freud already described this as "Proclivity" (Freud and Breuer, 1895) and "Somatic Compliance" (Freud, 1905[1901]). Freud illustrates this by a metaphor of a grain of dust (the neurological impairment) inside an oyster around which the pearl (the psychosomatic symptom) crystallizes (Freud, 1905[1901]). The traumatic sexual ideations are probably anchored around the bodily deficits and lead to the dramatic presentation described in the clinical vignette. The lack of substantial PTSD symptomatology in the CRPS group could further explain why presentations similar to that of the index patient are very rare.

A more contemporary psychoanalytic formulation is that of René Roussillon, who claims that hallucinatory traumatic perceptions infiltrate the impaired body part (Roussillon, 2011). According to Roussillon, the somatic ailment or somatic affliction is bound by a split-off traumatic state culminating in a state where part of the body is sacrificed to "bind" the threatening psychic representations.

LIMITATIONS

Our study has a few limitations. The first is the small number of subjects. However, the significance of the results even at this number of participants suggests that the results are of true value and not mere chance. The second is the small number of experimental stimuli. However, we preferred to use well-validated stimuli and only stimuli from WAIS-III and WAIS-R. The third is the nature of the experimental stimuli, as the non-human objects were both animate and inanimate. A follow-up study could examine the performance on three conditions—inanimate objects, non-human animate objects, and human animate objects. The fourth is the contribution of pain symptoms to the subjects' performance with CRPS. As CRPS subjects had relatively severe actual pain during the performance of the experimental task, it might be argued that the pain followed by inattention might have impaired their performance as compared with the control group. However, the pain could not explain the differentiated performance between HBO and Non-HBO stimuli. The fifth is the lack of clinical information in the CRPS subjects regarding psychotic ideation, especially somatic delusions. A similar observation could have strengthened our speculative hypothesis regarding the putative top-down cathexis. The BATH questionnaire sheds some light, although indirectly, on this dimension. Further studies can look directly at psychotic ideations and dissociations in this population in the context of body misrepresentations.

CONCLUSION

Patients with pain syndromes in general and CRPS, in particular, can present with what seems *prima facie* to be bizarre and semi-psychotic ideations related to their body. Based on our findings, we argue that these ideations are a combination of concrete cognitive deficit of body structural descriptions with psychological representation and cathexes that can be related to past traumatic experiences. This understanding can enable the clinician to listen to these patients more understandingly. It can also pave the way for further research looking at CRPS as a disease model for somatization and conversion disorders through classic analytic understanding, particularly the concept of somatic compliance.

To conclude, we were able to demonstrate a relative impairment in HBOA in subjects with CRPS compared with controls and a correlation of this task with the clinical characteristic of the patients. Further research can look at the utilization of the HBO task as a marker and as a clinical tool in the assessment of subjects with CRPS, especially the severity of their CRPS symptomatology.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The study was approved by the ethical committee of Chaim Sheba Medical Center and following the Helsinki declaration. All subjects were explained the study protocol and gave written informed consent.

AUTHOR CONTRIBUTIONS

IB, AB, LA, and AT – Study design. LA – Data collection. IB, AB, LA, NB, EB, and AT – Data interpretation. IB, AB, and LA – Data analysis. IB – Manuscript drafting. IB, AB, LA, NB, EB, and AT – Critical review. All authors contributed to the article and approved the submitted version.

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Self-Reported Body Awareness: Validation of the Postural Awareness Scale and the Multidimensional Assessment of Interoceptive Awareness (Version 2) in a Non-clinical Adult French-Speaking Sample

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Body awareness refers to the individual ability to process signals originating from within the body, which provide a mapping of the body's internal landscape (interoception) and its relation with space and movement (proprioception). The present study aims to evaluate psychometric properties and validate in French two self-report measures of body awareness: the Postural Awareness Scale (PAS), and the last version of the Multidimensional Assessment of Interoceptive Awareness questionnaire (version 2, MAIA-2). We collected data in a non-clinical, adult sample ($N=308$; 61% women, mean age 35 ± 12 years) using online survey, and a subset of the original sample ($n=122$; 62% women, mean age 44 ± 11 years) also completed the retest control. Factor analyses and reliability analyses were conducted. Construct validity of the PAS and the MAIA-2 were examined by testing their association with each other, and with self-report measures of personality (Big Five Inventory), alexithymia (Toronto Alexithymia Scale) and dispositional trait mindfulness (Freiburg Mindfulness Inventory). Factor analyses of the PAS supported the same two-factor structure as previously published versions (in other languages). For the MAIA-2, factor analyses suggested that a six-factor structure, excluding Not-Worrying and Not-Distracting factors, could successfully account for a common general factor of self-reported interoception. We found satisfactory internal consistency, construct validity, and reliability over time for both the PAS and the MAIA-2. Altogether, our findings suggest that the French version of the PAS and the MAIA-2 are reliable self-report tools to assess both components of body awareness (proprioception and interoception dimension, respectively).

Keywords: body awareness, proprioception, interoception, PAS, MAIA-2

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INTRODUCTION

The investigation of how the brain perceives the body has increased considerably in the past decade, particularly in clinical neuroscience. Indeed, disrupted body awareness is prominently featured in the diagnosis of a wide range of diseases encompassing physical (e.g., chronic pain; Van Der Maas et al., 2016) and mental disorders (e.g., anxiety, eating disorders, etc.; Khalsa et al., 2018). In parallel, body-centered practices (e.g., mindfulness-based programs, meditation, etc.) are increasingly investigated with a mechanistic focus on how they might improve mental health and well-being, in particular through enhanced awareness of bodily signals (Farb et al., 2015; Treves et al., 2019).

Body awareness has been defined (and operationalized) as a psycho-cognitive construct that refers to the individual ability to feel engaged by information coming from the body and noticing subtle changes (Mehling et al., 2009). From a neural perspective, bodily signals continuously provide the brain with a mapping of the body's internal physiological state (interoception), and with information about the relation the body has with space and movement (proprioception). Interoception entails the integrative interpretation of a variety of stimuli (e.g., signals from the heart, humoral receptors, and free nerve endings)—in a cognitive/emotional context—to derive an overall physiological representation of the state of the body, including conscious and nonconscious aspects (Craig, 2002; Berntson and Khalsa, 2021). On the other hand, proprioception is made up of signals from various peripheral receptors (e.g., somatosensory and vestibular receptors) that are integrated at the central level to provide representation of the body's orientation relative to gravity (Tuthill and Azim, 2018), which in turn contributes to postural control (Forbes et al., 2018). Of note, postural control relies on cerebral processes that mostly operate unconsciously, but individuals may be partially aware of action of postural balance and can volitionally control it when desired (Amboni et al., 2013; Forbes et al., 2018).

For some authors, the construct of body awareness may be considered as a trait-like characteristic since "the view one has regarding one's body and bodily processes are likely to influence the way persons experience themselves" (Fisher and Cleveland, 1958; Rani and Rao, 1994; Ferentzi et al., 2020, p. 2). This consideration is strengthened by the idea that an innate and primitive form of body awareness could exist at birth and allow the newborns to integrate primitive sensations such as interoceptive, proprioceptive and vestibular feelings (pleasure/pain and relaxation/tension). According to Riva (2018), bodily experiences characterize the childhood development of the self, through six forms of representations: the minimal selfhood (feel the body like a separate structure from the outside world), the self-location (bodily representation in space), the active body (recognize and actuate bodily actions), the personal body (the first-person experience), the objectified body (the knowledge of being exposed and visible to others), and the social body (the body perception generated by body-related narratives and directed by social norms such as the ideal body). This link between this inborn body awareness and the construction of the self-perception, suggests the existence of a personal body awareness associated with a unique way of perceiving the body, the space around it and the way we react to it through our motor and bodily reactions which are an important part of our personality (Riva, 2018). In that respect, it has been suggested that body awareness could be associated with major dimensions of personality, as measured with the Big Five Inventory (John et al., 1991; Goldberg, 1993). In line with this theoretical suggestion, some studies reported significant association between interoception and personality dimensions of Openness and Conscientiousness (Trapnell and Campbell, 1999; Ferentzi et al., 2017, 2020). The Openness dimension is used to characterize original, imaginative and curious people (Costa and McCrae, 1992) who feel inspired, interested and determined (Letzring and Adamcik, 2015). Because of their interest in new experiences and sensations, a variety of sensory experiences can be attractive for people with a high level of Openness who are more likely to engage in body-related activities such as physical activity (Wilson and Dishman, 2015; Sutin et al., 2016). Relationships between openness and mindfulness practice, which requires attention to the body, have also been found (van den Hurk et al., 2011) but sometimes only for participants who have already practiced mindfulness (Thompson and Waltz, 2007), suggesting that it is the engagement of these individuals in this type of practice that leads to a greater level of body awareness. With regard to the Conscientiousness dimension, the main characteristic of this personality type is self-discipline (Costa and McCrae, 1992). Indeed, it appears that people with a high level of Conscientiousness have the ability to control themselves and, more specifically, their emotions and behaviors through the use of functional regulation strategies (Jensen-Campbell et al., 2007) which requires the ability to direct attention to the bodily sensations caused by unpleasant emotions in order to manage and overcome them. In this view, we can suppose that these two dimensions of the personality are associated with a better body awareness. Yet, it should be noted that relationship between interoception and personality has not been reported systematically (Sze et al., 2010), and did not encompass all personality dimensions, e.g., body awareness was reported to be independent of the dimension of Neuroticism (Shields et al., 1989; Ferentzi et al., 2017, 2020). In contrast to Conscientiousness, neuroticism is characterized by poor emotional regulation strategies, which may explain that people with high levels of neuroticism are more sensitive to stress than others (Costa and McCrae, 1992) and experience more negative affect (Gross et al., 1998). This difficulty in regulating emotions has also been found in people with alexithymia (Swart et al., 2009), which is a disorder leading to difficulties in describing feelings and distinguishing emotions from bodily sensations (Taylor, 1984; Sifneos, 1991). In the case of a personality with a high level of neuroticism, as in the case of an alexithymia disorder, that implies poor interoception skills. Indeed, emotional feeling states arise from physiological changes that occur within internal organs, and emotions themselves track and steer the redirection of physiological resources to adapt behavior (Critchley and Garfinkel, 2017). Moreover, it has been shown that alexithymia is associated with deficit in interoception (as assessed with heartbeat perception tasks into which participants are instructed to report either the number or the timing of their heartbeats; Herbert et al., 2011; Murphy et al., 2018a,b).

Paralleling findings from clinical science, recent contemplative research suggests that body awareness is fundamental for adaptive behavior and is intimately connected to self-regulation and homeostasis (Farb et al., 2015). Contemplative practice, such as mindfulness meditation, relies on training the mind to pay sustained attention to the current body experience, primarily the breath, and deliberately returning attention to it whenever distracted (Lutz et al., 2015). Indeed, it can be argued that the more fully an individual is apprised of what is occurring within one's body, the more adaptive and value consistent the individual's behavior is likely to be. Previous studies have shown that trait mindfulness, i.e., individual differences in the ability to be mindful in daily life that are supposed to be relatively stable over time (Brown and Ryan, 2003), is associated with enhanced interoception (Mehling et al., 2012; Hanley et al., 2017; Verdonk et al., 2021) and proprioception (Cramer et al., 2018; Topino et al., 2020). In addition, body-centered interventions (e.g., contemplative training) was reported as increasing self-reported interoception, as well as interoceptive accuracy in heartbeat perception tasks (Bornemann et al., 2015; Bornemann and Singer, 2017).

Signals coming from the inside and the outside of the body (body awareness) are usually measured through a range of different tools: experimental tasks and self-report instruments. Furthermore, in the last decade, neuroimaging studies have implemented those measures together in order to explore the brain areas supporting the integration of information to build up the sense of bodily awareness (Salvato et al., 2020). The rubber hand illusion paradigm, based on visuotactile mismatched information, is the most famous experimental task to measure exteroceptive information. This task relies on a perceptual illusion in which the integration of artificial limbs into the body representation of a person lies on combined visual and tactile stimulation. Inside signals have been investigated through the integration of various body sensation state of the internal body and its visceral organs; In particular, heart beats perception paradigm in which participants have to count the number of times they perceive their heart beating during a period of time (Garfinkel et al., 2015). Secondly, body awareness can also be assessed using subjective measures such as self-report questionnaires. To our knowledge, there is currently no psychometric tool validated in French that enables assessment of the proprioceptive dimension of body awareness. Interestingly, Cramer et al. (2018) have developed the Postural Awareness Scale (PAS; Cramer et al., 2018), which was recently validated in Italian (Topino et al., 2020) and in English (Colgan et al., 2021). Furthermore, regarding the interoceptive dimension of body awareness, only the first version of the Multidimensional Assessment of Interoceptive Awareness questionnaire (MAIA-1; Mehling et al., 2012) has been very recently validated in a French-speaking sample (Willem et al., 2021). The PAS and the MAIA have the theoretical advantage to specifically assess one of the two main dimensions of body awareness, namely either interoception or proprioception, thus probably contributing to make them more robust than previously developed self-report measures that assess body awareness in a more global fashion (Mehling et al., 2009). Although self-report instruments raise some long-standing methodological concerns (social desirability biases, vulnerability to limitations of introspection, etc.; Baumeister et al., 2007), they remain widely used in the field of neuroscience because they are particularly attractive, especially, but not exclusively, for efficient field research.

In addition, the PAS is the only postural questionnaire that has been developed to capture increases in proprioceptive awareness in subjects after the implementation of a mind–body training program (i.e., yoga; Cramer et al., 2018). This ability of the questionnaire to assess the influence of body-related activities and therapies on proprioception makes it a particularly useful tool in the field of clinical neuroscience. Regarding to interoception tools, most existing self-report questionnaires on interoception either focus on emotionally induced bodily sensations (e.g., the Autonomic Perception Questionnaire, Mandler et al., 1958; the Somatic Perception Questionnaire, Stern and Higgins, 1969), bodily cycles and rhythms (Body Awareness Questionnaire, Shields and Simon, 1991), or have been developed to be adapted to populations suffering from psychopathological disorders (e.g., schizophrenia with Body Awareness Scale; Roxendal, 1985). The MAIA developed by Mehling et al. is unique in that it is the most comprehensive measure of interoceptive awareness in healthy individuals (Mehling et al., 2012, 2018). This is why, in the present study, we aimed to validate in French the PAS and the last version of the MAIA (version 2, MAIA-2) in a non-clinical adult sample. Construct validity was assessed with self-reporting measurements of mindfulness with the Freiburg Mindfulness Inventory (FMI; Walach et al., 2006; Trousselard et al., 2010), personality with the Big Five Inventory (BFI; John et al., 1991; Plaisant et al., 2010) and alexithymia with the Toronto Alexithymia Scale (TAS-20; Bagby et al., 1994a; Loas et al., 1995). We hypothesized good psychometric properties for the PAS and the MAIA-2, including good internal consistency and satisfactory reliability over time. We also expected positive intercorrelation between each other, and positive correlation with the FMI. Because of the emotional regulation difficulties of people with high levels of Neuroticism (Gross et al., 1998) and people with alexithymia (Swart et al., 2009), which can be attributed to poor body awareness, we expect negative correlation with the TAS-20 and the dimension Neuroticism of the BFI. On the contrary, due to the body awareness characteristics that constitute the Openness and Conscientiousness dimensions of personality, we expect to see positive correlations with these dimensions, in line with the links that have been previously found between personality and MAIA scores (Trapnell and Campbell, 1999; Ferentzi et al., 2017, 2020). Finally, we assumed to find a significant effect of several non-psychological factors, such as gender, sport activity and body-centered practices on the scores of the PAS and the MAIA-2.

MATERIALS AND METHODS

Translation Procedure

For the first step of the validation, we followed the international guidelines of cross-cultural adaptation of self-administered questionnaires (Beaton et al., 2000). With the agreement of the original authors (Mehling W.E. and Cramer H.), the questionnaires were translated by native French-speakers [one psychologist (CB), one researcher in the field of neuroscience (AD), and one medical doctor (CV)]. Then, a concertation meeting (with the initial translators CB, AD, and CV) and one additional medical doctor (MT) was conducted in order to harmonize the French translations. Subsequently, the translated questionnaires were back translated by three English speakers totally blind to the original version [one American student in neuroscience (BR), one professional translator (ES), and one naive French speaker with fluency in English (CGV)]. A final harmonization meeting involving translators of the two steps procedure (CB, AD, CV, ES, and CGV) as well as a student in clinical psychology (LDCS), was held in order to come to satisfactory formulations and validate the translation process. French versions of the PAS and the MAIA-2 that were validated in the present study are shown in the **Supplementary Material**. Of note, we completed the translation process of the MAIA-2 a few months ahead of the publication of the French version of the MAIA-1 (Willem et al., 2021). As a consequence, common items between MAIA-1 and MAIA-2 questionnaires may show slightly different formulations in their French version.

A "field test" was performed with a group of 20 participants to determine whether the translated items of the PAS and MAIA-2 retained the same meaning as the original items. In this pilot testing, each participant completed the two self-questionnaires and was interviewed to probe about what he or she thought was meant by each questionnaire item and the chosen response. The French translation of the PAS and the MAIA-2 has been validated when investigators were sure that there was no linguistic confusion. This process revealed a good understanding of the French translation and no revision was needed to the final translated version of the questionnaires.

Participants and Data Collection

Our study was conducted online following standards for Internet-based experimenting (Reips, 2002). Participants were recruited through announcements that were posted on different websites and social media. To be eligible for inclusion in the study, a subject had to (i) report no history of neuropsychiatric disease and chronic pain, (ii) be over 18 years and under the age of 65, and (iii) be able to read and understand French. At the beginning of the survey the participants were informed of the aim of the study and consented to participate by clicking the "next" button on the online survey. They also received, *via* email, the study information letter. No compensation was offered for the participation in the study. They were guaranteed privacy and anonymity. The data were collected online *via* the LimeSurvey tool (LimeSurvey Project Team/Schmitz, 2012).[1]

Measures

The socio-demographic data included age, gender, weight, height, educational level, sport practice (frequency, average duration of sport, body-oriented practice), history of injury which changed body perception and history of chronic pain.

Questionnaires

Postural Awareness Scale

The 12-item Postural Awareness Scale measures two facets of postural body awareness: (1) *Ease/familiarity with postural awareness* (PAS-EwPA): effortless awareness of the body posture and (2) *Need for attention regulation with postural awareness* (PAS-NfA): awareness of the posture requires efforts to balance conscious cognitive processes and bodily needs. The two facets can be interpreted as two opposite ends of a continuum effort necessary to becoming aware of one's posture (Cramer et al., 2018). The questionnaire is scored using a seven-point scale, with responses ranging from 1 (not like me at all) to 7 (completely like me). For each of the two subscales, the score was counted by adding the rating for all items; items related to the subscale *Need for attention regulation with postural awareness* (items 1, 2, 3, 4, 5 and 12) were reversed beforehand.

Multidimensional Assessment of Interoceptive Awareness (Version 2)

The 37-item Multidimensional Assessment of Interoceptive Awareness (MAIA-2) questionnaire, developed by Mehling et al. (2018), measures eight facets of interoceptive body awareness: (1) *Noticing* (MAIA-2-N): awareness of uncomfortable, comfortable, and neutral body sensations; (2) *Not-distracting* (MAIA-2-ND): tendency not to be distracted by oneself from sensations of pain or discomfort; (3) *Not-worrying* (MAIA-2-NW): tendency not to worry with sensations of pain or discomfort; (4) *Attention regulation* (MAIA-2-AR): ability to sustain and control attention to body sensation; (5) *Emotional Awareness* (MAIA-2-EA): awareness of the connection between body sensations and emotional states; (6) *Self-regulation* (MAIA-2-SR): ability to regulate psychological distress by attention to body sensations; (7) *Body listening* (MAIA-2-BL): actively listens to the body for insight; and (8) *Trusting* (MAIA-2-T): experiences one own's body as safe and trustworthy. The questionnaire is scored using a six-point scale, with responses ranging from 0 (never) to 5 (always). For each of the eight subscales, the score was counted by averaging the scores of items belonging to the subscale (items 5, 6, 7, 8 and 9 were reversed). Of note, the MAIA-2 includes five additional items with regard to the version 1 of the MAIA (MAIA-1; Mehling et al., 2012; Willem et al., 2021) that have been added to improve internal consistency and reliability of the MAIA (Mehling et al., 2018).

Freiburg Mindfulness Inventory

The 14-item Freiburg Mindfulness Inventory (FMI), developed by Walach et al. (2006) measures dispositional trait mindfulness by indexing facets of Presence (i.e., being aware of all experiences in the present moment) and Non-judgmental acceptance (i.e., understanding that things are not necessarily how one wishes them to be). This questionnaire is semantically independent from a meditation context and it is applicable to all population groups, in particular to those with no practice of mindfulness

[1]https://www.limesurvey.org

meditation (Walach et al., 2006; Trousselard et al., 2010). The questionnaire is scored using a four-point scale, with responses ranging from 1 (rarely) to 4 (almost always). In the French version, a total mindfulness score was computed by adding the rating for all items, except for the 13th item which was reversely scored (Trousselard et al., 2010).

Big Five Inventory

The 44-item Big Five Inventory (BFI-FR) was used to describe the five main personality traits: (1) E: Extraversion, Energy, and Enthusiasm; (2) A: Agreeableness, Altruism, and Affection; (3) C: Conscientiousness, Constraint, and Control of impulse; (4) N: Neuroticism, Negative affectivity, and Nervousness; and (5) O: Openness, Originality, and Open-mindedness. Each item is rated on a 5-point Likert scale from 1 (disagree a lot) to 5 (agree a lot; Plaisant et al., 2005, 2010).

Toronto Alexithymia Scale

The 20-item Toronto Alexithymia Scale (TAS-20) assesses the level of alexithymia (Bagby et al., 1994a,b). It is scored on a 1- to 5-point Likert scale. The questionnaire measures three main dimensions of alexithymia: (1) difficulty in identifying feelings and distinguishing between feelings and bodily sensations in emotional activation (DIF), (2) difficulty in the verbal expression of emotions (DVE), and (3) externally oriented thinking (EOT; Loas et al., 1995; Zimmermann et al., 2007).

Statistical and Data Analysis

Data analyses were performed using R (version 3.5.3; R Core Team, 2013) and JASP (version 0.11.1).[2]

Factor Structure

We tested whether the factor structure originally proposed for the PAS (Cramer et al., 2018) and for the MAIA-2 (Mehling et al., 2018) would replicate in the French version. For this purpose, we conducted Exploratory Factor Analysis (EFA) on a subset of the original sample including 50% of the available data (154 subjects). Horn's parallel analysis (HPA) was performed to determine the optimal number of factors to extract using principal axis factoring and promax rotation (Horn, 1965). Subsequently, Confirmatory Factor Analysis (CFA) were conducted on the remaining 50% of the available data (154 subjects). We tested a higher-order model in which a second-order factor (e.g., the factor *Interoceptive awareness* for the MAIA-2) causes individual differences in several first-order factors (e.g., the subscales *Noticing* and *Trusting* for the MAIA-2), which in turn directly influence the observed item responses (see **Figure 1** for the MAIA-2), in using the diagonally weighted least square (DWLS) estimation method. Of note, the DWLS is specifically designed for ordinal data, as this is the case for the PAS and the MAIA-2, and is less biased and more accurate than alternative methods (e.g., the maximum likelihood) in estimating the factor loadings (Li, 2016). For the PAS, we fixed the variance of the second-order factor to one, and made the loadings of the two first-order factors equal. Absolute model fit was evaluated with the Root Mean Square Error of Approximation (RMSEA), Standardized Root Mean Square Residual (SRMR), and Comparative Fit Index (CFI) based on common standards (good fit: RMSEA ≤ 0.05, SRMR ≤ 0.08, and CFI ≥ 0.95; Hu and Bentler, 1999; Marsh et al., 2004).

Reliability

Internal Consistency

Reliability of the PAS and the MAIA-2 was assessed using the coefficient omega in considering a higher-order model (ω_{HO}) for the two questionnaires. The rationale for using the coefficient omega, rather than the commonly used Cronbach alpha, is that the latter assumes an essential tau-equivalence model[3] that appeared to be inappropriate for the PAS and the MAIA-2. As a consequence, the Cronbach alpha can provide misleading reliability estimates (Flora, 2020). In the present paper, values of Cronbach alpha were also reported to provide a comparison with original validation works of the PAS (Cramer et al., 2018) and the MAIA-2 (Mehling et al., 2018).

Test–Retest

To ensure that measurement variation reported in our sample is due to replicable differences between participants regardless of time, we performed test–retest reliability analyses. To this end, a subset of participants ($N = 122$) were recalled to complete the PAS and the MAIA-2 questionnaire in a second online testing session [mean (SD) of test–retest interval = 44 (11) days]. Test–retest reliability was quantified by computing the Intraclass Correlation Coefficient (ICC) using the *psych* R package. Briefly, ICC quantifies the extent to which repeated measurements for each individual (within-individual) are statistically similar enough to discriminate between individuals (Aldridge et al., 2017). We used a two-way random effects model for absolute agreement, which corresponds to ICC (2,1) in the Shrout and Fleiss (1979) nomenclature (Shrout and Fleiss, 1979). ICC values less than 0.5, between 0.5 and 0.75, between 0.75 and 0.9, and greater than 0.90 are indicative of poor, moderate, good, and excellent reliability, respectively (Koo and Li, 2016).

Construct Validity

We assessed the PAS and the MAIA-2 for convergent and discriminant validity by performing Pearson's correlations between the two questionnaires and the other three psychological measures (the FMI, the TAS-20, and the BFI-FR). Regarding the convergent validity, we reasoned that if both the PAS and the MAIA-2 measure the construct of body awareness, then individuals felt engaged by information coming from their body should exhibit PAS and MAIA-2 scores that are positively correlated. Since mindfulness has been characterized by enhanced body awareness (Treves et al., 2019), we also expected a positive correlation between PAS and MAIA-2 scores and FMI score. For the discriminant validity, because of the theoretical

[2]https://jasp-stats.org/

[3]A tau-equivalence model includes a single factor (i.e., the model is unidimensional) that shows equal factor loadings across all items (Flora, 2020).

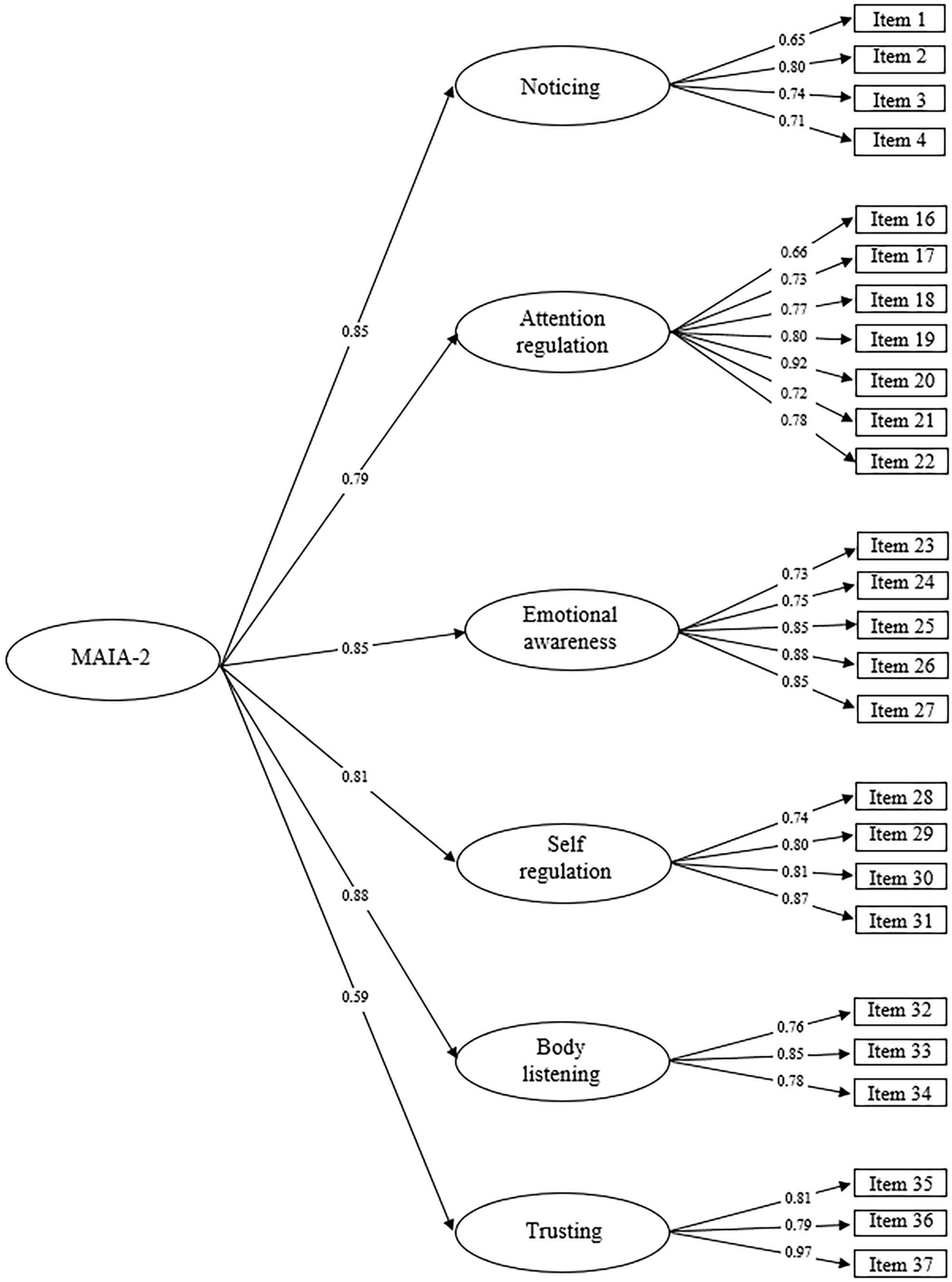

FIGURE 1 | Simplified illustration of the MAIA-2 factor model showing the best model fit based on our data. Specifically, this model excludes the factors Not-distracting and Not-worrying and responses to items related to these two factors have been removed from the dataset. Values presented represent the standardized regression coefficients.

distinction we make between body awareness and personality, we expected that PAS and MAIA-2 scores do not correlate with BFI-FR subscores. Nevertheless, despite these measurement differences between the BFI-FR and the PAS and MAIA-2 (which measure personality and body awareness respectively), in relation to the negative relationships found between neuroticism and body awareness scores (Trapnell and Campbell, 1999; Ferentzi et al., 2017, 2020), by the mediating role of the emotional regulation difficulties that characterize this personality trait (Gross et al., 1998), we expect to find the same negative correlation in our analyses. Moreover, given perception of bodily signals plays an important role in emotional experience (Critchley and Garfinkel, 2017), alexithymia that characterized individuals having difficulties in identifying their emotions should negatively correlate with postural and interoceptive body awareness.

Effect of Non-psychological Factors on Self-Report Measures

We assessed the potential effect on self-reported postural awareness of several "non-psychological" factors, including practice of sport, body-centered practice (e.g., yoga, mindfulness meditation), age, gender, body mass index (BMI) and education level to replicate and extend findings that have been recently published with the Italian version of the PAS (Topino et al., 2020). Based on findings from Topino et al. (2020), we anticipated non-significant statistical results when investigating the effect of gender and age on PAS score (Topino et al., 2020). Interestingly, Bayesian statistical tests have the advantage to provide insight and guide interpretation of non-significant values of *p*, which cannot be interpreted as support for the null hypothesis when using null hypothesis significance testing (Rouder et al., 2009; Wagenmakers et al., 2018). To circumvent this issue, we used both standard statistical tests and Bayesian equivalents. To confirm whether the potential non-significant results reported represent support for the null hypothesis, we calculated the log scale of the Bayes factor [noted $\log(BF_{10})$] that can be easily interpreted such that a negative value indicates support for the null hypothesis, whereas a positive value indicates evidence in favor of the alternative hypothesis [see **Supplementary Table S1** for an interpretation scale of $\log(BF_{10})$; Jeffreys, 1961]. Standard tests included Mann–Whitney (for the factors practice of sport, body-centered practice, and gender) and Kruskal–Wallis (for the factors education level, age, and BMI that were recoded to categorical variables with more than two classes, see **Supplementary Table S2**) nonparametric tests. If a significant difference was observed, we computed the effect size (to evaluate the magnitude of the difference) using a measure suited to nonparametric analyses: 95% CI of the rank biserial correlation (Glass, 1966). For the Bayesian analyses, we used the default JASP priors that assume a medium effect size on a Cauchy distribution of 0.707 for independent t-tests, and a *r* scale prior width of 0.5.

RESULTS

Socio-Demographic Characteristics

A total of 434 respondents completed the study. Of these, 113 (26%) had incomplete data, and 13 (3%) reported aberrant values for two non-psychological factors of interest (weight < 30 kg or > 200 kg, height < 100 cm or > 230 cm). Thus, these 126 respondents were excluded from the final study sample. The 308 remaining subjects (mean age: 35.22 ± 11.75 years; 189 females—61.40%) were included in the final analyses. This sample was used to compute socio-demographic statistics (**Supplementary Table S2**), to assess reliability, convergent and discriminant validity of the PAS and the MAIA-2 measures, and to investigate potential effects of non-psychological factors. Subsequently, this sample was randomly split into two subsamples. The first subsample was used for EFA and consisted of 154 subjects (mean age: 36 ± 12 years; 96 females—62%). The second subsample was used for CFA consisted of the remaining 154 subjects (mean age: 35 ± 12 years; 93 females—60%).

Reliability

Internal Consistency

Postural Awareness Scale

Overall, internal consistency was satisfactory: for total PAS, the coefficient omega based on a higher-order model (ω_{ho} , see Method section for detailed explanation) was 0.70; for the subscales PAS-EwPA and PAS-NfA, Cronbach alphas were 0.82 and 0.77, respectively (**Table 1**).

Multidimensional Assessment of Interoceptive Awareness-2

For total MAIA-2, internal consistency was satisfactory: ω_{ho} = 0.79. Cronbach alphas for the eight subscales ranged from 0.71 (MAIA-2-ND) to 0.89 (MAIA-2-AR; **Table 1**).

Test–Retest

Postural Awareness Scale

We found evidence that the PAS total score has good reliability over time (ICC = 0.76). The two subscales of the PAS showed moderate reliability with ICCs equal to 0.69 and 0.71 for the subscales PAS-EwPA and PAS-NfA, respectively (**Table 2**).

Multidimensional Assessment of Interoceptive Awareness-2

We found evidence that the MAIA-2 total score has good reliability over time (ICC = 0.81). Such a good reliability was also observed for the dimension Trusting (ICC = 0.82). Other subscales of the MAIA-2 showed moderate reliability over time, including ICCs that ranged from 0.63 (MAIA-2-AR) to 0.74 (MAIA-2-EA and MAIA-2-SR; **Table 2**).

Factor Structure

Postural Awareness Scale

Exploratory Factor Analysis

A two-factor structure was suggested with the Horn's Parallel Analysis (**Supplementary Figure S1A**), explaining 42% of the total variance. The first factor (EwPA) consisted of six items (items 6, 7, 8, 9, 10 and 11) that accounted for 26% of the total variance. The second factor (NfA) was made up of six items (items 1, 2, 3, 4, 5 and 12) that accounted for 16% of the total variance.

Confirmatory Factor Analysis

The higher-order model yielded a good model fit: RMSEA = 0.043 (90% CI: [0–0.070]), SRMR = 0.062, CFI = 0.996. First-order factor loadings range from 0.35 (item 7) to 0.88 (item 8) for the factor *Ease/familiarity with postural awareness*, and from 0.53 (item 4) to 0.85 (item 2) for the factor *Need for attention regulation with postural awareness* (**Figure 2**). To provide a comparison with the previously published Italian validation of the PAS (Topino et al., 2020), we also report values fit indexes when using Maximum Likelihood (ML) estimation method: RMSEA = 0.055 (90% CI: [X–X]), SRMR = 0.057 CFI = 0.960.

TABLE 1 | Descriptive statistics for the Postural Awareness Scale (PAS) and the Multidimensional Assessment of Interoceptive Awareness (MAIA-2) questionnaire in the total sample (*N* = 308).

	M	SD	[Min—Max]	α	ω_{ho}	Range of item-scale correlations[#]
PAS						
Total score	45.08 41.2[‡]	12.60 10.90[‡]	[12–84]	0.85 0.80[‡]	0.70	-
Subscale *Familiarity with postural awareness*	22.59 22.20[‡]	7.30 6.80[‡]	[6–42]	0.82 0.81[‡]	0.82	[0.39–0.77]
Subscale *Need for attention regulation with postural awareness*	22.49 19.10[‡]	7.15 6.80[‡]	[6–42]	0.77 0.77[‡]	0.77	[0.44–0.69]
MAIA-2						
Total score	23.80	5.11	[9.58–35.93]	0.90 0.74[§]	0.79	-
Subscale *Noticing*	3.44 3.34[§]	1 0.90[§]	[0–5]	0.77 0.64[§]	0.76	[0.64–0.75]
Subscale *Not-distracting*	2.38 2.06[§]	0.84 0.80[§]	[0–4.67]	0.71 0.74[§]	0.57	[0.18–0.39]
Subscale *Not-worrying*	3.10 2.52[§]	0.98 0.85[§]	[0–5]	0.84 0.67[§]	0.84	[−0.08–0.03]
Subscale *Attention regulation*	2.88 2.84[§]	1.04 0.86[§]	[0–5]	0.89 0.83[§]	0.89	[0.75–0.83]
Subscale *Emotional awareness*	3.51 3.44[§]	1.09 0.96[§]	[0–5]	0.85 0.79[§]	0.86	[0.66–0.77]
Subscale *Self-regulation*	2.84 2.78[§]	1.15 1.01[§]	[0–5]	0.85 0.79[§]	0.85	[0.72–0.81]
MAIA-2						
Subscale *Body listening*	2.34 2.20[§]	1.18 1.17[§]	[0–5]	0.77 0.80[§]	0.77	[0.72–0.81]
Subscale *Trusting*	3.30 3.37[§]	1.20 1.11[§]	[0–5]	0.84 0.83[§]	0.83	[0.53–0.67]

PAS, Postural Awareness Scale; MAIA-2, Multidimensional Assessment of Interoceptive Awareness (version 2); M, mean; SD, standard deviation; Min, minimum value; Max, maximum value; α, Cronbach alpha; and ω_{ho}, coefficient omega based on a higher-order model.

[#]*Correlations are intended to be descriptive and are not corrected for multiple comparisons.*

[‡]*Reference values extracted from the original version of the PAS (Cramer et al., 2018).*

[§]*Reference values extracted from the original version of the MAIA-2 (Mehling et al., 2018).*

TABLE 2 | Intraclass correlation coefficients that inform about reliability over time at the individual level for the PAS and the MAIA-2.

	ICC	95% CI
PAS		
Total score	0.76	0.69–0.82
Subscale *familiarity with postural awareness*	0.69	0.61–0.76
Subscale *need for attention regulation with postural awareness*	0.71	0.63–0.78
MAIA-2		
Total score	0.81	0.75–0.85
Subscale *noticing*	0.69	0.60–0.76
Subscale *not-distracting*	0.66	0.56–0.73
Subscale *not-worrying*	0.72	0.64–0.78
Subscale *attention regulation*	0.63	0.53–0.71
Subscale *emotional awareness*	0.74	0.67–0.80
Subscale *self-regulation*	0.74	0.67–0.80
Subscale *body listening*	0.73	0.65–0.79
Subscale *trusting*	0.82	0.77–0.87

PAS, Postural Awareness Scale; MAIA-2, Multidimensional Assessment of Interoceptive Awareness (version 2); ICC, Intraclass Correlation Coefficient; and 95% CI, 95% confident interval for the Intraclass Correlation Coefficient.

Multidimensional Assessment of Interoceptive Awareness-2

Exploratory Factor Analysis

Horn's Parallel Analysis suggested that a six-factor model would be optimal given available data (**Supplementary Figure S1B**), explaining 55% of the total variance. The six first-order factors accounted for from 6% to 13% of the total variance. It should be noted that an eight-factor model, which is the factor structure originally proposed for the MAIA-2 (Mehling et al., 2018), increased to 60% the proportion of total variance that is explained.

Confirmatory Factor Analysis

The higher-order model including a second-order factor on top of six first-order factors, as results of EFA suggested, showed mixed evidence for an acceptable model fit: RMSEA = 0.111 (90% CI: [0.105–0.117]), SRMR = 0.104, CFI = 0.950. When considering the eight-factor model that was originally proposed for the MAIA-2 (Mehling et al., 2018), the model fit increased slightly: RMSEA = 0.106 (90% CI: [0.100–0.112]), SRMR = 0.102, CFI = 0.955. Of note, we also

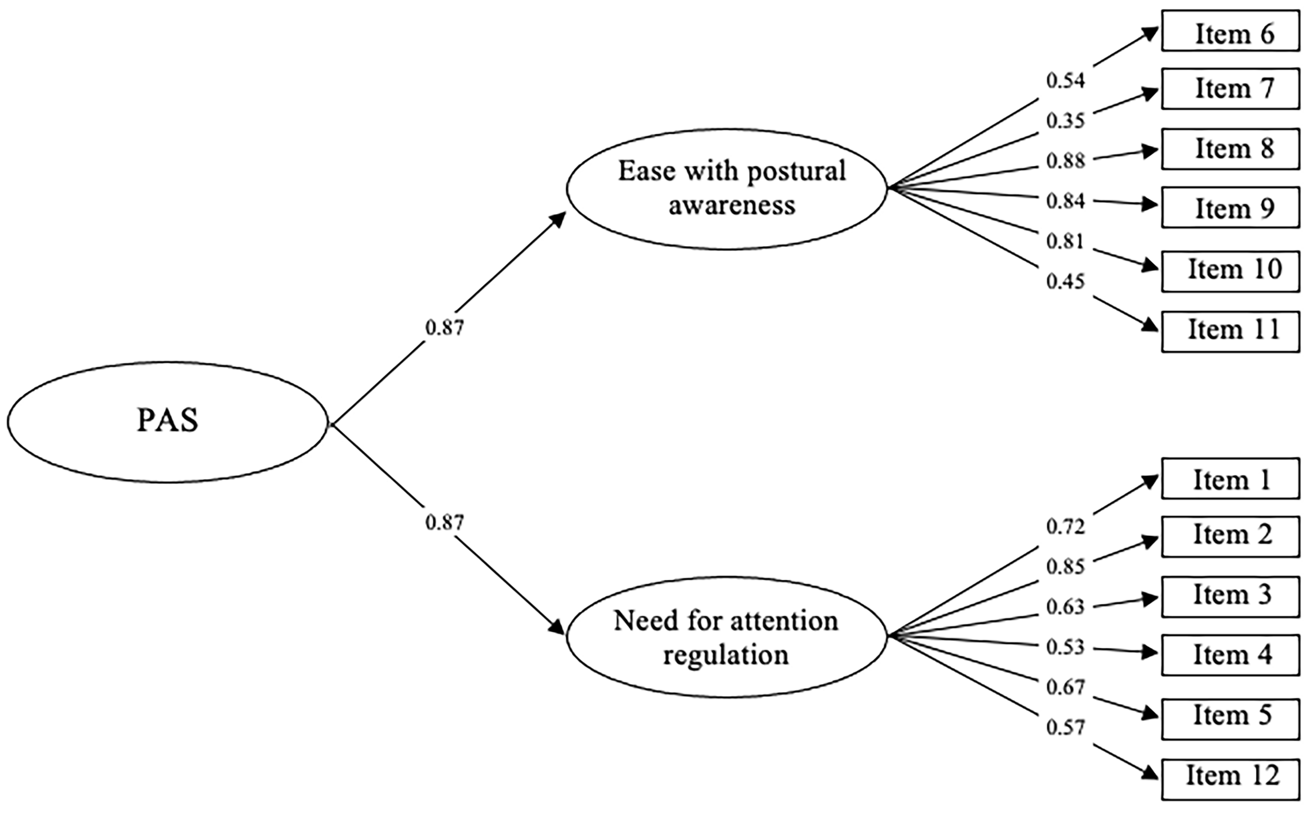

FIGURE 2 | Simplified illustration of the PAS factor model. Values presented represent the standardized regression coefficients.

computed values fit indexes when using Maximum Likelihood (ML) estimation method to provide a direct comparison with original validation work of the MAIA-2 (Mehling et al., 2018): RMSEA = 0.075 (90% CI: [0.064–0.078]), SRMR = 0.102, CFI = 0.813. Finally, because it was recently suggested that the first-order factors *Not-distracting* and *Not-worrying* could be independent from the second-order factor *Interoceptive awareness* (Ferentzi et al., 2020), we tested a third higher-order model (**Figure 1**) in which the first-order factors *Not-distracting* and *Not-worrying* were excluded, and we removed responses to items related to these two factors from the dataset. This latter model yielded the best model fit: RMSEA = 0.079 (90% CI: [0.069–0.088]), SRMR = 0.076, CFI = 0.986. According to this model, first-order factor loadings range from 0.65 (factor *Noticing*, item 1) to 0.97 (factor *Trusting*, item 37; **Figure 1**).

Construct Validity

Correlation matrix showed significant correlations with different measures used for the analysis of construct validity of the PAS and the MAIA-2 (**Table 3** includes correlation coefficients between total scores, and **Supplementary Table S3** includes correlation matrix between all subscales). Descriptive statistics of these measures, including the BFI-FR, the FMI and the TAS-20 questionnaires in the total sample ($N = 308$) are summarized in **Supplementary Table S4**.

Postural Awareness Scale

Both subscales scores were positively, strongly and significantly correlated with the total score (PAS-EwPA, $r = 0.88$, $p < 0.001$ and PAS-NfA $r = 0.87$, $p < 0.001$). The two subscales scores were also significantly intercorrelated ($r = 0.52$, $p < 0.001$).

Convergent Validity

Overall, the pattern of correlations (direction and significance) with the different measures was similar for the PAS total score and its two subscales. Of note, the measure of MAIA-2-NW was an exception in that it only correlated with the PAS-EwPA subscale ($r = -0.14$, $p < 0.05$). Specifically, we observed strong positive correlation between the PAS and the MAIA-2 total scores ($r = 0.60$, $p < 0.001$). Positive correlations were found between the PAS total score and the MAIA-2's subscales, ranging from $r = 0.21$, $p < 0.001$ (MAIA-2-ND) to $r = 0.54$, $p < 0.05$ (MAIA-2-AR; see **Supplementary Table S3**). We also observed positive correlations between all PAS scores (total and subscales) and the FMI total score ($r = 0.47$, $p < 0.001$ for PAS-EwFA and PAS-NfA; $r = 0.54$, $p < 0.001$ for PAS total score). Similar positive correlations were found with the two FMI subscales (see **Supplementary Table S3**). All PAS scores were moderately and positively correlated with the BFI-E, the BFI- A, the BFI-C, and the BFI-O (ranging from $r = 0.14$, $p < 0.05$ to $r = 0.26$, $p < 0.001$; see **Supplementary Table S3**).

TABLE 3 | Pearson's correlations of the total scores of measures used to assess construct validity.

	1	2	3	4	5	6	7	8	9
1—PAS	1	0.60**	0.54**	−0.35**	0.20**	0.23**	0.26**	−0.29**	0.21**
2—MAIA-2		1	0.64**	−0.50**	0.19*	0.22**	0.28**	−0.28**	0.25**
3—FMI			1	−0.47**	0.22**	0.34**	0.26**	−0.58**	0.21**
4—TAS-20				1	−0.25**	−0.25**	−0.24**	−0.31**	−0.24**
5—BFI-E					1	0.04	0.23**	−0.15*	0.25**
6—BFI-A						1	0.22**	−0.34**	0.06
7—BFI-C							1	−0.24**	0.05
8—BFI-N								1	−0.02
9—BFI-O									1

*Correlation is significant at the 0.05 level.
**Correlation is significant at the 0.001 level.
Correlations are intended to be descriptive and are not corrected for multiple comparisons. PAS, Postural Awareness Scale; MAIA-2, Multidimensional Assessment of Interoceptive Awareness (version 2); FMI, Freiburg Mindfulness Inventory; TAS20, 20-item Toronto Alexithymia Scale; BFI-E: "Extraversion"; BFI-A: "Agreeableness"; BFI-C: "Conscientiousness," BFI-N: "Neuroticism"; and BFI-O: "Openness to experience."

Discriminant Validity

Negative correlations were found with all TAS scores, ranging from $r = -0.16$, $p < 0.001$ (PAS-EwPA and TAS-DIF and TAS-DVE) to $r = -0.40$, $p < 0.001$ (PAS-NfA and TAS-DIF). PAS total and subscales were also negatively, but moderately, correlated with the BFI-N (the weakest correlation: $r = -0.14$, $p < 0.05$ for PAS-EwFA; **Supplementary Table S3**).

Multidimensional Assessment of Interoceptive Awareness-2

Convergent Validity

All MAIA-2 scores (total and subscales) showed positive correlation with the FMI total score ($r = 0.64$, $p < 0.001$ for the MAIA-2 total score, and from $r = 0.16$, $p < 0.001$ (MAIA-2-ND) to $r = 0.58$, $p < 0.001$ (MAIA-2-SR) for MAIA-2 subscales; see **Supplementary Table S3**).

Discriminant Validity

Negative correlation has been found between the MAIA-2 total score and the total score of the TAS-20 ($r = -0.50$, $p < 0.001$), as well as the dimension Neuroticism of the BFI-FR ($r = -0.28$, $p < 0.001$). Almost all subscale scores of the MAIA-2 (except one: Not-worrying) were significantly negatively correlated with the TAS total score, ranging from $r = -0.27$, $p < 0.001$ (MAIA-2-NW) to $r = -0.42$, $p < 0.001$ (MAIA-2-T). Regarding the dimension Neuroticism of the BFI-FR, it was negatively correlated with four MAIA-2 subscales, ranging from $r = -0.24$, $p < 0.001$ (MAIA-2-NW) to $r = -0.44$, $p < 0.001$ (MAIA-2-T).

Effect of Non-psychological Factors on Self-Report Measures

Supplementary Table S5 summarizes statistics that inform the effects of categorical non-psychological factors (sport practice, body-centered activity, and gender) on the self-report measure of interoceptive (MAIA-2) and postural (PAS) body awareness.

Practice of Sport

Individuals who reported practice of sport showed significantly higher score for the dimensions PAS-NfA, MAIA-2-AR and MAIA-2-T, compared to individuals who did not. For the dimension PAS-EwPA, individuals who reported practice of sport tend to have a higher score than those who did not. There was no significant effect of sport practice on other subscales of the MAIA-2.

Body-Centered Activity

Figure 3 describes the body-centered activities that were reported in our sample. Individuals who reported practice of a regular body-centered activity showed significantly higher scores for all the dimensions of the PAS and the MAIA-2, except for the dimensions MAIA-2-ND and MAIA-2-NW, compared to individuals who did not.

Gender

We did not find any effect of the gender on self-reported postural body awareness. By contrast, regarding the interoceptive body awareness, we found that scores for the dimensions MAIA-2-N, MAIA-2-EA, and MAIA-2-BL were significantly higher in females than in males. Furthermore, the score for the dimension MAIA-2-T was significantly higher in males than in females.

Age

None of the dimensions of the PAS and the MAIA-2 did correlate with age of participants, with $\log(BF_{10})$ ranging from −1.30 (MAIA-2-N) to −2.63 (MAIA-2-BL) suggesting extreme evidence for the null hypothesis. To provide a direct comparison with results from Topino et al. (2020), we also tested the effect of age when transforming as a categorical variable in using Topino's criteria (Topino et al., 2020) on the PAS subscales. We did not find any effect of age classes on the two dimensions of the PAS-EwPA: $\log(BF_{10}) = -2.51$, suggesting extreme evidence for the null hypothesis; PAS-NfA: $\log(BF_{10}) = -3.92$, suggesting extreme evidence for the null hypothesis.

Education Level

We did not find any effect of the education level on self-reported postural body awareness, with $\log(BF_{10})$ ranging from −2.86 (PAS-EwPA) to −3.34 (PAS-NfA) suggesting extreme evidence for the null hypothesis. Regarding the interoceptive

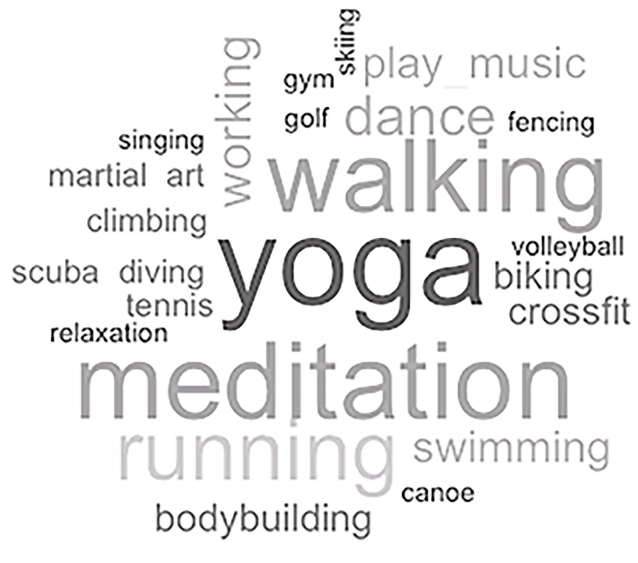

FIGURE 3 | Word cloud of body-centered activities that were reported in our sample based on their relative frequency. The bigger the word, the greater the frequency influences. The figure is a representation of words that have been entered at least more than twice (minimum frequency = 2).

awareness, there was no significant effect of education level on the eight subscales of the MAIA-2, with $\log(BF_{10})$ ranging from −3.20 (MAIA-2-T), which suggests extreme evidence for the null hypothesis, to 0.45 (MAIA-2-EA) suggesting no evidence for the alternative hypothesis.

Body Mass Index

All the dimensions of the PAS and most of the dimensions of the MAIA-2 (except the dimension MAIA-2-T) did not correlate with BMI of participants, with $\log(BF_{10})$ ranging from −1.12 (MAIA-2-BL) to −2.63 (PAS-EwPA), suggesting strong to extreme evidence for the null hypothesis. The dimension MAIA-2-T showed significant negative correlation with the BMI of participants ($r = -0.21$, $p < 0.001$). To provide a direct comparison with results from Topino et al. (2020), we also tested the effect of BMI when transforming as a categorical variable in using Topino's criteria (Topino et al., 2020) on the PAS subscales. We did not find any effect of BMI classes on the two dimensions of the PAS-EWPA: $\log(BF_{10}) = -1.59$, suggesting very strong evidence for the null hypothesis; PAS-NfA: $\log(BF_{10}) = -2.78$, suggesting extreme evidence for the null hypothesis.

DISCUSSION

General Discussion

The aim of this study was to evaluate psychometric properties and validate in French the PAS, a recently developed questionnaire to assess postural body awareness (Cramer et al., 2018), and the MAIA-2, which is the latest version of a popular questionnaire assessing interoception (the interoceptive component of body awareness; Mehling et al., 2018). Our data, collected in a non-clinical adult sample, showed that the French version of the PAS and the MAIA-2 have both good construct validity and good internal consistency, as well as a good reliability over time. First, regarding the construct validity of the two questionnaires, significant positive correlations were found with the dispositional trait mindfulness, which is characterized by enhanced body awareness (Treves et al., 2019). Our finding is consistent with previously published applications of the MAIA (Mehling et al., 2012; Bornemann et al., 2015; Hanley et al., 2017; Verdonk et al., 2021) and the PAS (Cramer et al., 2018; Topino et al., 2020). On the other hand, scores of the PAS and the MAIA-2 showed negative correlation with alexithymia (inability to identify and describe emotions in the self), which is a psychological construct that is theoretically and empirically in opposition to body awareness (Herbert et al., 2011; Murphy et al., 2018a,b; Zamariola et al., 2018; Topino et al., 2020). This result suggests the idea that individuals with alexithymia may have a disrupted processing of bodily signals, which could ultimately lead to impairments in emotional awareness since the ability to feel bodily sensations is thought to be a central antecedent of the conscious experience of emotions (Zamariola et al., 2018). This is in line with studies that have shown a general failure of interoception, as measured by heartbeat perception task, in alexithymia (Brewer et al., 2016). Regarding the dimension *Neuroticism* of the BFI-FR, our analyses showed significantly negative correlation with the interoceptive dimensions of *Attention Regulation*, *Self-regulation*, *Trusting*, and *Not-worrying*. This finding is in line with the work from Pearson and Pfeifer (2020) but contrasts with results from Ferentzi et al. (Ferentzi et al., 2020; Pearson and Pfeifer, 2020). Neuroticism is considered as an individual's tendency to worry and be anxious, as well as to overreact to negative affect (Costa and McCrae, 1992). Previous studies have reported that higher neuroticism individuals have a diminished ability to regulate emotion regulation, specifically a diminished capacity to downregulate negative emotions (Harenski et al., 2009; Yang et al., 2020). Our finding suggests that difficulty experienced by individuals with high neuroticism in regulating their emotion could partly result from inability to actively pay attention to their body sensations, which are proposed to shape emotional experience (Critchley and Nagai, 2012; Critchley and Garfinkel, 2017). Taken together, our results suggest that the psychological construct of body awareness, i.e., the ability to feel engaged by information coming from the body, might potentially play a mediator role in the relationship between personality traits, such as neuroticism and alexithymia, and emotion dysregulation (Harenski et al., 2009; Yang et al., 2020; Preece et al., 2021). Specifically, we suggest that low level of emotion regulation characterizing people with high level of neuroticism, on one hand, and inability of people with alexithymia to identify, describe and thus regulate their emotions on the other hand, may be responsible for the negative correlation reported between these two factors and body awareness scores. This hypothesis needs to be tested in further studies by using mediation analyses to reveal potential role of body awareness in the transmission of (causal) effect of personality traits to emotion dysregulation (Baron and Kenny, 1986; Agler and De Boeck, 2017). Regarding other personality dimensions assessed with the BFI-FR, we reported a moderate positive correlation between scores of the PAS and the MAIA-2 and the dimensions of *Conscientiousness*, *Extraversion* and *Openness*. These results are consistent with the findings from Ferentzi et al. (2017, 2020), and are in line with our expectations, especially for the dimension of Openness to experience, which is characterized by the tendency to engage in body-related activities (Wilson and Dishman, 2015; Sutin et al., 2016), as well as for the dimension of Conscientiousness characterized by self-control abilities that require good body awareness (Costa and McCrae, 1992). Regarding the association between Extraversion and scores on the PAS and MAIA-2, our results are in line with findings from Baer et al. (2004) suggesting that this personality dimension is related to the ability of extraverted individuals to describe their internal experiences. They point out that the body awareness of people with high levels of extraversion could be explained by their ability to put words to their experiences through speech and social interaction (Baer et al., 2004). Finally, we observed that self-reported postural and interoceptive body awareness strongly and positively correlate to each other, thus suggesting that proprioception and interoception refer to two components of a homogeneous, unified psychological construct of body awareness. Interestingly, recent neuroimaging studies also accounted for this hypothesis by highlighting that some of the brain areas involved in the processing of interoceptive and proprioceptive signals, notably the parietal cortex, could overlap (García-Cordero et al., 2017; Salvato et al., 2020). It has also been shown that redundancy and complementarity characterize signals originating from within the body, and such features appear to be functionally relevant for cardiac interoception (Khalsa et al., 2009), as well as for postural response in stressful situations (Volchan et al., 2017).

Factor analyses showed that the French version of the PAS has the same underlying two-factor structure as previously published versions (Cramer et al., 2018; Topino et al., 2020). The first factor regards the ability to have a high postural awareness in a natural and effortless way (Ease/familiarity with postural awareness), and the second refers to the need for high efforts to be aware of their own posture (Need for attention regulation with postural awareness). Regarding the French version of the MAIA-2, results from EFA suggested a model in which the optimal number of factors is limited to six. This model differs from the eight-factor model that has been proposed with the first version of the MAIA (MAIA-1; Mehling et al., 2012). Of note, the recent development of a modified version of the MAIA (MAIA-2) aimed to improve its psychometrics by adding new items to the *Not-worrying* and *Not-distracting* subscales, which have been reported to be of limited internal consistency reliability in numerous applications (Mehling et al., 2018). We observed that *Not-worrying* and *Not-distracting* scores are only weakly correlated with MAIA-2 total score, in line with the recent work from Ferentzi et al. (2020). They suggested that *Not-worrying* and *Not-distracting* subscales could be unrelated to the common general factor of interoceptive body awareness. Based on this hypothesis, we performed additional CFA on a subset of the original dataset, in which responses to items related to *Not-worrying* and *Not-distracting* factors were removed, and we found the best model fit with a six-factor model including factors of *Noticing*, *Attention regulation*, *Emotional Awareness*, *Self-regulation*, *Body listening*, and *Trusting*. Our findings, which need to be confirmed in a larger French-speaking sample, contribute to the call for a reconsideration of the MAIA structure, in particular the relevance of keeping items that are related to *Not-worrying* and *Not-distracting* factors. Nonetheless, the reader should bear in mind that differences in model fit between the six-factor and the eight-factor models remain relatively small, thus supporting the 37-item MAIA-2 as an appropriate instrument for interoception research to assess subjective body awareness.

In our work, we also investigated the effect of "non-psychological" factors on the PAS and the MAIA-2 scores. In line with findings of the Italian version of the PAS (Topino et al., 2020), we found that practices of sport and body-centered activity are associated with higher self-reported postural awareness. Contrary to results from Topino et al. (2020), we did not observe any significant relationship between BMI and PAS score. For the MAIA-2 questionnaire, we also found that practices of sport and body-centered activity are associated with higher self-reported interoceptive body awareness. Furthermore, we observed a significant effect of gender on the dimensions *Noticing*, *Emotional Awareness*, *Body listening*, and *Trusting*, which is consistent with findings from interoception literature (Grabauskaitė et al., 2017).

Limitations, Constraints on Generality, and Perspectives

This study has some limitations that might need to be addressed in future research. First, this study was not pre-registered. The assumptions and analyses made in this study were derived from the original design studies of the PAS (Cramer et al., 2018) and MAIA-2 (Mehling et al., 2018), as well as validation articles of these scales available in other languages (Topino et al., 2020 for the PAS; Ferentzi et al., 2020 for the MAIA). Secondly, concerning the conduct of the study, a relatively small number of self-report measures were collected to test construct validity of the PAS and the MAIA-2. This results from the limited collection of questionnaires used in interoception research that are currently validated in the French-speaking population. Regarding the data collected, it should be noted that no control measures were carried out on psychiatric symptoms that could affect self-reported body awareness, although people with neurological or psychiatric illnesses requiring psychotherapeutic and/or drug treatment were asked not to respond to our questionnaires. Some data from people with current or ongoing psychopathological symptoms that affect their level of body awareness could therefore have been considered and contributed to influencing the scores we find for these two questionnaires. Similarly, no individual-level measures were proposed to monitor participants' actual ability to speak and understand French and the questionnaire items correctly. We ensured that the instructions and items of the PAS and MAIA-2 questionnaires were unanimously understood by conducting a pilot test on a small sample of

French people. We also asked participants not to respond to our study if they did not master the language. Our sample included a relatively large proportion of participants with an education level higher than 2 years of university courses ($n = 244$—79.22%), and hence differs from the French general population in which the proportion of individuals reporting more than 2 years of university courses is between 28.6% and 36.1%. Of note, our data showed that education level does not affect self-reported interoception and postural awareness. Participation in the second phase of the study, i.e., the retest, was relatively limited with only 122 of the 306 participants (40%) completing the PAS and MAIA-2 a second time. There are also some limitations inherent in the self-report psychological scales, among which social desirability and response bias, but in the field of body awareness self-report questionnaire seem to be one of the most relevant tools. Indeed, like patient reported outcome—PRO—used in chronic pathologies (such as chronic arthritis or irritable bowel syndrome) to assess how well patients respond to treatment from the patients' perspective, assessment of body awareness has to be patient/subject centered and this is made possible by self-report measures. Furthermore, one could argue that self-report questionnaires are only one of the well-established methods of capturing individual differences in psychology. Objective measures, including behavioral tests and physiological signals, are also of particular interest to investigate inter-subject variability in the process of sensing signals coming from the body. Behavioral tests enable objective measure of body awareness (e.g., heartbeat perception task for cardiac interoception; Brener and Ring, 2016), but their features that make them robust in an experimental sense make behavioral tests unreliable in a psychometric sense (Hedge et al., 2018). In addition, behavioral tests and self-report questionnaires inform about two dissociable dimensions of body awareness, the body awareness accuracy (i.e., performance on bodily signal detection tasks) and body awareness sensibility (i.e., degree to which individuals feel engaged by bodily signals) respectively, according to the model of (cardiac interoceptive) body awareness proposed by Garfinkel et al. (2015). Regarding physiological signals associated with body awareness, the Heartbeat Evoked Potential (HEP), which refers to evoked changes in brain activity (measured using magnetoencephalography, electroencephalography, or intracranial neural recordings) that occurs after a heartbeat, has been proposed as a neurophysiological marker of interoception (Coll et al., 2021). It should be noted that Verdonk et al. (2021) have recently shown that the HEP amplitude is not associated with the self-reported interoceptive awareness, as measured with the MAIA-1. Regarding the postural component of body awareness, we suggest that the postural signal could be a candidate physiological biomarker to assess construct validity of the PAS. Future studies are encouraged to investigate the relationship the self-reported postural body awareness, as measured with the PAS, could have with the postural signal recorded during standing posture.

DATA AVAILABILITY STATEMENT

All requests for raw and analyzed data should be addressed to dcssa-paris@sante.defense.gouv.fr, because they will be reviewed by our legal department (French Military Health Service) to verify whether the request is subject to any confidentiality constraints. Requests regarding materials, including programming code, should be addressed to the corresponding author (ChV).

ETHICS STATEMENT

The study has been reviewed and approved by the H.I.A. Saint Anne Ethics Committee (0011873-2021-02). The participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

LD, AD, and ChV equally contributed to the work, including conceptualization of the research question, design of the methodology, execution of the study, data analysis, and writing of the paper. CB, BR, ES, CoV, and MT actively took part in the process of cross-cultural translation of the two questionnaires. All authors approved the submitted version of the article.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2022.946271/full#supplementary-material

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Body experience influences lexical-semantic knowledge of body parts in children with hemiplegic cerebral palsy

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Background: Disorders in different levels of body representation (i.e., body schema, body structural description, and body image) are present in hemiplegic cerebral palsy (HCP). However, it remains unclear whether the body image develops from aspects of body schema and body structural description, and how this occurs in children with HCP.

Objective and methods: In a cross-sectional study, we investigated 53 children with HCP (mean age about 10 years) and 204 typically developing (TD) control children to qualitatively evaluate whether and how body schema (related sensorimotor experiences) and body structural description (related visuospatial experiences) affect the development of children's body image and whether this development is delayed through HCP. Graph analysis was used to create a lexical-semantic map of body representation from data of a semantic word fluency task.

Results: Results indicated a similar qualitative pattern of influences of sensorimotor and visuospatial experiences on lexical-semantic knowledge of body parts, with a delayed developmental course in children with HCP compared to TD children.

Conclusion: These findings suggest that children's body image seemed to be influenced by body schema and body structural descriptions as indicated by poorer lexical-semantic knowledge of body parts in children with HCP due to missing physical experiences of the affected body parts. This might imply that "body talk" may beneficially complement physical therapy for children with HCP to promote body image development.

KEYWORDS

body representation, body image, sensorimotor experience, neuropsychology, hemiplegic cerebral palsy

Introduction

Children with hemiplegic cerebral palsy (HCP) learn strategies to manage their everyday life using only one hand as the affected limb is usually being neglected or not used – a phenomenon known as "developmental disregard" (Houwink et al., 2013). They may present functional limitations related to the affected upper limb that cannot be explained by muscle strength impairments and may be aggravated by visuoperceptual disorders (de Ajuriaguerra and Stucki, 1969). Additionally, unilateral neglect may further impair the processing of perceptual information from the environment (Katz et al., 1998). Interestingly, children with HCP often also show atypical processing of information associated with their body, resulting in sensory deficits in their upper extremities such as threshold disturbances in proprioception as well as the perception of touch and pain (Riquelme and Montoya, 2010). To account for these symptoms, the hypothesis of a disorder of higher-level body representation in HCP was proposed by DeAjuriaguerra and Stucki decades ago (de Ajuriaguerra and Stucki, 1969). Taken together, one might speculate that some symptoms observed in children with HCP may be due to an impairment of body representation at different levels (Fontes et al., 2014).

Body representations have been suggested to be organized into three neuropsychological levels: sensorimotor, visuospatial, and semantic-lexical (Sirigu et al., 1991; Goldenberg, 2003). The sensorimotor representation of the body, henceforth, referred to as body schema, incorporates proprioceptive information about the body itself and is characterized by continuous updating and consequent adaptation to changes in body properties and relative positions due to movements (Sirigu et al., 1991; Coslett et al., 2002; Goldenberg, 2003). The visuospatial representation, also termed and henceforth referred to as body structural description, describes the topographical representation of the body, providing information about its shape and surface contours as well as continuity and proximity relations among different body parts (Sirigu et al., 1991; Coslett et al., 2002; Goldenberg, 2003). Finally, body-related semantic-lexical knowledge is part of what we henceforth refer to as body image, which includes general information about names of body parts, associations of body parts with tools and artifacts, functions of different body parts, and affective information about the body (Sirigu et al., 1991; Coslett et al., 2002; Goldenberg, 2003).

Contrary to the extensive literature on representational deficits regarding the body in adults with (unilateral) brain damage, only a few studies investigated impairments of body representation in brain-damaged children (Frassinetti et al., 2012; Fontes et al., 2014, 2016; Corti et al., 2018; Butti et al., 2019; Di Vita et al., 2020). Of those, three evaluated all levels of body representation in children with cerebral palsy (Fontes et al., 2014, 2016; Di Vita et al., 2020) whereas two of them only considered children with HCP (Fontes et al., 2014, 2016). The results of Fontes et al. (2014) suggest that similar to adult stroke patients, impairments of body representation in children with HCP are related to a decrease in spontaneous use of the affected limb not explained by motor problems directly associated with the respective brain damage (Fontes et al., 2014). Fontes et al. (2016) reported evidence substantiating those damages to the immature brain, such as HCP, which seem to drive disorders in all three levels of body representation (Fontes et al., 2016). "Interestingly, by categorizing 5- to 11-year old children into two age groups (5–7 and 8–11 years old), Di Vita et al. (2020) found alterations in different body representations in children with cerebral palsy (including the three main types of cerebral palsy: hemiplegia, diplegia, and quadriplegia) at specific developmental stages. In particular, when compared to typically developing (TD) children of the same age, children with cerebral palsy aged from 5 to 7 years old did not show significant differences in body representation tasks (Di Vita et al., 2020). However, the group of older children with cerebral palsy (aged 8–11 years) showed significant differences in body structural description and body schema, but not body image (related to body semantics) (Di Vita et al., 2020). These findings might be explained by the fact that body structural description and body schema were not yet fully developed in TD children with 5–7 years old (Raimo et al., 2021)."

Impairments of different levels of body representation are dissociable in adults with brain damage, (Sirigu et al., 1991; Schwoebel and Coslett, 2005; Raimo et al., 2022) but interact. The latter is inferred from the observation that body structural description was observed to influence body schema in experiments using the rubber hand illusion (Botvinick and Cohen, 1998). Moreover, in TD children aged between 5 and 10 years, body structural description was observed to influence body image as indicated by children's naming performance for the location of the body parts (e.g., body parts *vs.* head features and also upper *vs.* lower limbs) or their involvement in motor skills (e.g., distal segments, joints, and broader body parts) (Auclair and Jambaqué, 2014). Furthermore, performance on tasks assessing body structural description (e.g., finger gnosia, verbal and visual body parts localization, matching body parts by location) was found associated positively with performance on tasks measuring body schema (e.g., imitation of meaningful and meaningless gestures) in a study investigating and comparing TD children and children with HCP (Fontes et al., 2016). Also, performance on body image tasks (e.g., naming body parts) was associated positively with performance on tasks measuring body structural description (e.g., finger gnosia, verbal and visual body parts localization, matching body parts by location) and body schema tasks (e.g., hand laterality judgment task and imitation of meaningful gestures) (Fontes et al., 2016). Against the background of this brief overview of the literature, it seems that body representations develop in a more or less hierarchical manner with body structural description gradually developing based on body schema, and body image gradually developing from body structural description.

However, little is known so far about whether and how body representations of children with HCP develop as compared to TD children. In particular, there are only a few investigations of how an injury to the immature brain may impact the development of body representations during childhood (Christie and Slaughter, 2009; Simons and Dedroog, 2009; Simons et al., 2011; Frassinetti et al., 2012; Fontes et al., 2016; Corti et al., 2018; Butti et al., 2019; Di Vita et al., 2020). Therefore, this study investigated the development of body image using a word fluency task comparing the performance of TD children with that of children with HCP. We were particularly interested in whether body schema (related sensorimotor information) and body structural description (related visuospatial information) contribute to the development of body image (by qualitatively analyzing the body parts most cited in the word fluency task), and whether this development is delayed in children with HCP. As such, we compared performance on word fluency not only for body parts but also for animals, based on lexical-semantic maps using Graph Analysis across different age groups and comparing TD children and children with HCP.

Materials and methods

Participants

This cross-sectional study involved a convenience sample of children with a diagnosis of HCP recruited in rehabilitation centers in Minas Gerais (Brazil). TD control children were recruited from public and private schools in Minas Gerais (Brazil). Children eligible to participate in the study met the following inclusion criteria: (i) performance above the 15^{th} percentile in the assessment of general cognitive ability, (ii) no uncontrolled epilepsy, and (iii) ability to respond to the assessment procedures. The sample comprised 257 children in total, of which 204 were TD control children (age range 4–12 years, mean age = 8.09 years, SD = 2.60 years) and another 53 children with HCP [age range 7–12 years; mean age = 10.19 years, SD = 1.83 years; 36 right hemiplegic cerebral palsy (RHCP) and 17 left hemiplegic cerebral palsy (LHCP)]. To evaluate a potential delay in development of body image, we compared performance of children with HCP to that of TD children separated into three age groups: (i) 4–6 years (n = 69; mean age = 5.40 years, SD = 0.72 years), (ii) 7–9 years (n = 59; mean age = 8.89 years, SD = 1.03 years), and (iii) 10–12 years (n = 76; mean age = 11.21 years, SD = 0.96 years).

Ethics

This study was approved by the Research Ethics Committee of the Federal University of Minas Gerais (protocol number 2.155.379). Participation was conditioned to get written informed consent from parents or legal guardians, and oral consent from children.

Materials

General cognitive abilities

General cognitive abilities were assessed using the Raven's Progressive Coloured Matrices (RCPM) (Angelini et al., 1999) validated for the Brazilian population. Children who scored below 15_{th} percentile were not considered for the study. Analyses considered z-scores (M = 0, SD = 1), computed as described in the test manual.

Semantic word fluency task

The Semantic Word Fluency task evaluates the spontaneous production of words under restricted search conditions (Strauss et al., 2006). In two runs, each child had to produce as many animals in one and body parts in the other run, respectively, within 60 s each. We recorded the total number of words produced, the total number of categorically correct words produced, the total number of repetitions, and the total number of intrusion errors as measures of children's performance. The number of categorically correct and repeated words was considered the dependent variable in the graph analysis.

Procedure

Data collection took place in schools and rehabilitation centers that children attended. Assessment of general cognitive abilities and application of the Semantic Word Fluency task was carried out by a team of trained undergraduate students in one-on-one sessions lasting about 40 min per child.

Graph analysis

The sequence of words produced in the Semantic Word Fluency task was represented as an individual graph using *SpeechGraphs* software (Mota et al., 2012). The graphical structure reflects associations between a set of items expressed in the form of a network composed of nodes and edges, where nodes represent the items (i.e., words produced by children) and the edges the connections between these items (Albert and Barabasi, 2002; Mota et al., 2012). In addition to the sum of categorically correct words as well as repetitions (number of correct words and number of repetitions – CWR) obtained from the verbal fluency task, the software estimated six attributes: (i) number of nodes (N), (ii) number of edges (E), (iii) density (D – number of edges divided by the number of possible edges), (iv) diameter (DI), and (v) average shortest path (ASP – the shortest path length between pairs of more distant nodes in a network) (Albert and Barabasi, 2002). Better semantic networks would be indicated by $N - 1$ edges of low density and with great distances, thereby generating direct graphs. When words were repeated, the graphs generated presented $E \geq N$ and high density. In addition to individual graphs, group graphs were created to reflect semantic networks of children with HCP and the three age groups of TD children. Semantic network scores for body parts were used to identify the most frequent or typical words, which were then used for further analyses.

Statistical analyses

Preliminary analyses indicated that children with left HCP and right HCP did not differ in their scores on general cognitive ability as well as semantic word fluency. Therefore, these two groups were pooled for the analyses. In the next step, analyses of variance (ANOVA) were conducted to evaluate differences in general cognitive abilities between the group of children with HCP and the three different age groups of TD children.

For the Semantic Word Fluency task, group differences in the number of correct words, repeated words, and errors, as well as parameters obtained from the graph analysis, were analyzed using mixed model analyses of covariance (ANCOVA) discerning the between-participant factor group (i.e., children with HCP *vs.* the three different age groups of TD children) and stimulus category (i.e., animals *vs.* body parts) while controlling for influences of general cognitive abilities. Additionally, we evaluated performance in the word fluency task using within-participant repeated measures ANOVA discerning the number of correct animals and number of correct body parts for each participant group.

We also explored the effects of body schema and body structural description on body image by qualitatively analyzing words that composed the semantic network nuclei for the four groups.

Results

Differences in general cognitive abilities between groups

Despite all children scoring above percentile 15, the ANOVA revealed a significant effect of the participant group on children's scores for general cognitive ability ($F_{(4;256)} = 7.945; p < 0.01; \eta^2_p = 0.11$). Bonferroni corrected pair-wise comparisons indicated that children from the HCP group ($M = -0.03$, SD = 0.49) had significantly lower scores than the three TD groups (*all* $p < 0.001$; TD 4–6 years: $M = 0.55$, SD = 0.89; TD 7–9 years: $M = 0.62$, SD = 0.68; and TD 10–12 years: $M = 0.54$, SD = 0.64). In contrast, there was no significant difference between any two of the three groups of TD children (*all* $p > 0.05$). Therefore, we considered general cognitive ability as a control variable in our subsequent analyses.

Semantic word fluency task

Number of categorically correct words produced

The mixed model ANCOVA revealed a significant main effect of group for the number of correct answers. **Table 1** provides statistical details and descriptive results. *Post hoc* pairwise comparisons indicated that there was no significant difference between children with HCP and TD 4-6 years for both animals and body parts ($p > 0.45$). Children from the TD 7–9 and TD 10–12 groups produced more animals and body parts than children with HCP and those from the TD 4–6 group (all $p < 0.001$). Finally, children from the TD 10–12 group produced more animals and body parts than children from the TD 7–9 group ($p < 0.001$).

Additionally, the main effect of the stimulus category was significant indicating that overall children produced more body parts than animals within the respective 60 s runs (**Table 2**). Interestingly, simple effects for the individual groups indicated that this was only the case for all TD control groups (all $p < 0.02$), but not for children with HCP ($p = 0.13$). Additional Bayesian analysis following the recommendations by Masson (2011) of the posterior probability substantiated that there was no difference between the number of animals and body parts produced by children with HCP (> 0.63 probability) by providing weak evidence in favor of the null hypothesis. The interaction of group and stimulus category was not significant though.

Finally, the covariate significantly influenced the results for the number of correct answers for both animals ($p < 0.02$) and body parts ($p < 0.01$) with children with higher general cognitive ability producing more correct answers.

Repetitions

There was no significant difference neither between groups nor for stimulus category for the number of repetitions with the respective main effects being not significant. Additionally, the interaction was also not significant. The covariate was not significant for the number of repetitions for both animals ($p > 0.06$) and body parts ($p > 0.51$).

Number of errors committed

There was a significant main effect of group for errors committed. *Post hoc* pairwise comparisons indicated that there

TABLE 1 Results of the semantic word fluency task.

	TD 4–6 years	TD 7–9 years	TD 10–12 years	HCP	F (3; 252)	*P*	Partial η 2	*Post hoc* (Bonferroni test)
	Mean (sd)							
Animals								
Correct words	9.22 (3.31)	12.81 (3.36)	15.38 (3.74)	9.94 (2.82)	46.726	< 0.01	0.357	HCP = TD 4–6 years < TD 7–9 years < TD 10–12 years.
Repetitions	0.94 (1.40)	0.75 (1.35)	0.58 (1.36)	0.49 (0.75)	2.164	< 0.09	0.025	–
Errors	0.16 (0.47)	0.05 (0.22)	0.01 (0.11)	0.04 (0.19)	3.359	< 0.01	0.038	HCP = TD 4–6 years = TD 7–9 years; HCP = TD 7–9 years = TD 10–12 years; TD 4–6 years > TD 10–12 years.
Body parts								
Correct words	10.26 (3.31)	14.15 (3.45)	16.61 (4.40)	10.47 (3.52)	43.288	< 0.01	0.340	HCP = TD 4–6 years < TD 7–9 years < TD 10–12 years.
Repetitions	0.75 (1.02)	1.14 (1.49)	0.66 (1.09)	0.60 (0.86)	2.784	< 0.08	0.032	–
Errors	0.49 (1.14)	0.17 (0.37)	0.07 (0.25)	0.06 (0.23)	7.198	< 0.01	0.079	TD 4–6 years > TD 7–9 years = TD 10–12 years = HCP.

Comparisons between typically developing children group (TD groups: TD 4–6 years, TD 7–8 years, TD 10–12 years) and children with hemiplegic cerebral palsy (HCP). TD 4–6 years, Typically developing children group (4–6 years old); TD 7–9 years, Typically developing children group (7–9 years old); TD 10–12 years, Typically developing children group (10–12 years old); HCP, hemiplegic cerebral palsy; sd, standard deviation; F, ANCOVA's ratio F; partial η2, partial eta squared.

was no significant difference between the number of errors committed by children with HCP and children in the TD 7–9 years and 10–12 years age groups for both animals as well as body parts (all $p > 1.00$). The number of errors committed by children with HCP and children in the 4–6 years for animals' categories was not significant ($p > 0.29$). However, the number of errors committed by children with HCP was significantly lower than the number of errors committed by TD children in the 4–6 years group for body parts categories ($p < 0.001$). The number of errors committed by TD children in the 4-6 years group was significantly higher than the number of errors committed by TD children in the 10-12 years group for the animals' category ($p < 0.04$), and higher than the number of errors committed by TD children in the 7-9 TD 7-9 years and 10-12 years age groups (all $p < 0.03$). There was no significant difference in the number of errors committed by TD 7–9 years and 10–12 years age groups ($p > 1.00$). The interaction was not significant. The covariate was also not significant for the number of repetitions for both animals ($p > 0.4$) and body parts ($p > 0.20$).

Graph parameters

The mixed model ANCOVA revealed a significant main effect of group for all parameters (see **Table 3**). Bonferroni-corrected pairwise comparisons indicated the three TD groups differed significantly from each other with respect to the number of nodes, density, diameter and mean of the shortest path (all $p < 0.03$). For children of the TD 10–12 years group graphs were significantly less dense with a higher number of nodes and edges, larger diameters, and ASP than for children of the TD 7–9 years and TD 4–6 years groups. The group TD 7–9 years presented intermediate parameters, which differed significantly from all parameters presented in the other TD age groups. The graphical parameters obtained for the HCP group differed significantly from the parameters obtained for the TD 7–9 years and TD 10–12 years groups (all $p < 0.001$), but showed no significant difference from parameters observed for the TD 4–6 years group. The interaction was not significant. The covariate was also not significant for the graph parameters (all $p > 0.7$).

To substantiate the observed null effect for the differences between the children with HCP and those from the TD 4–6 year group, we again conducted Bayesian analysis as recommended by Masson (2011). The comparison of the HCP group with the TD 4–6 years group revealed > 0.89 probability and thus positive evidence in favor of the null hypothesis (**Table 4**) according to classification guidelines proposed by Masson (2011).

Semantic network cores

The networks formed by the HCP group and TD 4–6 years, TD 7–9 years, and TD 10–12 years groups and the semantic nuclei obtained from the networks, which represent the words quoted more frequently for each category, are shown in **Figures 1**, **2**. All groups presented a common central semantic network core.

TABLE 2 Comparison between animals and body parts production (correct words).

Groups	Animals	Body parts	F	*P*	Partial η [2]
	Mean (sd)				
HCP	9.94 (2.82)	10.47 (3.52)	2.308	< 0.135	0.043
TD 4–6	9.22 (3.31)	10.26 (3.31)	5.935	< 0.017	0.080
TD 7–9	12.81 (3.36)	14.15 (3.45)	9.251	< 0.004	0.138
TD 10–12	15.38 (3.74)	16.61 (4.40)	6.317	< 0.014	0.078

TD 4–6 years, Typically developing children group (4–6 years old); TD 7–9 years, Typically developing children group (7–9 years old); TD 10–12 years, Typically developing children group (10–12 years old); HCP, hemiplegic cerebral palsy; sd, standard deviation; F, ANCOVA's ratio F; partial η2, partial eta squared.

TABLE 3 Comparisons among groups in word fluency task (graph analysis of body parts category).

	TD 4- 6 years	TD 7- 9 years	TD 10- 12 years	HCP group	F (3;252)	*P*	Partial η [2]	*Post hoc* (Bonferroni test)
	Mean (sd)							
Nodes	10.23 (3.07)	14.12 (3.60)	16.58 (4.14)	10.13 (3.34)	48.792	< 0.001	0.367	HCP = TD 4–6 years < TD 7–9 years < TD 10–12 years
Edges	9.88 (3.44)	13.90 (3.85)	16.20 (4.45)	9.72 (3.62)	41.663	< 0.001	0.332	HCP = TD 4–6 years < TD 7–9 years < TD 10–12 years
Density	0.21 (0.07)	0.16 (0.05)	0.13 (0.03)	0.23 (0.08)	33.493	< 0.001	0.285	HCP = TD 4–6 years > TD 7–9 years > TD 10–12 years
Diameter	7.80 (2.83)	10.93 (4.07)	13.29 (4.57)	7.53 (2.81)	34.643	< 0.001	0.292	HCP = TD 4–6 years < TD 7–9 years < TD 10–12 years
Average Shortest Path	3.29 (0.97)	4.39 (1.33)	5.19 (1.48)	3.22 (0.94)	37.861	< 0.001	0.311	HCP = TD 4–6 years < TD 7–9 years < TD 10–12 years

TD 4–6 years, Typically developing children group (4–6 years old); TD 7–9 years, Typically developing children group (7–9 years old); TD 10–12 years, Typically developing children group (10–12 years old); HCP group, hemiplegic cerebral palsy group; sd, standard deviation; F, ANCOVA's ratio F; partial η2, partial eta squared.

TABLE 4 Bayesian analysis investigating non-significant differences between the HCP and TD 4–6 year groups.

Graph parameter	HCP	TD 4—6 years	*df*	SS_{effect}	SS_{error}	*F*	*BF*	$p_{BIC}(H_0\|D)$
Nodes	10.13 (3.34)	10.23 (3.07)	1; 119	4.516	1175.270	0.457	8.68302409	0.89672648
Edges	9.72 (3.62)	9.88 (3.44)	1; 119	3.816	1433.889	0.317	9.3131287	0.90303621
Density	0.23 (0.08)	0.21 (0.07)	1; 119	0.001	0.741	0.131	10.0675661	0.9096459
Diameter	7.53 (2.81)	7.80 (2.83)	1; 119	0.897	940.861	0.113	10.3074047	0.91156238
Average Shortest Path	3.22 (0.94)	3.29 (0.97)	1; 119	0.131	106.801	0.146	10.1413887	0.91024458

SSeffect, sum of squares for the effect; SSerror, sum of squares for errors; F, ANCOVA's ratio F; BF, Bayes factor; $p_{BIC}(H_0|D)$, posterior probability generated by bayesian information criterion (BIC).

Discussion

The current study aimed to investigate the development of body image using a word fluency task and compare the performance of TD children on this task to the performance of children with HCP. We not only evaluated performance on word fluency for body parts but also for animals, based on lexical-semantic maps of the body image generated with Graph Analysis across different age groups and between TD and children with HCP. Apart from quantitative differences between groups and stimulus categories, we were also interested in examining (by qualitatively analyzing the body parts most cited) whether body schema (related sensorimotor information) and body structural description (related visuospatial information) contribute to the development of body image, and whether this development is delayed in HCP.

Children with HCP presented a representational profile of body image (as reflected by their performance in the semantic fluency task), which seemed equivalent to that of children from the TD 4–6 years group. However, they performed significantly worse than TD children of the other age groups including those of the same age. This may reflect a continuing maturation of body image in TD children not seen in children with HCP in

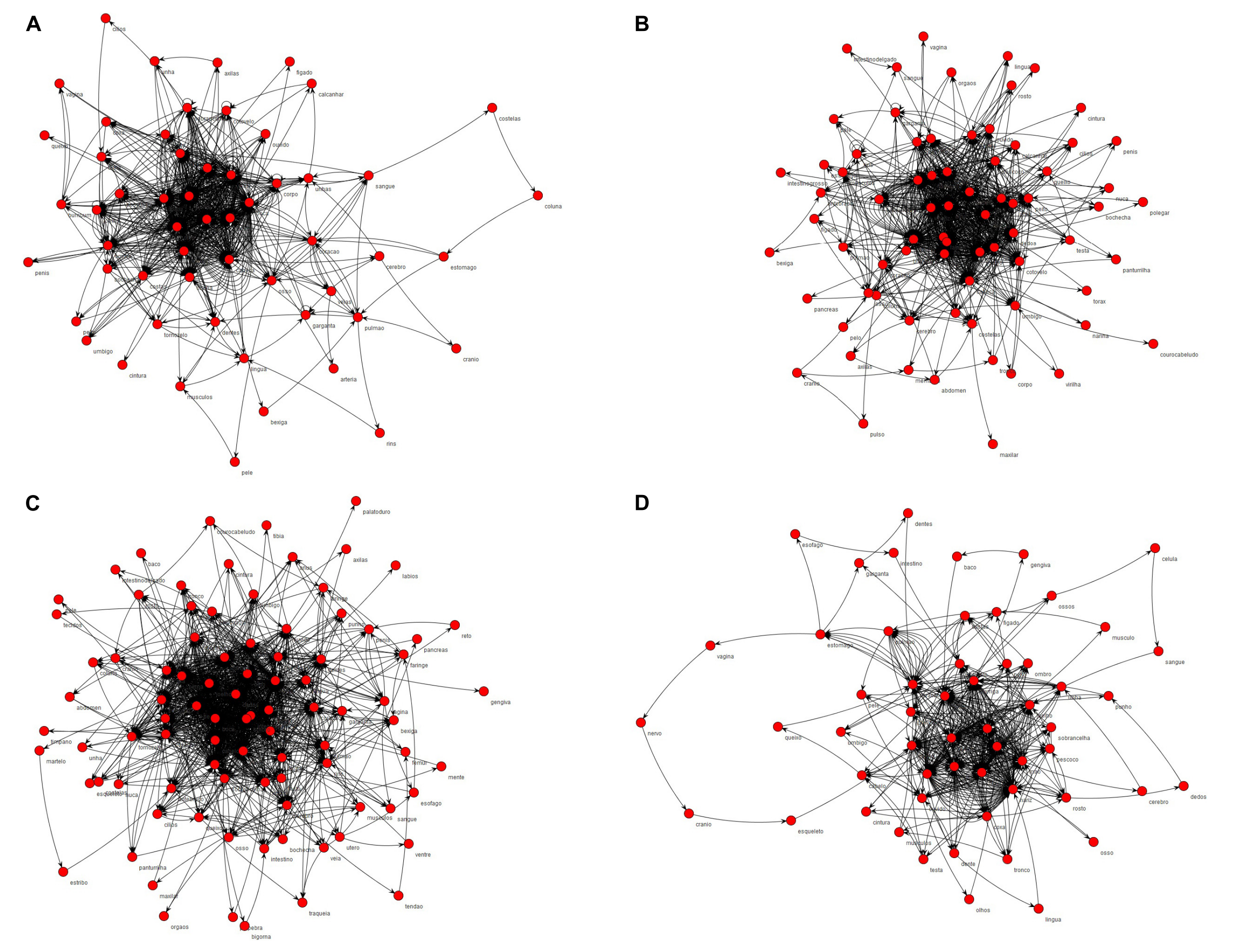

FIGURE 1
Semantic networks of body parts category formed by the groups. In **(A)** semantic network formed by TD 4–6 years; **(B)** semantic network formed by TD 7–9 years; **(C)** semantic network formed by TD 10–12 years; **(D)** semantic network formed by HCP group.

a comparable manner. These results will be discussed in more detail in the following.

Semantic word fluency in hemiplegic cerebral palsy children

Children with HCP (aged from 7 to 12 years old) performed significantly worse than TD children 7–9 years and 10–12 years of age as regards the number of correct words produced, related to the retrieval of the semantic memory content. This is consistent with previous findings (Carlsson et al., 1994; Kolk and Talvik, 2000). Interestingly, they performed comparably to the youngest TD group (i.e., 4–6 years of age) as substantiated by Bayesian analyses. In relation to the number of errors and repetitions in semantic word fluency [reflecting influences of executive functions (Anderson, 2002), children with HCP did not perform significantly differently than TD 7–9 years and TD 10–12 years. This contrasts with previous research, which observed impairment of executive functions (evaluated by verbal fluency) following early brain injury (Bodimeade et al., 2013). In addition, there was no evidence for differences in semantic verbal fluency according to the side of hemiplegia (Bodimeade et al., 2013). According to a recent review, results regarding the presence of language impairments in children with HCP are inconclusive and whether they are observed might be due to differences in the neural reorganization, and in location and extent of neural lesions (Liegeois et al., 2004; Bottcher, 2010).

Regarding the potential differential influence of HCP on verbal fluency for animals and body parts, our results indicated a significant difference in the number of body parts and animals produced, with more body parts than animals produced overall. However, this difference was only significant for the control groups (TD 4–6, TD 7–9, and TD 10–12 years). For the HCP group, this advantage for body parts was not observed. This may reflect a specific relative impairment for the representation of body parts due to HCP.

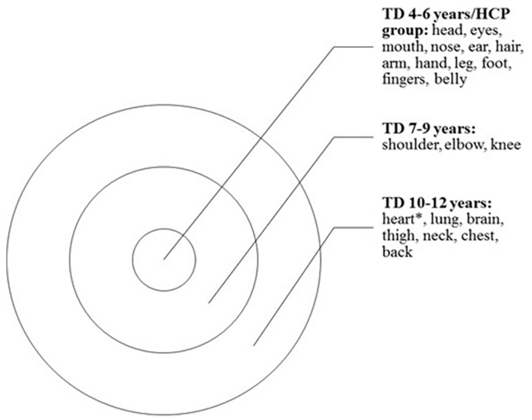

FIGURE 2
Illustration representing the semantic network core obtained from networks, representing the words quoted more frequently for each category. All groups presented a common central core. TD 4–6 years, Typically developing children group (4–6 years old); TD 7–9 years, Typically developing children group (7–9 years old); TD 10–12 years, Typically developing children group (10–12 years old); HCP group, hemiplegic cerebral palsy group; *heart was also cited by HCP group.

Structural characteristics of lexical-semantic body representation networks

Graph-theoretical analyses revealed qualitatively similar profiles for children with HCP and TD children. The qualitative conservation of the basic graphical properties across the four groups seems to suggest that basic mechanisms of categorical fluency might be similar (Strauss et al., 2006; Vitevitch, 2008). This also implies that connections formed may not be random, because some nodes presented many connections and many more nodes had few only connections, characterizing a free scale network. Free scale networks emerge from growth and preferential attachment mechanisms. Growth refers to the addition of new nodes (reflecting words cited) to the network over time (Vitevitch, 2008). Preferential attachment is a constraint that makes it more likely for new nodes being added to the system to connect to nodes that are already highly connected (Vitevitch, 2008). In terms of words, it means that a new word included in the networks will be probably connected to the words that were produced more often previously.

Overall, the performance of children with HCP was quite similar to that of the group TD 4–6 years with quantitative parameters suggesting a lower degree of complexity of their networks than those presented by TD children older than seven years. Also, the semantic networks produced by TD 7–9 years and TD 10–12 years groups were more direct (with less repetition of words), resulting in less dense networks. In addition to the larger vocabulary of older children their networks probably also reflect the establishment of functional relations between body parts (e.g., feet are named after legs, or hands after arms). In contrast, children with HCP performed similar to the TD 4–6 years group and thus the youngest group of control children at the beginning of their body image development. This finding might reflect differences in sensory experience between children with HCP and their TD peers, as discussed below.

Sensory experience and lexical-semantic body representation in hemiplegic cerebral palsy children

Our data on the semantic networks for body parts in TD children suggest a developmental pattern similar to that observed previously in studies of body part identification (Witt et al., 1990; Christie and Slaughter, 2009; Camões-Costa et al., 2010; Auclair and Jambaqué, 2014). In all groups of TD children, words denoting specific body part categories (e.g., face structures, limbs, joints, internal organs) were added to the semantic network cores as age increased. Children of the group TD 4–6 years were found to primarily produce head/face structures and limbs in a non-hierarchical way (including arms, hands, legs, and feet but not dividing the upper limb into the shoulder, arm, elbow, forearm, wrist, etc.). This might reflect influences from sensorimotor afferences contributing to body schema (Christie and Slaughter, 2009). Parts of the body that receive more pronounced and early sensorimotor inputs (such as hands) may be learned preferentially (Ayres, 1961). This is substantiated by correlational analyses indicating that the body parts most frequently named by children are the structures best represented in the sensory cortex (Camões-Costa et al., 2010).

Joints were first mentioned systematically by children in the TD 7–9 years group. When reaching 7 years of age, children are in a period of consolidation and improvement of the basic patterns of movement developed as compared to early childhood (Goodway et al., 2019). In this age group, a refinement of basic motor patterns, the adaptation of motor patterns, and improvement of coordination, and motor control are observed. These new sensorimotor experiences depend on tactile, kinesthetics, proprioceptive, vestibular, and visual inputs. According to this line of reasoning, somatosensory afferences underlying body schema may also influence the development of body image at this age, improving the ability to identify and name body parts.

Only at 10–12 years did the children add internal organs and hierarchize the limbs (e.g., arm and forearm, etc.) and axial structures (e.g., neck, nape, trunk, belly, etc.). Visuospatial experience contributing to body structural description seemed to influence representations of body image at this age

(Auclair and Jambaqué, 2014). Following this rationale, it seems possible that internal organs might only be learned later because they are not visible. The most salient and visible parts of the body are more identifiable and have easily observable functions and may therefore be learned before other non-visible and harder-to-experience parts of the body. Functional knowledge of some internal body parts may also emerge from formal learning about the biology of the human body (Christie and Slaughter, 2009; Auclair and Jambaqué, 2014).

The hierarchy of some axial structures (such as the division of the trunk into the neck, chest, and back) only occurs later in development. This may be due to the influence of motor learning about joints and cultural influences related to formal learning about the human body (Jaakkola and Slaughter, 2002). Studies suggest that body parts can be segmented (e.g., the arm might be considered as whole as the superior limb, or the body part joined to the forearm by the elbow) according to language, and the division of body parts can vary between different languages (Enfield, 2006; Majid, 2010). Older children are more experienced and more likely to expand their vocabulary, and the development of language is very closely related to the development of body awareness (Facon et al., 2002). Despite this, children with HCP (aged from 7 to 12 years old) presented a lexical-semantic network of body parts similar to that of the youngest TD 4–6 years group (as substantiated by Bayesian analysis). This is in line with but also expands previous studies which suggested that children with unilateral brain injury present lower performance in mental motor imagery (body schema) (Fontes et al., 2016; Di Vita et al., 2020) and also in pointing (body structural description) (Christie and Slaughter, 2009; Fontes et al., 2016) and naming (body image) (Christie and Slaughter, 2009; Fontes et al., 2016) body-part tasks than TD children.

Although joints are expected to be a part of the semantic network core of children with HCP because they were part of the semantic-lexical repertoire of children of the same age, we did not observe these children name joints in the semantic fluency task. This is an important aspect because joints are a point of reference for the segmentation of body parts, representing more detailed knowledge about the structuring of the human body (de Vignemont et al., 2009). Segmentation of the body into parts may derive from the organization of the proprioceptive and motor systems, or from perceptual factors such as the visual discontinuity of the body parts (de Vignemont et al., 2009). Following this rationale, motor activity may help to structure the mental representations of the body into functional units, according to the parts of the body that move together. In addition to representing anatomical points of reference, joints constitute the kinesiological basis of movement because the brain needs to identify the joints' position (from a set of proprioceptive signals coming from muscles, tendons, ligaments, and joint capsule) and then plan the desired motor action (Marini et al., 2018). Difficulties in controlling movements, as often experienced by children with HCP, may thus influence their functional performance by restricting new sensorimotor experiences.

For effective motor action, for instance, when manipulating objects, it is necessary to represent the positioning and configuration of the upper limb to avoid uncomfortable or movement restrictive postures (Mutsaarts et al., 2006). Planning impairments have also been reported in young adolescents with HCP (Mutsaarts et al., 2006; Souto et al., 2020). Our study points to a delay in the development of lexical-semantic knowledge of body parts in children with HCP, which might reflect reduced sensorimotor and visuoperceptual experiences of their own bodies. Thus, it is plausible that lexical-semantic knowledge of body parts is influenced in a bottom-up manner.

When interpreting the results of the current study, some limitations have to be considered. The group of children with HCP was rather small, making it impossible to create subgroups of different ages for this group. Furthermore, it needs to be noted that the present study focused primarily on body image as only one level of body representation. In this context, it is also worth noticing that the task to evaluate participants' body image task only drew on the semantics of body parts – which seems like a limitation in scope. Moreover, future studies might also include tasks to evaluate body schema and body structural description as well as measures for other executive function components. We used a controlled word fluency task to assess children's knowledge of body parts. This test has a considerably higher degree of freedom compared to responses in a task requiring the naming of body parts.

Furthermore, the graph-theoretical analysis identified an emergent structure of a lexical-semantic network, qualitatively similar but less complex in children with HCP compared to TD children. Our results also suggested that the building of the lexical-semantic network for body parts and thus body image seems influenced by sensorimotor and visuoperceptual experiences. As suggested by Baumard and Osiurak (2019), bodily experience develops in everyday life under the influence of language by thinking and talking about body parts and actions. Investigations about the relationship between language and action demonstrate the involvement of motor systems in the processing of action-related language (Dalla Volta et al., 2009; Crivelli et al., 2018; Shebani and Pulvermüller, 2018). Shebani and Pulvermüller (2018) hypothesized that processing of action words semantically related to complex actions (e.g., citing "finger" and "grasping") might facilitate elementary movements, by pre-activating a part of the movement circuit. In this context, it would also be desirable to examine if explicit conversations about body parts ("body talk") might benefit the development of body image in children with HCP.

Data availability statement

The original contributions presented in this study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

This study was approved by the Research Ethics Committee of the Federal University of Minas Gerais (protocol number: 2.155.379). Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Author contributions

TC, DS, PF, and VH were involved in the conceptualization and design of the original research. TC and KM were involved in the analysis. TC, VH, and KM were involved in the writing of the manuscript. All authors contributed to the revisions of the manuscript and approved the final manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The relationship between mental representations of self and social evaluation: Examining the validity and usefulness of visual proxies of self-image

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Reverse correlation (RC) method has been recently used to visualize mental representations of self. Previous studies have mainly examined the relationship between psychological aspects measured by self-reports and classification images of self (self-CIs), which are visual proxies of self-image generated through the RC method. In Experiment 1 (N=118), to extend the validity of self-CIs, we employed social evaluation on top of self-reports as criterion variables and examined the relationship between self-CIs and social evaluation provided by clinical psychologists. Experiment 1 revealed that the valence ratings of self-CIs evaluated by independent raters predicted social evaluation after controlling for the effects of self-reported self-esteem and extraversion. Furthermore, in Experiment 2 (N=127), we examined whether a computational scoring method – a method to assess self-CIs without employing independent raters – could be applied to evaluate the valence of participants' self-CIs. Experiment 2 found that the computational scores of self-CIs were comparable to independent valence ratings of self-CIs. We provide evidence that self-CIs can add independent information to self-reports in predicting social evaluation. We also suggest that the computational scoring method can complement the independent rating process of self-CIs. Overall, our findings reveal that self-CIs are a valid and useful tool to examine self-image more profoundly.

KEYWORDS

self-image, reverse correlation, visual representations, self-perception, self-evaluation, social evaluation

1. Introduction

Self-image is an essential element of personality that has been studied for a long time (Rogers, 1959; Rosenberg, 1965; Coon, 1997). Self-image is defined as how we see ourselves, and it affects how we feel, think, and act in society (Rogers, 1959). Also, it is known as a multi-dimensional construct that includes subjective perceptions of not only oneself but also one's own mental functioning, adjustment, and social attitudes in different areas of life (Lindfors et al., 2005; Di Blasi et al., 2015). Self-image is closely related to self-esteem (Rosenberg, 1965; Hulme et al., 2012), which can be viewed as an evaluative constituent of self-image (Lindfors et al., 2005). It is also linked to optimistic attitude toward life's challenges (Mikulincer, 1995). In addition, negatively distorted self-image is a core feature of mental disorders, such as social anxiety disorder (Di Blasi et al., 2015; Meral and Vriends, 2022), body dysmorphic disorder (Didie et al., 2012), and eating disorder (Hrabosky et al., 2009). Furthermore, how people conceive themselves is associated with interpersonal relationships (Bartholomew and Horowitz, 1991; O'Koon, 1997) and behaviors in a social interaction situation (Hirsch et al., 2004).

Although self-image, or mental picture of self contains *imagery* properties (Bailey, 2003), traditional assessments of self-image have mainly employed verbal assessments (e.g., Offer et al., 1989; Amos et al., 1997; O'Koon, 1997). For example, Amos et al. (1997) found that participants with more positive self-image were more likely to relate themselves to positive adjectives such as "Healthy," "Confident," or "Nice" than to negative ones. In addition, Offer et al. (1989) developed the Offer Self-Image Questionnaire (QSIQ) to assess adolescents' self-image. Recently, it has also been suggested that mental representations of self can be visualized by means of a technique called *reverse correlation* (Moon et al., 2020; Maister et al., 2021; Steiner et al., 2021). The reverse correlation (RC) method is a data-driven technique used to create a visualization of an individual's mental representation (Dotsch et al., 2008, 2011; Brinkman et al., 2017; Brown-Iannuzzi et al., 2017). Application of the RC method in studying self-image allows researchers to investigate self-image in a novel way by visualizing mental representation of self (Moon et al., 2020; Maister et al., 2021; Steiner et al., 2021). In a RC image classification task designed to visualize an individual's self-image, the individual selects the one out of a pair of faces that better resembles himself or herself across 300–500 trials. The presented facial stimuli consist of a single base face with superimposed random grayscale noise. By averaging the selected facial stimuli, one classification image of self (self-CI) is generated, which can be regarded as a visual proxy of mental representation of self (e.g., Moon et al., 2020).

Application of the RC method to measure self-image has notable advantages. The RC method incorporates participants' spontaneous use of information to visualize their mental representations. In the RC task, participants freely adopt the criteria of their judgments that are necessary in selecting the stimuli (Brinkman et al., 2017). For example, some participants may choose stimuli that resemble themselves by focusing on facial features such as eyes, whereas others may select facial stimuli by focusing on more vague factors like overall impressions. Because participants can use criteria that come to mind without constraints when choosing facial stimuli, diverse criteria can be incorporated into the mental representation of self (Brinkman et al., 2017; Moon et al., 2020; Maister et al., 2021).

Another advantage of using the RC method is that researchers can visualize self-image with fewer biases due to social desirability. A typical RC paradigm uses a two-image forced choice RC task in which participants are forced to make spontaneous and instinctive decisions (Dotsch and Todorov, 2012). During the task, some participants may be unaware of the criteria that they adopt to select images (Brinkman et al., 2017). Therefore, mental representations visualized through the RC method may be less susceptible to social desirability as compared to explicit measures, such as self-reports (Pauzé et al., 2021). Supporting this argument, Moon et al. (2020) reported that participants' social desirability was not significantly associated with their self-CIs but with self-reported variables related to self-image. This implies that application of the RC method in investigating self-image may allow us to further comprehend the features of self-image with fewer biases.

Prior studies have shown that the RC method can be a novel and promising method for studying self-image. In a pioneering study, Moon et al. (2020) provided evidence that the self-CIs generated through the RC method are valid proxies of mental representations of self. Participants reported that they perceived their self-CIs as bearing a stronger resemblance to themselves than did CIs of others, without knowing which images corresponded to their self-CIs. In addition, the valence ratings of self-CIs were significantly associated with self-image relevant variables (e.g., self-esteem, extraversion). Moreover, Steiner et al. (2021) utilized the RC technique to investigate the distortion and enhancement of one's self-image in relation to narcissism. Their findings revealed that the narcissistic traits mediated the relationship between low self-concept clarity and self-image distortion, and that narcissistic insecurity mediated the relationship between the distortion of self-image and self-image enhancement. Furthermore, Maister et al. (2021) found that participants' self-CIs were similar to their real faces, and that independent raters reliably inferred Big Five personality traits from self-CIs created by the RC method.

The existing studies have shown that the self-CIs generated by the RC method are related to self-reported psychological factors (e.g., Moon et al., 2020; Maister et al., 2021; Steiner et al., 2021). However, to the best of our knowledge, no empirical study has yet shown whether one's self-CI would be associated with psychological aspects measured by methods other than self-reports. Therefore, to extend the validity of self-CIs, we employed social evaluation on top of self-reports as criterion variables and examined the relationship between self-CIs and social evaluation. Previous studies have constantly found that how an individual sees himself or herself may influence how that person is perceived by other people (Hirsch et al., 2004; Zeigler-Hill et al., 2013). For example, when the socially anxious people were asked to hold negative self-image in mind before a conversation with a stranger, they were evaluated more negatively by their partners in the quality of conversation than when they held a less negative self-image in mind (Hirsch et al., 2004). Similarly, Zeigler-Hill et al. (2013) reported that individuals with greater self-worth were evaluated more positively by others than were those with less self-worth.

These studies may indicate that examining social evaluation contributes to a further understanding of self-image. In this respect, examining the relationship between social evaluation and self-CIs may provide additional evidence for the validity of the self-CIs.

In addition, given that the RC method incorporates the visual aspects, which is not included in self-reported measures (Moon et al., 2020), testing whether the self-CIs can provide incremental information to self-reports would help in investigating the usefulness of the RC method for studying self-image. Specifically, we aimed to examine the validity of self-CIs by investigating the association between the valence ratings of self-CIs and social evaluation provided by clinical experts (i.e., expert ratings). We also investigated the usefulness of the self-CIs by testing whether the self-CIs would provide incremental information in predicting social evaluation after controlling for the effects of self-reported measures.

Moreover, CIs have been mainly rated by independent raters on the judgments of interests (e.g., trustworthiness, dominance, and attractiveness; see Dotsch and Todorov, 2012; Brown-Iannuzzi et al., 2017). However, employing independent raters inevitably necessitates more time and effort. Therefore, we proposed a *computational scoring method* – a method to assess self-CIs more objectively and efficiently, eliminating the repeated process of recruiting independent raters to evaluate the self-CIs every time.

2. Experiment 1

The primary purpose of Experiment 1 was to examine the validity and usefulness of the self-CIs generated by the RC method, using both self-reports and expert ratings as the criterion variables. For this purpose, Experiment 1 consisted of three separate phases. In the first phase, participants completed self-reports, then had their facial photographs taken, and performed the RC task designed to generate their self-CIs. In addition, they evaluated whether their self-CIs resembled themselves. Also, they recorded a 5-min self-introduction video for social evaluation. In the second phase, we recruited a new sample of independent raters. The independent raters evaluated the valence of the participants' self-CIs and facial appearance. In the final phase, licensed clinical psychologists evaluated the psychological adjustment of participants based on the self-introduction videos.

We hypothesized that participants with higher valence ratings of self-CIs would be rated more positively by clinical experts in terms of psychological adjustment than would be those with lower valence ratings of self-CIs. Moreover, we postulated that the valence ratings of self-CIs would predict social evaluations provided by experts even after controlling for the effects of self-reported features related to self-image and facial appearance. In addition to main hypothesis, we postulated that the valence ratings of self-CIs would be positively correlated with self-reported self-esteem, extraversion, and explicit self-evaluation. Lastly, we expected that the valence ratings of self-CIs would not be significantly associated with social desirability.

2.1. Methods

2.1.1. Participants

In Experiment 1, we recruited 118 undergraduate students (87 females and 31 males) to perform the RC task *via* an online advertisement and printed flyers. The mean age of participants was 20.92 ($SD_{age}=2.02$; age range = 18–27). They received a $15 gift voucher for their participation. They signed a written informed consent form. Additionally, we recruited 59 independent raters (29 females and 30 males; $M_{age}=23.00$, $SD_{age}=2.88$; age range = 19–34) to evaluate the valence of the participants' self-CIs and facial appearance. The independent raters consisted of 49 undergraduate students (83.05%) and 10 graduate students (16.95%). They received $25 for their participation. Before evaluating the images, they signed a consent form. All participants and independent raters were Asian.

To blind participants to our hypothesis, before the experiment we said that we were examining the relationship between personality traits and the ways that people perceive social stimuli. We debriefed the purpose of this study after the experiment. Experiment 1 was approved by the Institutional Review Board.

2.1.2. Materials and procedures

2.1.2.1. Self-reports

2.1.2.1.1. Rosenberg self-esteem scale (RSES)

We used the RSES, a 10-item measure originally developed by Rosenberg (1965) and later validated in Korean (Lee and Won, 1995), to assess global self-esteem. Each question is answered on a 5-point Likert scale (1 = *not very true of me*; 5 = *very true of me*). The internal consistency of the RSES was 0.86.

2.1.2.1.2. Explicit self-evaluation

Participants rated how they evaluated themselves using seven items from 14 self-presentation domains (Leary and Allen, 2011). Each question was scored on a 9-point bipolar scale (e.g., unfriendly, unlikable vs. friendly, likable). We used the Korean version of explicit self-evaluation (Moon et al., 2020). The internal consistency of explicit evaluation was 0.65.

2.1.2.1.3. Extraversion

We used 10 items related to extraversion in the HEXACO-60 scale to assess extraversion (Ashton and Lee, 2009).[1] The

1 Participants also completed the remaining 50 items on the HEXACO-60 scale. The scale assesses Honesty-Humility (H), Emotionality (E), Agreeableness (A), Conscientiousness (C), Openness to Experience (O), and Extraversion (E). Consistent with Moon et al. (2020), the other five dimensions were not significantly associated with the independent valence ratings of self-CIs or the computational scores of self-CIs in Experiment 1 and 2b, $|r|s<0.17$, p = ns.

HEXACO-60 is answered on a 5-point Likert scale (1 = *strongly disagree*; 5 = *strongly agree*). The extraversion in the HEXACO-60 includes the factors of social self-esteem, social boldness, sociability, and liveliness. We used the Korean version of HEXACO-60 (Lee and Ashton, 2013). The internal consistency was 0.77.

2.1.2.1.4. Center for epidemiological studies depression scale (CES-D)

We used the CES-D, a 20-item measure developed by Randloff (1977) and later validated in Korean (Chon et al., 2001), to assess depressive symptoms. Each question ranged from "0 = rarely or none of the time (less than 1 day per week)" to "3 = most or all the time (5 to 7 days in a week)." The internal consistency of the CES-D was 0.91.

2.1.2.1.5. Taylor manifest anxiety scale (TMAS)

We used the TMAS, developed by Bendig (1956) and later validated in Korean (Lee, 2000a), to assess chronic anxiety symptoms. The TMAS consisted of 20 binary items (Cronbach's $\alpha = 0.84$).

2.1.2.1.6. Marlowe-Crowne social desirability scale (MCSDS)

We used the MCSDS, originally developed by (Crowne and Marlowe, 1960) and later validated in Korean (Lee, 2000b), to measure social desirability. This scale consists of 33 binary items (Cronbach's $\alpha = 0.77$).

2.1.2.2. Facial photographs

After completing self-reported questionnaires, participants had their photographs taken. To control for the effect of extraneous factors on the evaluation of the facial photographs, we asked participants to (1) put on neutral facial expression, (2) take off all accessories, including glasses and visible jewelry, and (3) tie their hair back to show ears if necessary. We then cropped the facial photographs from the top of the head to the neck and aligned the photographs so that every facial feature is in the same position in every photograph by using Python and the OpenCV library (Bradski, 2000). In addition, we converted all facial photographs into black and white, since CIs were in black and white.

2.1.2.3. Reverse correlation (RC) task

Participants then performed the RC task to generate their self-CIs. Facial stimuli used in the RC task were generated from two base faces, which are morphed composites of 100 Asian faces for each sex (Moon et al., 2020). Using the rcicr package (Dotsch, 2016), we superimposed random grayscale noise on each base face to generate 300 pairs of facial stimuli per sex. Each pair of stimuli included a particular noise pattern and its inverse noise pattern (see Figure 1A). The inverse noise pattern is the mathematical opposite of the particular noise pattern, which makes facial stimuli look different with each noise pattern (Dotsch and Todorov, 2012).

Participants completed 300 trials of the RC task to select an image that bore a stronger resemblance to themselves from a pair of images to each generate a self-CI (see Figure 1B). On each trial, two facial stimuli were presented side by side. Upon presenting a pair of stimuli, participants were forced to choose the one from two facial stimuli within 3 s (Moon et al., 2020). The 300 pairs of facial stimuli were presented in random order. Using the rcicr package (Dotsch, 2016), we generated a self-CI for each participant by superimposing the averaged noise of all selected images on the base face. The R codes found in the repository[2] provide a tutorial for generating self-CIs. We computerized the entire procedure of the RC task using the PsychoPy program (Peirce et al., 2019).

2.1.2.4. Resemblance ratings of self-CIs

Upon the completion of the RC task, participants evaluated their self-CIs on resemblance without knowing that the self-CIs were generated from 300 trials of the RC task.[3] The purpose of the resemblance evaluation was to test whether the self-CIs of participants reflected their facial appearance as part of a manipulation check. As Moon et al. (2020) did, we included five filler-CIs per sex with their self-CIs to check whether participants perceived their self-CIs as more similar to themselves than were the filler-CIs. We utilized the filler-CIs used in Moon et al. (2020). The six CIs (a participant's self-CI and five filler-CIs) were presented in random to avoid experimental biases. The resemblance was rated on a 9-point Likert scale (1 = *weaker resemblance to myself*; 9 = *stronger resemblance to myself*).

2.1.2.5. Videotaped self-introductions

Participants were asked to freely introduce themselves to potential job interviewers for 5-min as part of a job interview simulation. Before the self-introduction task, we set the laptop camera to match the eye-level of the participants to capture non-verbal communication (e.g., gestures, facial expression, and eye contact). Participants were informed that their brief videos were evaluated by three clinical psychologists.

2.1.2.6. Independent valence ratings of self-CIs and facial appearance

In the second phase, the independent raters evaluated both the valence of the participants' facial appearance and self-CIs without knowing the study hypotheses or how the self-CIs were generated. They performed the evaluation tasks on an online experimental platform[4]. We randomly assigned the raters to two groups, considering the sex ratio and the fact that evaluating too many images might cause fatigue and reduce the reliability of the evaluation. Two groups of randomly assigned independent raters evaluated 59 self-CIs of the participants and the same number of facial photographs on the valence.

2 https://osf.io/rstwv/

3 Participants also evaluated the valence of their self-CIs with seven items. We decided to only use the valence ratings of self-CIs by independent raters because the independent ratings of self-CIs were comparable to the valence ratings of self-CIs by the participants (see Supplementary Table S1 for details).

4 pavlovia.org

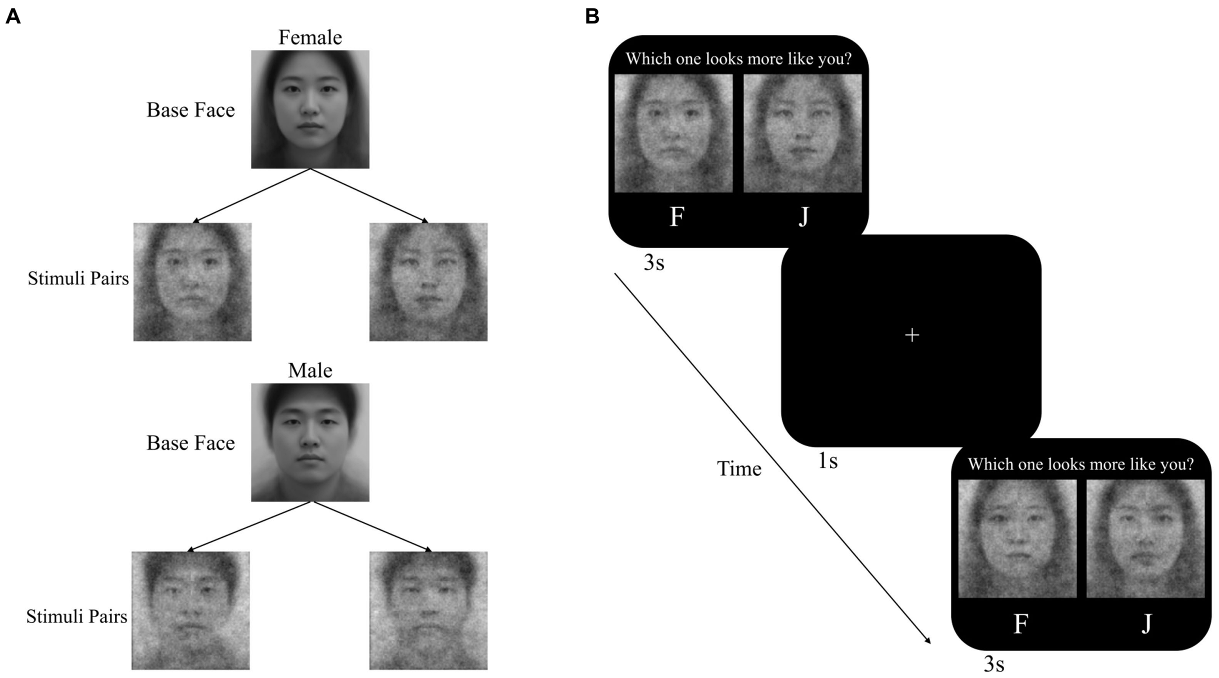

FIGURE 1
(A) Base faces and examples of stimuli pairs used in the reverse correlation task. **(B)** Illustrations of the image-generation phase.

We used the seven items from 14 self-presentational domains (Leary and Allen, 2011) to assess the valence of self-CIs and facial appearance (see Moon et al., 2020 for specific items). The items were rated on 9-point bipolar scale (e.g., 1 = "unfriendly, unlikable," 9 = "friendly, likable"). We averaged the result of the seven items to calculate one independent valence rating. All items were presented in random order. The independent raters evaluated the next image after all seven items were evaluated for one image. The internal consistency of the independent valence ratings of self-CIs and facial appearance was 0.97 and 0.92, respectively.

2.1.2.7. Evaluations of self-introduction videos

In the final phase, three licensed clinical psychologists (1 female and 2 males) completed evaluations of the participants' psychological adjustment level based on their self-introduction videos. Three clinical experts were unaware of the study hypotheses. The perceived psychological adjustment was measured with five items on 9-point Likert scales: (1) emotional instability, (2) psychological maturity, (3) interpersonal competence, (4) psychological flexibility, and (5) invoking positive emotions.[5] These five items were averaged to calculate one expert rating ($\alpha = 0.98$). Inter-rater reliability of expert ratings proved to be good using intraclass correlation coefficients (ICC; Cicchetti, 1994) for the averaged expert ratings of ICC(2, k) = 0.62, $p < 0.001$, and ICC(3, k) = 0.70, $p < 0.001$.

2.2. Results and discussion

2.2.1. Resemblance rating

We examined whether participants perceived that their self-CIs reflected their facial appearances as part of a manipulation check. A paired sample t-test revealed that participants perceived their self-CIs ($M = 5.63$, $SD = 1.89$, 95% CI [5.28, 5.97]) to be more similar to themselves than were filler-CIs ($M = 4.02$, $SD = 0.99$, 95% CI [3.84, 4.20]) in the resemblance rating, $t(117) = 8.47$, $p < 0.001$.

2.2.2. Relationship between independent valence ratings of self-CIs and self-reported variables

As shown in Table 1, valance ratings of self-CIs rated by independent raters were positively correlated with self-esteem ($r = 0.23$, $p < 0.05$), extraversion ($r = 0.29$, $p < 0.01$), and explicit self-evaluation ($r = 0.29$, $p < 0.01$). The independent valence ratings of self-CIs were negatively correlated with trait anxiety ($r = -0.24$, $p < 0.05$), and were not significantly correlated with depression ($r = -0.11$, $p = 0.222$) or social desirability ($r = 0.18$, $p = 0.054$). This is consistent with the findings of Moon et al. (2020) that the

5 We also asked the experts to evaluate the participants in the video with the same seven items for rating the valence of self-CIs. The results were generally consistent with the five items for psychological adjustment but less salient. Therefore, we did not include the valence ratings evaluated by experts in further analysis (see Supplementary Table S2 for details).

self-CIs are associated with one's attitude toward oneself and personality traits related to interpersonal relationships.

2.2.3. Relationship between independent valence ratings of self-CIs and facial appearance

Because the correlation between independent valence ratings of self-CIs and facial appearance was significant ($r = 0.37$, $p < 0.001$), we conducted a multiple linear regression analysis to examine whether the mental representation of self is predicted by psychological factors even after controlling for actual facial appearance. Specifically, we entered both self-reported explicit self-evaluation and independent valence ratings of facial appearance as predictor variables, and independent valence ratings of self-CIs as a dependent variable in the model. We included explicit self-evaluation among self-reported variables, because explicit self-evaluation was measured with the same items used in the independent valence ratings. Explicit self-evaluation predicted the independent valence ratings of self-CIs, $\beta = 0.21$, $t(115) = 2.46$, $p < 0.05$, 95% CI [0.04, 0.39], even after controlling for the independent valence ratings of facial appearance, $\beta = 0.32$, $t(115) = 3.66$, $p < 0.001$, 95% CI [0.15, 0.49]. In line with Maister et al. (2021), we provide evidence that individuals' self-CIs do not simply reflect their facial appearances but are influenced by psychological factors.

2.2.4. Relationship between independent valence ratings of self-CIs and expert ratings

To examine the validity and usefulness of the self-CIs generated by the RC method, we investigated the relationship between the independent valence ratings of self-CIs and expert ratings on psychological adjustment after watching participants' self-introductory videos. As presented in Table 1, we found that expert ratings on psychological adjustment were significantly correlated with the independent valence ratings of self-CIs ($r = 0.28$, $p < 0.01$) but not with the independent valence ratings of facial appearance ($r = 0.12$, $p = 0.212$). Among self-reported variables related to self-image, extraversion was significantly correlated with expert ratings on psychological adjustment ($r = 0.29$, $p < 0.01$), as was self-esteem ($r = 0.21$, $p < 0.05$). On the other hand, other self-reported variables were not significantly correlated with psychological adjustment ($|r|s = 0.06 \sim 0.16$, $p =$ ns).

Given that extraversion and self-esteem were positively correlated with the psychological adjustment as evaluated by experts, we performed a multiple linear regression analysis to investigate the independent and incremental effect of the valence of self-CIs on expert ratings after controlling for the effects of extraversion and self-esteem. The relationship between the independent valence ratings of self-CIs and expert ratings remained significant, $\beta = 0.21$, $t(114) = 2.32$, $p < 0.05$, 95% CI [0.03, 0.39], after controlling for the effects of extraversion, $\beta = 0.20$, $t(114) = 1.77$, $p = 0.080$, 95% CI [−0.02, 0.43], and self-esteem, $\beta = 0.03$, $t(114) = 0.30$, $p = 0.762$, 95% CI [−0.19, 0.26].

In support of our main hypothesis, our findings revealed that higher the independent valence ratings of self-CIs, participants were evaluated more positively by experts. This is consistent with previous literature that individuals with positive self-perceptions are viewed more favorably by others than those with negative self-perceptions (Taylor et al., 2003; Zeigler-Hill et al., 2013). Building on previous studies, we demonstrated that the significant relationship between self-image and social evaluation can be revealed through the RC method. In addition, these findings imply that the self-CIs add information to self-reported variables in predicting social evaluation. This suggests that the RC method can be a valid and useful tool for understanding the features of self-image that are hard to capture with self-reports.

3. Experiment 2a

The independent-rating method necessitates a considerable number of independent raters to reliably evaluate participants'

TABLE 1 Descriptive statistics and correlations between study variables.

	1	2	3	4	5	6	7	8	9
1. VR_{IR}	–								
2. VR_{FA}	0.37***	–							
3. Expert ratings	0.28**	0.12	–						
4. Self-esteem	0.23*	0.19*	0.21*	–					
5. Explicit self-evaluation	0.29**	0.24**	0.16	0.49***	–				
6. Extraversion	0.29**	0.16	0.29**	0.63***	0.52***	–			
7. Depression	−0.11	−0.14	−0.08	−0.67***	−0.37***	−0.48***	–		
8. Anxiety	−0.24*	−0.22*	−0.15	−0.64***	−0.35***	−0.49***	0.70***	–	
9. Social desirability	0.18	0.09	−0.06	0.19*	0.23*	0.08	−0.21*	−0.28**	–
M	4.76	5.18	5.34	28.81	6.45	30.76	16.56	8.78	16.42
SD	0.86	0.59	1.20	5.55	0.79	5.95	9.99	4.67	5.13

$N = 118$, VR_{IR} = Valence ratings of the independent raters (self-CIs); VR_{FA} = Valence ratings of facial appearance. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

self-CIs generated through the RC method. In addition, the independent-rating method requires an additional recruitment of raters each time participants' self-CIs are evaluated. In Experiment 2a, we aimed to propose a computational scoring method to efficiently and objectively measure self-CIs as an alternative approach to independent ratings.

3.1. Methods

3.1.1. Participants

Participants in Experiment 1 visited the laboratory again about a month after the entire completion of Experiment 1. Experiment 2a was also approved by the Institutional Review Board.

3.1.2. Materials and procedures

3.1.2.1. Computational scoring method

To compute the valence of self-CIs objectively and efficiently, the RC task was designed to select an image that looked more positive, with the instruction, "Which one looks more positive?" The instruction was adapted from a study by Dotsch and Todorov (2012). Based on the number of times a positive stimulus was selected from each pair, the positivity score of all stimuli used in the RC task was computed. For example, if 40 percent of participants chose the image on the left in a certain pair, the left image was granted a positivity score of 0.4, while the score of the right image was coded as 0.6. Given that each facial stimulus has a positivity score, the total positivity score, which we refer to as *computational scores* can be calculated by averaging all positivity scores for the images selected to generate self-CIs. For example, if a participant selected images with positivity scores of 0.4, 0.5, and 0.6, the total positivity score was 0.5. Repeating this method, the total positivity score can be computed for 300 selected images (see Figure 2 for procedure details). Considering the occurrence of non-response caused by the 3 s limit for each trial, the positivity scores of the participants' self-CIs generated in Experiment 1 were not summed but averaged. The R codes found in the repository[6] provide the method of granting the positivity scores of all facial stimuli presented in the RC task and calculating the positivity scores of self-CIs.

3.1.2.2. Independent valence ratings of positive-CIs

To test whether participants reliably selected facial stimuli that looked more positive, the aforementioned independent raters evaluated the valence of the positive-CIs, each created by the participants with the same items as those used to assess the valence of self-CIs in Experiment 1. To be specific, we conducted a paired sample t-test to examine whether the positive-CIs created in Experiment 2a were evaluated more positively than the self-CIs of participants. We found that the independent raters perceived the positive-CIs created by the participants ($M = 5.34$, $SD = 0.58$, 95% CI [5.23, 5.44]) as more positive than the participants' self-CIs ($M = 4.76$, $SD = 0.86$, 95% CI [4.60, 4.92]), $t(117) = 6.01$, $p < 0.001$. For the descriptive purpose, we superimposed the averaged grayscale visual noise of all selected images on the base images to create standard positive-CIs by sex. In an equivalent manner, we created standard anti-positive CIs for all non-selected images (see Figure 3).

6 https://osf.io/rstwv/

3.2. Results and discussion

3.2.1. Validity of the computational scores of self-CIs

The validity of computational scores (positivity scores) of self-CIs created in Experiment 1 was examined by assessing their relationship with variables used in Experiment 1 (self-reported variables and social evaluations by experts). In other words, we tested whether computational scores of self-CIs can substitute independent ratings of self-CIs. We found that the computational scores of self-CIs were strongly correlated with the independent valence ratings of self-CIs ($r = 0.86$, $p < 0.001$). In addition, the computational scores of self-CIs were significantly correlated with self-esteem ($r = 0.22$, $p < 0.05$), explicit self-evaluation ($r = 0.32$, $p < 0.001$), extraversion ($r = 0.33$, $p < 0.001$), trait anxiety ($r = -0.23$, $p < 0.05$), and psychological adjustment as evaluated by experts ($r = 0.33$, $p < 0.001$).

Moreover, we reanalyzed the multiple linear regression model predicting participants' social evaluations provided by the clinical experts. We entered the computational scores of self-CIs as a predictor variable instead of the independent valence ratings of self-CIs. We found that the effect of the computational scores of self-CIs on expert ratings remained significant, $\beta = 0.26$, $t(114) = 2.86$, $p < 0.01$, 95% CI [0.08, 0.44], even after controlling for the effect of extraversion, $\beta = 0.17$, $t(114) = 1.50$, $p = 0.136$, 95% CI [−0.06, 0.40] and self-esteem, $\beta = 0.04$, $t(114) = 0.40$, $p = 0.694$, 95% CI [−0.18, 0.27]. Overall, these findings revealed that the computational scoring method could be a valid approach in assessing the self-CIs and may supplement the commonly used independent rating method.

4. Experiment 2b

To examine whether the computational scoring method made in Experiment 2a is valid and applicable to evaluate newly recruited participants' self-CIs, we replicated the findings of Experiment 2a. For this purpose, Experiment 2b comprised two separate phases. In the first phase, newly recruited participants answered a set of self-reported measures. They then performed the RC task to generate their self-CIs and evaluated these images in terms of resemblance. Because the entire process was conducted online, participants were guided to perform the RC task and the resemblance evaluation in a quiet environment as much as possible. We calculated the computational scores of the

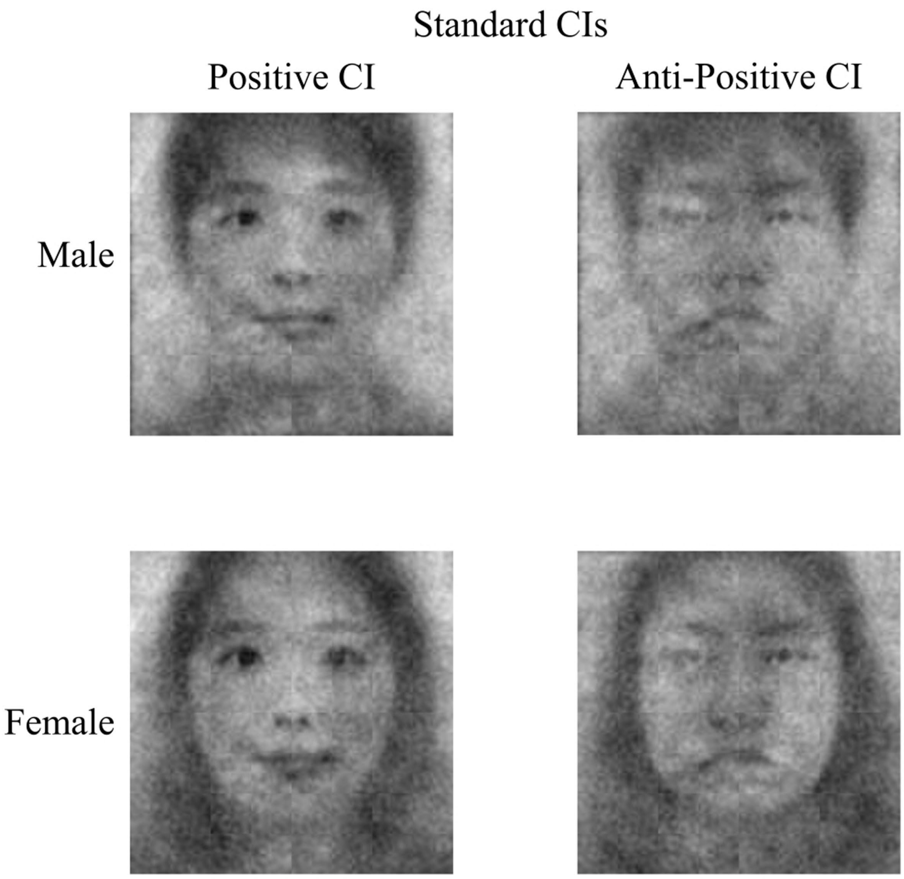

FIGURE 2
The standard classification images (CIs) generated by superimposing the averaged grayscale noise patterns of all selected images on the base images (left) and all non-selected images on the base images (right).

participants' self-CIs upon the completion of task. In the second phase, a new sample of independent raters evaluated the valence of the participants' self-CIs.

We hypothesized that the computational scores of self-CIs would be correlated with the valance ratings of self-CIs as evaluated by independent raters and self-reported variables related to self-image, such as self-esteem, explicit self-evaluation, and extraversion.

4.1. Methods

4.1.1. Participants

In Experiment 2b, we recruited 127 participants (86 females and 41 males) that performed the RC task *via* an online advertisement and printed flyers. They consisted of 91 undergraduate students (71.65%) and 36 graduate students (28.35%). The mean age of participants was 25.35 ($SD_{age} = 5.41$; age range = 18–47). For their participation, they received a $10 gift voucher. They voluntarily signed a written informed consent form. In addition to the participants, we recruited 62 independent raters (32 females and 30 males) to rate the valence of self-CIs generated by the participants. The independent raters consisted of 53 undergraduate students (85.48%) and 9 graduate students (14.52%). The mean age of the independent raters was 22.45 ($SD_{age} = 2.47$; age range = 19–31). They received $10 for their participation. They provided informed consent electronically. All participants and independent raters were Asian. Experiment 2b was also approved by the Institutional Review Board.

4.1.2. Materials and procedures

4.1.2.1. Self-reports

We used the questionnaires used in Experiment 1. The internal consistency of each self-reported measure is as follows: RSES, $\alpha = 0.92$, Explicit Self-Evaluation, $\alpha = 0.73$; Extraversion, $\alpha = 0.86$; CES-D, $\alpha = 0.93$; TMAS, $\alpha = 0.89$; MCSDS, $\alpha = 0.64$.

4.1.2.2. Reverse correlation (RC) task

For the RC task, we utilized 300 pairs of facial stimuli used in Experiment 1. Unlike Experiment 1, the RC

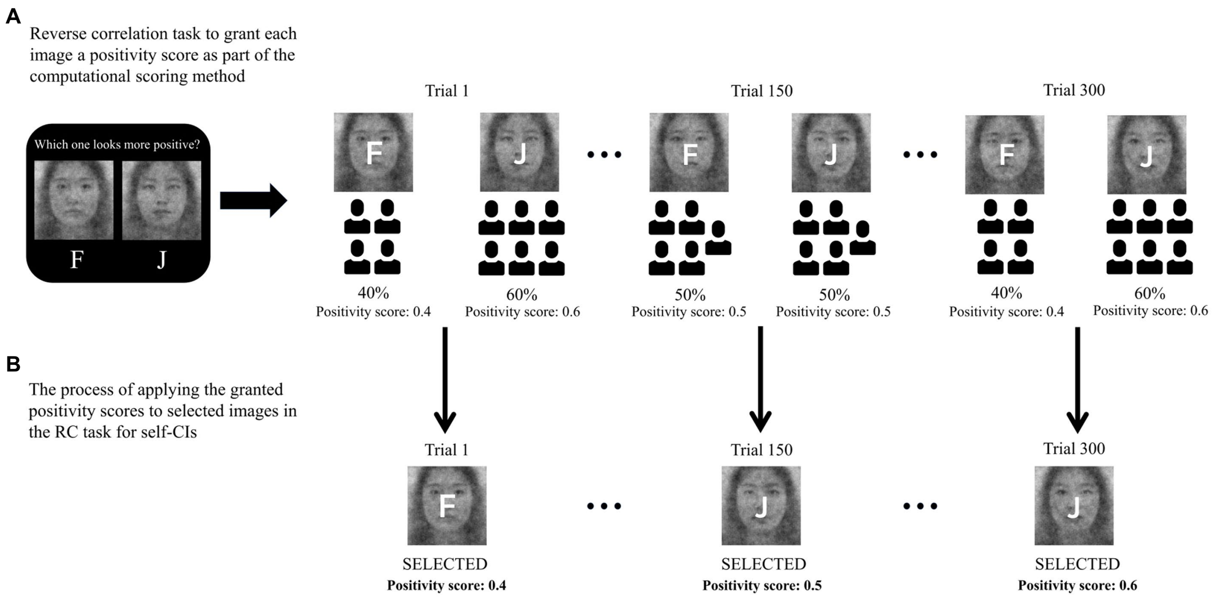

FIGURE 3
Procedure to evaluate positivity of the selected images in the reverse correlation (RC) task for self-CIs, which we named the computational scoring method. **(A)** RC task was performed to select the more positive image out of two to grant each image a positivity score as part of the computational scoring method. **(B)** The granted positivity score in **(A)** was applied to the selected images in the RC task for self-CIs, in which participants chose one that bore stronger resemblance.

task was performed *via* an online experimental platform (pavlovia.org). The remaining detailed procedures of the RC task were identical to those in Experiment 1 (see Figure 1B).

4.1.2.3. Resemblance ratings of self-CIs

Participants evaluated how similar their self-CIs were to themselves online 1 week after the completion of the RC task.

4.1.2.4. Independent valence ratings of self-CIs

One group of independent raters (32 raters) evaluated 64 of the 127 CIs, while the other group (30 raters) evaluated the rest. As did in Experiment 1, the independent raters evaluated the valence of the participants' self-CIs with the seven items *via* the online platform. The internal consistency of the independent ratings of self-CIs was 0.97.

4.2. Results and discussion

4.2.1. Resemblance rating

A paired sample t-test revealed that participants perceived their self-CIs ($M = 5.53$, $SD = 1.86$, 95% CI [5.20, 5.85]) as bearing a stronger resemblance to themselves than filler-CIs ($M = 3.71$, $SD = 1.04$, 95% CI [3.53, 3.89]) in the resemblance ratings, $t(126) = 10.14$, $p < 0.001$.

4.2.2. Relationship between independent valence ratings of self-CIs and self-reported variables

All the significant correlations between the independent valence ratings of self-CIs and variables related to self-image in Experiment 1 were replicated in Experiment 2b. To be specific, as presented in Table 2, the valence ratings of self-CIs evaluated by independent raters were significantly associated with self-esteem ($r = 0.19$, $p < 0.05$), explicit self-evaluation ($r = 0.32$, $p < 0.001$), and extraversion ($r = 0.31$, $p < 0.001$). In Experiment 2b, trait anxiety was not significantly correlated with the independent valence ratings of self-CIs ($r = -0.09$, $p = 0.313$). Meanwhile, the valence ratings of independent raters did not show significant correlations with depression symptoms ($r = -0.15$, $p = 0.098$) or social desirability ($r = -0.03$, $p = 0.769$).

4.2.3. Replication of Experiment 2a: Validity of the computational scores of self-CIs

As expected, the correlation between the computational scores and the independent valence ratings evaluated was strongly significant ($r = 0.80$, $p < 0.001$). In addition, the computational scores were positively correlated with all variables related to self-image: self-esteem, $r = 0.25$, $p < 0.01$, explicit self-evaluation, $r = 0.38$, $p < 0.001$, and extraversion, $r = 0.37$, $p < 0.001$ (see Table 2). For better understanding of results of computational scores, we presented an imagery outcome in Figure 4. We separately averaged the self-CIs in high (+1 SD) and in low (−1 SD) groups of computational scores and of independent valence ratings (see Figure 4; two faces: female and male; two conditions: Experiment 2a and Experiment 2b). Taken together, these findings imply that the computational scoring method may be used to measure the valence of self-CIs more efficiently.

5. General discussion

The RC technique is a data-driven method that can provide a new perspective on self-image. We demonstrated that a mental representation of self is associated with not only self-reported variables related to self-image but also with social evaluation. More importantly, as we expected, the valence ratings of self-CIs evaluated by independent raters predicted the expert ratings on psychological adjustment, after controlling for the effects of self-reported self-esteem and extraversion. Also, despite the significant relationship between the independent valence ratings of self-CIs and facial appearance, only the independent valence ratings of self-CIs, but not the facial appearance, were significantly correlated with expert ratings. In addition, we provide evidence that the computational scoring method can supplement the independent rating process. The computational scores of self-CIs were closely related to the valence ratings of self-CIs by independent raters. Also, the computational scores were positively correlated with variables relevant to self-image and social evaluation.

This study is the first, to the best of our knowledge, to address the relationship between self-image visualized by means of the RC method and social evaluation by incorporating expert evaluations. Our findings are consistent with previous research suggesting that people with positive self-views tend to be perceived more favorably by others than those with negative self-views (Taylor and Brown, 1988; Taylor et al., 2003; Zeigler-Hill et al., 2013). Our results extend these findings by employing the RC method to show the significant association between self-image and social evaluation. Particularly, we confirmed the validity of self-CIs by using the evaluations of psychological adjustment by three clinical psychologists, which are generally deemed to be more credible than are those by untrained raters. More importantly, the self-CIs provided independent and incremental information to self-reported variables in predicting social evaluation. This implies that the RC method has an important advantage, in that it can provide additional information about self-image by making the ineffable explicit as a visual form (Mangini and Biederman, 2004; Moon et al., 2020).

One possible explanation for the information that self-CIs add to self-reports in predicting social evaluations could lie in the implicit nature of self-CIs. That is, self-CIs can reflect implicit attitudes toward self. For example, Dotsch et al. (2008) showed that individuals' mental representations of racial faces generated by the RC method were associated with their level of implicit prejudice toward Moroccans, a highly stigmatized out-group in the Netherlands, measured by an Implicit Association Test (IAT). Paulhus (1984) also pointed out that when participants perform self-reports, their responses may be affected by self-deception and impression management, which are closely related to social desirability. However, in a RC task, participants can freely adopt any dimensions (e.g., emotional impressions or facial features) to make judgments about facial resemblance. Moreover, participants can be unaware of the criteria they adopt, because the RC approach allows them to make instantaneous and instinctive choices when selecting facial stimuli that more resemble their faces (see Brinkman et al., 2017, for review). In addition, previous studies have suggested that mental representations visualized through the RC method are less affected by certain response patterns or social desirability than are self-reported measures (e.g., Moon et al., 2020; Pauzé et al., 2021). Likewise, our findings showed that social desirability was not significantly related to self-CIs but was to self-image relevant variables, such as explicit self-evaluation and self-esteem. Thus, relying solely on self-reports to understand self-image may hinder a thorough comprehension of self-image. Taken together, our findings suggest that employing both self-reports and the RC method can lead to a better understanding of the link between self-image and social evaluation.

TABLE 2 Descriptive statistics and correlations between study variables.

	1	2	3	4	5	6	7	8
1. VR_{IR}	–							
2. CS	0.80***	–						
3. Self-esteem	0.19*	0.25**	–					
4. Explicit self-evaluation	0.32***	0.38***	0.71***	–				
5. Extraversion	0.31***	0.37***	0.77***	0.71***	–			
6. Depression	−0.15	−0.20*	−0.80***	−0.55***	−0.59***	–		
7. Anxiety	−0.09	−0.20*	−0.78***	−0.51***	−0.63***	0.73***	–	
8. Social desirability	−0.03	0.05	0.34***	0.28**	0.17	−0.25***	−0.34***	–
M	4.90	0.54	28.61	6.46	30.98	19.09	9.72	16.28
SD	0.83	0.04	6.66	1.00	7.09	11.78	5.36	4.17

$N = 127$, VR_{IR} = Valence ratings of the independent raters (self-CIs); CS = Computational scores (self-CIs). *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

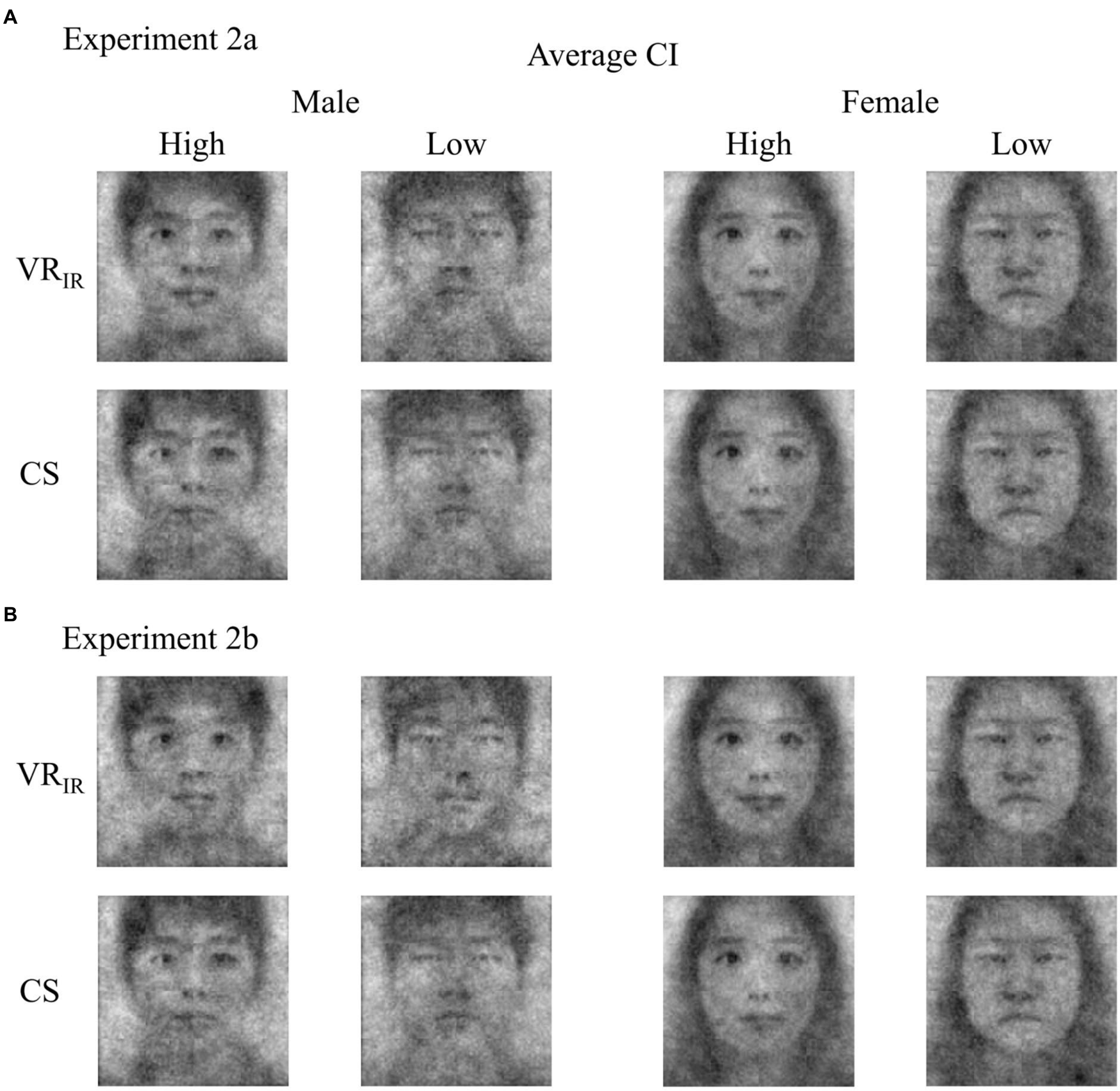

FIGURE 4
The average classification images of self (self-CIs) generated in Experiment 2a **(A)** and Experiment 2b **(B)** by high (+1 *SD*) and low (−1 *SD*) groups of independent valence ratings and of computational scores. VR_{IR}=Valence ratings of the independent raters (self-CIs); CS=Computational scores (self-CIs).

Some may raise an alternative explanation that the relationship between self-CIs and social evaluations is merely the effect of facial appearance, because participants with more attractive facial features can generate more attractive self-representations and can be evaluated more favorably by others in social situations (i.e., halo effect; Dion et al., 1972). However, our findings can rule out the aforementioned explanation. Although we concede that visual mental representations inevitably reflect facial appearance to some degree, we found that the valence ratings of self-CIs of participants were not explained solely by those of their facial appearance. Also, social evaluation was only associated with the self-CIs but not facial attractiveness. These results reveal that the visual proxies of self-image are not just a reflection of facial appearance but are a multifaceted composite colored by psychological factors (Maister et al., 2021).

Additionally, we present the first evidence that the computational scoring method can be valid and useful in assessing the valence of self-CIs across Experiment 2a and 2b. Prior studies have employed independent raters to evaluate participants' self-CIs on valence (Moon et al., 2020; Steiner et al., 2021) and personality traits (Maister et al., 2021). However, incorporating newly recruited independent raters each time to evaluate self-CIs can cause inefficiency by necessitating substantial time and effort. Moreover, individuals' self-CIs may be too noisy and unclear for independent raters to detect the inter-individual differences in the valence of self-CIs (Imhoff et al., 2013). Our findings show that the computational scoring method that we proposed can measure the valence of self-CIs objectively and efficiently without recruiting additional independent raters. We expect that this method can be extended to other areas of interest, such as competence and dominance.

5.1. Limitations and future directions

There are a few limitations of this study that need to be addressed in future research. First, we used only expert ratings to examine whether participants' self-CIs were associated with how they were perceived by other people. However, the amount of information that experts can grasp about participants by means of a brief self-introductory video may be limited (Zeigler-Hill et al., 2013). Previous studies employing acquaintance evaluation have shown that the more information acquaintances know about participants, the more reliable and accurate their reports are (Paulhus and Bruce, 1992; Vazire, 2010). Thus, future studies can be designed to examine the relationship between participants' self-CIs and social evaluations by close others (e.g., friends, romantic partners, and family members).

Second, another limitation in our paradigm was that we could not be sure whether participants selected the one from two facial stimuli that looked more like themselves or selected the stimuli that gave more positive impressions. However, we did not intend to rule out the possibility of incorporating impressions when making their choices. Rather, we expected the participants to make visual mental representations that inevitably incorporated factors like affective impression while selecting the one from two facial stimuli that looked more like themselves. Further, because participants were able to freely adopt criteria without *a priori* assumptions, we believed that resulting self-CIs can provide incremental information to participants' facial appearance. Nevertheless, incorporation of an experimental method to systemically distinguish standards that participants employ while carrying out the RC task can lead to further understanding of the visual mental representation (Brinkman et al., 2019). In addition, future works can explore neural activations in brain regions related to self-other discrimination (e.g., the medial prefrontal cortex and the right temporo-parietal junction; D'Argembeau et al., 2007; Zeugin et al., 2020) to investigate specific neural mechanisms while participants perform the RC task to generate their self-CIs.

Finally, participants in this study mainly consisted of young adults and were limited to Asians, which means that the external validity of our results is quite restricted. Therefore, future studies need to be done on participants of various age groups to generalize the current findings, and need to examine whether our findings are applicable to participants of various ethnic groups.

6. Conclusion

We extend the validity of self-CIs by demonstrating that the significant relationship between self-image and social evaluation can be captured by means of the RC method. More importantly, we reveal that the self-CIs add information to self-reports and facial appearance in predicting social evaluation. Additionally, we propose that the computational scoring method complements the independent rating process in measuring the valence of self-CIs. Our findings suggest that self-CIs are a valid and useful tool to comprehend the relationship between self-image and social evaluation.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: Open Science Framework (OSF): https://osf.io/rstwv/.

Ethics statement

The studies involving human participants were reviewed and approved by the Institutional Review Board at Korea University (KUIRB-2019-0220-03 and KUIRB-2019-0221-01). The patients/participants provided their written informed consent to participate in this study.

Author contributions

JK: conceptualization, methodology, investigation, software, visualization, formal analysis, validation, data curation, writing – original draft, writing – review and editing, project administration. KM: conceptualization, methodology, software, visualization, data curation, writing – original draft, writing – review and editing. SK: conceptualization, methodology, data curation, writing – original draft, writing – review and editing. HK: conceptualization, writing – review and editing, supervision. YK: conceptualization, methodology, writing – review and editing, supervision, project administration. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2022.937905/full#supplementary-material

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Interoceptive accuracy is associated with benefits in decision making in children

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Introduction: Decision making results not only from logical analyses, but seems to be further guided by the ability to perceive somatic information (interoceptive accuracy). Relations between interoceptive accuracy and decision making have been exclusively studied in adults and with regard to complex, uncertain situations (as measured by the Iowa Gambling Task, IGT).

Methods: In the present study, 1454 children (6-11 years) were examined at two time points (approximately 1 year apart) using an IGT as well as a delay-of-gratification task for sweets-items and toy-items. Interoceptive accuracy was measured using a child-adapted version of the Heartbeat Perception Task.

Results: The present results revealed that children with higher, as compared to lower, interoceptive accuracy showed more advantageous choices in the IGT and delayed more sweets-items, but not toy-items, in a delay-of-gratification task at time point 2 but not at time point 1. However, no longitudinal relation between interoceptive accuracy and decision making 1 year later could be shown.

Discussion: Results indicate that interoceptive accuracy relates to decision-making abilities in situations of varying complexity already in middle childhood, and that this link might consolidate across the examined 1-year period. Furthermore, the association of interoceptive accuracy and the delay of sweets-items might have implications for the regulation of body weight at a later age.

KEYWORDS

cardiac perception, interoception, emotion, decision making, Iowa gambling task, somatic-marker hypothesis, childhood development

1. Introduction

To decide in favor of positive outcomes in the future rather than of short-term benefits accompanied by long-term disadvantage is a common and crucial challenge of daily life. Impaired decision making has been related to a diverse range of problems, such as impulsivity (e.g., Franken et al., 2008), drug use (e.g., Grant et al., 2000), or extreme weight conditions and eating disorders (e.g., Brogan et al., 2010). Considering multiple alternatives and reflecting about future consequences has long been seen as a pure rational function. However, there is evidence that decision making is not only a result of logical analyses, but is further guided by somatic information (e.g., Werner et al., 2009).

Research on this topic has mainly been based on the somatic-marker hypothesis (SMH) proposed by Damasio (1994, 1996), which builds on earlier work linking bodily activity to the experience of emotion (e.g., James, 1884) and to decision making (e.g., Nauta, 1971). The SMH suggests that somatic information assists decision making, especially in complex or uncertain situations. More specifically, in such situations each response option should be associated with specific learned somatic responses (e.g., heart rate, skin conductance, tonicity) that either encourage or discourage the particular option. These so-called somatic markers are thought to be represented and regulated in secondary representation areas, in particular the ventromedial prefrontal cortex (VM-PFC; Damasio, 1996; Bechara et al., 2000) or the anterior cingulate (ACC; Bechara and Naqvi, 2004).

Evidence for the SMH is mainly based on adults' performance in the Iowa Gambling Task (IGT), which has been designed in order to mimic real-life decision-making, thereby incorporating factors like uncertainty, reward, and punishment. For a successful performance on this task, participants have to learn during the course of trials to forgo short-term benefit for long-term profit while choosing between alternatives varying in pay-off and punishment. More precisely, they need to draw cards selecting between card decks which result in larger gains but also in high unpredicted losses, and decks which result in smaller gains, similarly small losses, and an overall net profit (Bechara et al., 1994).

According to the SMH, individuals who ascribe more precision to signals from the viscera should show superior performance in this task. Indeed, a successfully learning to choose the advantageous decks (with smaller gains, but also smaller loss) in the IGT has been linked to somatic-marker signals, indexed by anticipatory skin conductance responses. For example, adult patients with lesions in the VM-PFC do not seem to develop somatic markers in the form of skin-conductance responses and continue to choose disadvantageous options during the IGT, indicating that they are driven more by the immediate reward than by future consequences ("myopia for the future"; Bechara et al., 1996, 1997; see Dunn et al., 2006 for a review).

To date, most research on the SMH has rarely used other sources of bodily feedback except from skin-conductance responses (Dunn et al., 2006). However, cardiac cues should just as well function as a potential somatic marker guiding decision making. Individual differences in perception of and sensitivity to changes within the internal bodily state are one way of quantifying the access to bodily cues (Herbert and Pollatos, 2008). Research regarding interoception has mainly focused on the ability to detect cardiovascular signals (e.g., Critchley et al., 2004; Pollatos et al., 2005), mostly quantified in heartbeat-perception tasks. Results underscore that there are significant interindividual differences in adults' cardiac perception, being interpreted as trait-like sensitivity toward one's visceral signals, which is understood as a long-term result of "visceral" learning processes. Such processes depend on autonomic reactivity during different situations of daily life that evoke substantial changes in autonomic activity (Herbert and Pollatos, 2012; Herbert et al., 2013).

Garfinkel et al. (2015) proposed a differentiation between three separable dimensions of interoception, namely interoceptive accuracy (IAcc; i.e., performance on objective behavioral tests of heartbeat detection), interoceptive sensibility (i.e., self-evaluated assessment of subjective interoception) and interoceptive awareness (i.e., metacognitive awareness of interoceptive accuracy). More recently, this differentiation was extended by Pollatos and Herbert (2018) who suggested interoceptive emotional evaluation (i.e., interpretation of perceived bodily signals) as a fourth dimension of interoception.

To our knowledge, only a few studies have examined associations between interoceptive accuracy and decision making, and these studies report mixed results. Werner et al. (2009) found that adult individuals with particularly accurate cardiac-perception ability show superior decision-making performance in the IGT compared to individuals with low perception accuracy, but these results were not replicated in a more recent publication (Werner et al., 2013). Werner and colleagues attributed this to the small number of participants with high interoceptive accuracy. Furthermore, in a refined version of the IGT, interoceptive accuracy was associated with either good or poor decision-making performance, depending on whether anticipatory bodily signals favored advantageous or disadvantageous choices (Dunn et al., 2010). In a modified Go-No Go paradigm, not interoceptive accuracy but interoceptive awareness was related to voluntary inhibition decisions, such that subjects with lower awareness of bodily signals were more likely to act and respond faster when they had the choice (Rae et al., 2020). Moreover, Wölk et al. (2014) showed that higher interoceptive accuracy is related to improved decision making only in healthy participants, but to impaired performance in patients with panic disorder. Accordingly, impaired decision-making performance on an IGT was found to be predicted by diminished interoceptive accuracy in individuals with gambling disorder (Moccia et al., 2021) and alcohol use disorder (Avcu Meriç and Sönmez, 2022). Sugawara et al. (2020) identified a positive link between the shift toward rationality in a decision-making task and the improvement of interoceptive accuracy after an interoceptive training. This relation was further demonstrated to have an affective dimension as well: Sokol-Hessner et al. (2015) identified interoceptive accuracy to predict aversion to loss in a gambling task.

So far, the role of somatic markers in decision making has been investigated exclusively in adult populations. Thus, it remains unclear whether this association is already present in

Abbreviations: DoG, Delay of gratification; IAcc, Interoceptive accuracy; IGT, Iowa gambling task; PFC, Prefrontal cortex; SMH, Somatic marker hypothesis; VM-PFC, Ventro-medial prefrontal cortex.

children or whether it arises later in the course of development. There is evidence that already children differ in their ability to perceive ongoing signals deriving from the heart, and that this ability might function as a basis for their emotional experience in similar ways as it has been reported for adults (Koch and Pollatos, 2014a). Crone and van der Molen (2007) found that the autonomic bodily processing of decision outcome is similar across age groups (8–10, 12–14, and 16–18 years of age) in children. Furthermore, the role of interoceptive development was emphasized in the context of mental health and pain: Hechler (2021) postulates a bilateral relation between interoceptive processes on the one hand and the genesis of mental health problems and chronic pain on the other hand: in a complex framework including physiological, cognitive and emotional aspects, somatic responses potentially contribute to the co-occurrence of mental health problems *via* interoceptive fear conditioning. Opdensteinen et al. (2021) identified a positive relation between interoceptive accuracy and emotion regulation, another important aspect of executive functioning, in a sample of preschool children. However, it remains an open question whether the access to these bodily signals (i.e., interoception) influences decision making in children. Furthermore, it has been found that executive function, which as a higher-level construct includes decision-making abilities, improves most rapidly during the preschool period, but continues to develop during middle childhood and adolescence. Such developmental changes in executive function are related to substantial structural and functional changes in neural systems involving the PFC (Pennington and Ozonoff, 1996; Zelazo et al., 2008; Hughes, 2011). Thus, the first aim of the present study was to examine whether children with higher (as compared to lower) interoceptive accuracy show better decision-making (i.e., more advantageous choices) as early as in middle childhood, when both abilities have presumably not yet been finally developed.

Research on the role of somatic markers in decision making has exclusively focused on variants of the IGT, which measures intuitive decision-making patterns given incomplete information or ambiguous consequences, respectively. Because originally, the implicit nature of somatic markers has been emphasized, the IGT was designed to study decision making in complex situations that cannot completely be captured by reflective knowledge alone (Dunn et al., 2006). Another ability related to affective decision making and also regulated by the VM-PFC is delay of gratification (DoG), which is usually assessed by tasks requiring a choice between receiving a smaller reward immediately or a more valuable reward later on (Happaney et al., 2004; Hongwanishkul et al., 2005). Whereas both the IGT and DoG tasks require deciding in favor of an advantageous outcome in the future, they differ with respect to the time that children need to wait for rewards, and to the certainty with which rewards are obtained: choice contingencies remain purposely unclear in the IGT, but are clearly stated in DoG tasks, making the latter less ambiguous and complex (Hongwanishkul et al., 2005). In adults, there is evidence that affective somatic markers such as mood might influence impulsive behavior in tasks that require delaying a reward in order to optimize the outcome (Lerner et al., 2013; Weafer et al., 2013; for review see Herman et al., 2018), indicating the relevance for a DoG task in research on the SMH and interoception. Thus, our second aim in the present study was to explore whether interoceptive accuracy is also related to children's performance in a DoG task, that is, in decision-making processes that are emotionally or motivationally relevant, but less complex than those elicited in the IGT.

From a developmental perspective, it would furthermore be interesting to address the direction of effect between interoceptive accuracy and decision making. To date, however, longitudinal studies are lacking. Because higher interoceptive accuracy relates to an enhanced central-nervous-system processing of bodily signals (Dunn et al., 2010; Werner et al., 2013), it can be assumed that a higher interoceptive accuracy in the long term leads to a behavioral advantage in situations generating somatic-marker signals. Thus, a better perception of and higher sensitivity to somatic-marker information should lead to an advantage in the development of decision-making abilities in situations that are emotionally or motivationally relevant.

To sum up, we examined a large sample of children between 6 and 11 years of age and expected children with higher interoceptive accuracy to opt for more advantageous options or learn to do so during the course of several trials in a child-adapted IGT (research question 1), and also to opt for more advantageous choices in a DoG task (research question 2), as compared to children with lower interoceptive accuracy. We examined these hypotheses at two measurement time points, about 1 year apart, in order to detect developmental differences in the relation of interoceptive accuracy and decision making. Moreover, we expected level of interoceptive accuracy to function as a longitudinal predictor of IGT and DoG performance 1 year later (research question 3).

2. Materials and methods

2.1. Participants and procedure

Data for this study was collected within a large longitudinal study on intrapersonal developmental risk-factors in childhood and adolescence (PIER study), which has started in 2012. Data on the PIER study has already been reported elsewhere using the same measures as the present study while focusing on different research questions (Groppe and Elsner, 2014, 2015, 2017; Koch and Pollatos, 2014a,b). The first two assessments of the PIER study were separated by a time interval of approximately 1 year ($M = 273$ days, $SD = 55$ days).

At the first measurement time point (t1), a total of 1,658 children (52.1% girls) aged 6 to 11 years were recruited from 33 elementary schools from the federal state of Brandenburg (German school classes 1–3). Schools were preselected for a representative variety of social backgrounds, both urban and rural. At the second time point (t2), 1,619 of these children now aged 7 to 11 years took part. The samples used in the present analyses consisted of 1,446 children at t1 (*M* age = 8.4 years, *SD* = 0.95; 51.9% girls) and 1,454 children at t2 (*M* age = 9.1 years, *SD* = 0.92; 51.7% girls) who provided data on the Heartbeat-Perception Task. Missing data was mainly due to technical problems leading to invalid data on this task.

At each measurement time point, children were tested individually with regard to various psychological variables by a trained and supervised doctoral student or research assistant. Testing took place during the morning hours in a quiet room either at school or at home on 2 days within 1 week. The order of tasks was counterbalanced across participants (blocks of ABCD/BADC). Subsequent analyses, however, revealed no effect of task sequence. Informed consent was obtained for each child from a primary caregiver, and the children received a cinema voucher for their participation at both time points. Approval for the study was obtained by the Research Ethics Board at the University of Potsdam and by the Ministry of Education, Youth and Sports of the Federal State of Brandenburg.

2.2. Materials

All measures were obtained at both t1 and t2. Because measures were identical to those used in our previous studies (see Groppe and Elsner, 2014, 2015, 2017; Koch and Pollatos, 2014a,b), we will only give a short synopsis at this point.

In order to measure complex decision making, we used a slightly modified version of the computer-based Hungry Donkey Task (Crone and van der Molen, 2004), which is a child-adapted version of the IGT (Bechara et al., 1994). Children were asked to assist a hungry donkey in collecting as many apples as possible across 60 trials. Furthermore, participants were told that they could win a marble if they collected at least 20 apples. Each trial consisted of pressing 1 of 4 keys, each opening a corresponding door (A, B, C, D) that appeared side by side on a computer screen. Upon pressing a key, an outcome display indicated the number of apples gained (in green) and/or lost (in red), as well as the overall sum of gained and lost apples across previous trials. Selecting doors A or B resulted in larger gains but also in high unpredicted losses, leading to an overall net loss of 10 apples per 10 trials. Selecting doors C or D resulted in smaller gains but similarly small losses and an overall net profit of 10 apples per 10 trials. Usually, participants start the task by choosing doors more or less randomly, followed by an increasing preference for the advantageous doors (C, D; e.g., Crone et al., 2005). As dependent variables, we used the number of advantageous doors selected. For the analyses of research questions 1 and 2, the number of advantageous doors selected was broken down into 6 blocks of 10 trials in order to depict potential learning effects over time (see Crone and van der Molen, 2004).

To measure delay of gratification (DoG), we asked children to choose between receiving a smaller reward immediately or a larger reward 1 week later (which they would actually get at the second test session; adapted from Wulfert et al., 2002). There were 4 trials, in which the child always saw the immediate (smaller) reward and was verbally informed about the delayed (larger) reward that always consisted of more items of the same type. Two trials contained sweets-items (immediate vs. delayed: 1 vs. 2 chocolate drops; 1 vs. 5 chewing candies) or toy-items (1 vs. 2 bouncing frogs, 1 vs. 3 tattoos), respectively. As dependent variables, we used the number of trials (0 to 2) in which the child chose to delay sweets or toys. As this variable reflects the actual number of delayed items, it is a ratio variable with adequate scaling for the subsequent analysis. The order of item-presentation (alternating between sweets and toys) was counterbalanced across participants (with two different sequences). Subsequent analyses, however, revealed no effect of item sequence. In a pretest (Groppe and Elsner, 2014) on 41 children who did not participate in the present study (*M* age = 8.41, *SD* = 0.49; 54% girls), the number of delayed trials showed positive associations in the medium range ($r = 0.31$–0.37, $p \leq 0.05$) with impulsivity (German version of Eysenck's I6 Impulsivity Scale; Stadler et al., 2004), delay-of-gratification in eating (subscale from the Delaying Gratification Inventory; Hoerger et al., 2011) and academic delay-of-gratification (Academic Delay of Gratification Scale for Children; Zhang et al., 2011). These results suggest good convergent validity of our DoG measure. Furthermore, in the pretest, the four trials used in the present study were highly associated with an 8-item version of the DoG task ($r = 0.88$, $p < 0.001$).

Interoceptive accuracy was measured by the Heartbeat-Perception Task, following the mental-tracking method proposed by Schandry (1981) and adapted for children (see Koch and Pollatos, 2014a). The original interval length was shortened, resulting in three fixed intervals of 15, 20, and 18 s, plus a short initial training interval of about 10 s. During each interval, children were seated and told to silently count their own heartbeats without feeling for their pulse and without trying to facilitate heartbeat detection by physical manipulations (e.g., holding their breath). Simultaneously, cardiac activity was recorded noninvasively using the mobile heart-frequency monitor RS800CX (Polar Electro Oy, Kempele, Finland), which has shown equally good validity and reliability as compared to alternative ECG measurement devices in populations of children and adults (e.g., Kingsley et al., 2005; Gamelin et al., 2008; Nunan et al., 2008). The electrode strip was attached to both hands and affixed to a table. Signals were sampled at 1,000 Hz and analyzed by the Polar ProTrainer 5 software (version 5.40.172), which is based on the HRV analysis software of the University of Kuopio, Finland (Niskanen et al., 2004). Heartbeat-perception scores were calculated taking the mean difference between recorded and counted heartbeats across the three intervals ($1/3 \sum [1 - (|\text{recorded heartbeats} - \text{counted heartbeats}| / \text{recorded heartbeats})]$). According to this formula, higher scores indicate a higher interoceptive accuracy with a maximum score of 1 (absolute accuracy) and a minimum score of 0 (child did not perceive any heartbeat). The internal consistency of the task was excellent at both measurement time points (Cronbach's α t1: 0.91, t2: 0.90).

2.3. Statistical analyses

We divided the sample into children with higher versus lower interoceptive accuracy scores using a median-split (Mdnt1 = 0.59; Mdnt2 = 0.59). The two groups were compared using a two-tailed unpaired *t*-test. Additionally, intercorrelations between the distinct variables at both time points were explored. Analyses for the first two research questions were conducted separately at both measurement time points in order to detect possible developmental changes.

In order to answer our first research question (whether children with higher as compared to lower interoceptive accuracy opt for more advantageous options in the IGT, or learn to do so across the course of trials) we calculated separate ANOVAs at t1 and t2 on the mean number of advantageous doors (C, D) selected, with the within-subjects factor Trial Block (1–6) and the between-subjects factor Interoceptive Accuracy (higher vs. lower). Subsequently, this analysis was repeated across distinct age groups in order to gain closer insights in the development of the described abilities. Because Mauchly's test indicated some violations of the assumption of sphericity, the respective degrees of freedom were corrected using Greenhouse–Geisser estimates. For each analysis, children with complete data on all variables of interest were included. Thus, the number of children slightly varies for the three hypotheses depending on the examined variables.

For our second research question (whether children with higher as compared to lower interoceptive accuracy opt for more advantageous options in the DoG task) we conducted separate MANOVAs at t1 and t2 on the number of toy-items delayed and the number of sweets-items delayed, with the between-subjects factor Interoceptive Accuracy (higher vs. lower).

For our third research question (whether interoceptive accuracy longitudinally predicts later performance in the IGT and DoG task) we calculated first a regression of IGT performance t2 (overall score across trials 1–60) on interoceptive accuracy t1, controlling for age and IGT performance at t1, and second a regression of DoG performance t2 (separately for toy- and sweets-items) on interoceptive accuracy t1, controlling for age and DoG performance at t1. We treated interoceptive accuracy t1 again as a dichotomous variable to allow for a comparability of results.

3. Results

Bivariate correlations, as well as means and standard deviations, for all of the assessed variables are summarized in Table 1. In general, correlations of assessed variables and age were low or non-significant. Furthermore, the two groups of children differed significantly with regard to their interoceptive accuracy at t1 [$M_{lower\ IAcc} = 0.34$, $SD = 0.19$; $M_{higher\ IAcc} = 0.76$, $SD = 0.10$, $t(1121.49) = -52.89$, $p < 0.001$, $r = 0.15$] and t2 ($M_{lower\ IAcc} = 0.36$, $SD = 0.17$; $M_{higher\ IAcc} = 0.75$, $SD = 0.10$), $t(1189.28 = -52.70$, $p < 0.001$, $r = 0.14$), but they did not differ with respect to age at both measurement time points [t1: $Age_{lower\ IAcc}$: $M = 8.39$ years, $SD = 0.94$; $Age_{higher\ IAcc}$: $M = 8.35$ years, $SD = 0.96$; $t(1444) = 0.75$, $p = 0.45$; t2: $Age_{lower\ IAcc}$: $M = 9.10$ years, $SD = 0.91$, $Age_{higher\ IAcc}$: $M = 9.15$ years, $SD = 0.93$; $t(1450) = -0.69, p = 0.49$].

3.1. Interoceptive accuracy and performance on the IGT

The two ANOVAs for the IGT at t1 and t2, respectively, revealed that learning across trials was evident in both groups of Interoceptive Accuracy, indicated by a significant main effect of Trial Block at t1, $F(4.84, 6924.98) = 53.23$, $p \leq 0.01$, $\eta^2 = 0.04$, and at t2, $F(4.67, 6645.87) = 115.76$, $p \leq 0.01$, $\eta^2 = 0.08$. Moreover, at t2, children with higher interoceptive accuracy selected more advantageous doors than did children with lower interoceptive accuracy, indicated by a significant main effect of Interoceptive Accuracy, $F(1, 1{,}422) = 4.73$, $p = 0.03$, $\eta^2 < 0.01$. This, however, was not yet the case at t1, $F(1, 1{,}432) = 0.04$, $p = 0.84$, $\eta^2 < 0.01$ (see Figure 1). The interaction between Interoceptive Accuracy and Trial Block was not significant at t1, $F(4.84, 6924.98) = 1.06$, $p = 0.38$, $\eta^2 < 0.01$, or at t2, $F(4.67, 6645.87) = 1.32$, $p = 0.25$, $\eta^2 < 0.01$, indicating that higher vs. lower Interoceptive Accuracy did not significantly influence children's progress of learning across IGT trials (see Figure 2). Subsequent analyses across distinct age groups (for descriptive statistics see Supplementary Table 1) indicated that all children, independent of age and interoceptive abilities, were able to learn to opt for more advantageous choices over the course of trials (see Supplementary material). Furthermore, in the middle age group (7.84–8.88 years) interoceptive accuracy was found to positively influence this learning process, but not the overall performance in the IGT (see Supplementary Figure 1); this effect was absent in the younger and older group.

3.2. Interoceptive accuracy and performance on the DoG task

The two MANOVAs at t1 and t2, respectively, for the DoG task revealed no significant main effect of Interoceptive Accuracy on the number of sweets-items or toy-items delayed at t1, *Pillai's trace*, $V = 0.002$, $F(2, 1{,}345) = 1.04$, $p = 0.35$, $\eta^2 < 0.01$ or at t2, $V = 0.004$, $F(2, 1{,}379) = 2.57$, $p = 0.077$, $\eta^2 < 0.01$. Separate *post-hoc* univariate ANOVAs on the outcome variables revealed a significant main effect of Interoceptive Accuracy at t2, but only for sweets-items delayed, $F(1, 1{,}380) = 5.15$, $p = 0.02$, $\eta^2 < 0.01$, and not for toy-items delayed, $F(1, 1{,}380) = 0.52$, $p = 0.47$, $\eta^2 < 0.01$ (see Figure 3). Subsequent repetition of the analysis for distinct age

TABLE 1 Intercorrelations of and descriptive statistics for the assessed variables at measurement points t_1 and t_2.

	1.	2.	3.	4.	5.	6.	7.	8.	9.
1. Interoceptive Accuracy t_1									
2. IGT t_1	−0.01								
3. DoG sweets t_1	0.05	0.04							
4. DoG toys t_1	0.04	0.01	0.39**						
5. Interoceptive accuracy t_2	0.32**	0.04	0.01	−0.01					
6. IGT t_2	0.00	0.27**	0.00	0.03	0.05				
7. DoG sweets t_2	0.02	0.01	0.22**	0.17**	0.04	0.02			
8. DoG toys t_2	0.03	0.03	0.24**	0.28**	0.01	0.06**	0.31**		
9. Age t_1	−0.02	0.07**	0.09**	0.06*	0.05*	0.07**	0.03	0.00	
Mean	0.55	32.91	1.42	1.38	0.56	34.41	1.68	1.60	8.37
SD	0.26	6.22	0.71	0.76	0.24	6.92	0.57	0.64	0.94
Min-Max (sample)	0–0.98	13–58	0–2	0–2	0–1	12–60	0–2	0–2	6.23–11.33
Min-Max (theoretical)	0–1	0–60	0–2	0–2	0–1	0–60	0–2	0–2	

IGT, Child version of the Iowa Gambling Task; DoG, delay of gratification; period between t1 and t2 = approx. 1 year. $N = 1,285–1,454$.
$*p \le 0.05$; $**p \le 0.01$.

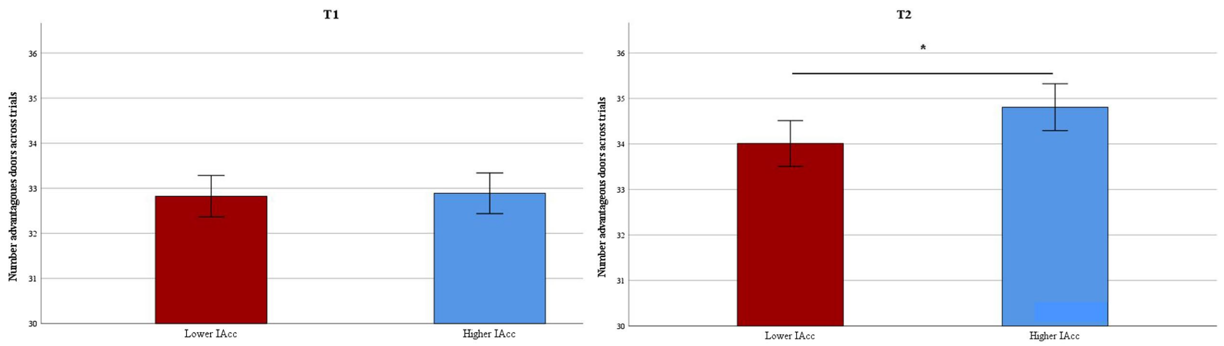

FIGURE 1
IGT performance: Mean number of advantageous choices (i.e., doors C and D) across trials in children with higher vs. lower interoceptive accuracy at t1 and t2 (error bars represent the 95% confidence interval). $*p \le 0.05$.

groups at t_1 revealed no significant effect of Interoceptive Accuracy on either of the age groups (see Supplementary material).

3.3. Longitudinal prediction of IGT and DoG performance by interoceptive accuracy

Regressing decision-making performance at t2 on Interoceptive Accuracy at t1 (lower versus higher), controlling for decision-making performance at t1 as well as for age, did not reveal a significant incremental effect of Interoceptive Accuracy on any of the three decision-making measures, IGT at t2 (number of advantageous doors selected): $B = -0.25$, $SE\ B = 0.36$, $p = 0.49$; DoG at t2 (sweets-items delayed): $B = 0.01$, $SE\ B = 0.03$, $p = 0.79$; DoG at t2 (toy-items delayed): $B = 0.03$, $SE\ B = 0.03$, $p = 0.39$ (see Table 2).

4. Discussion

The aim of the present study was to investigate whether 6- to 11-year-old children with higher interoceptive accuracy (assessed by a Heartbeat-Perception Task; Schandry, 1981) show better decision-making performance (in terms of forgoing short-term benefit for long-term profit) than do children with lower interoceptive accuracy. Decision-making ability was assessed at two measurement time points (t1/t2, about 1 year apart) by two tasks that differed with respect to the time that children needed to wait for rewards as well as to the certainty with which rewards were obtained: a child-version of the IGT (i.e., Hungry-Donkey task; Crone and van der Molen, 2004) and a DoG task (with 2 sweets-items and 2 toy-items). Moreover, we studied whether children's interoceptive accuracy would predict their later decision-making performance.

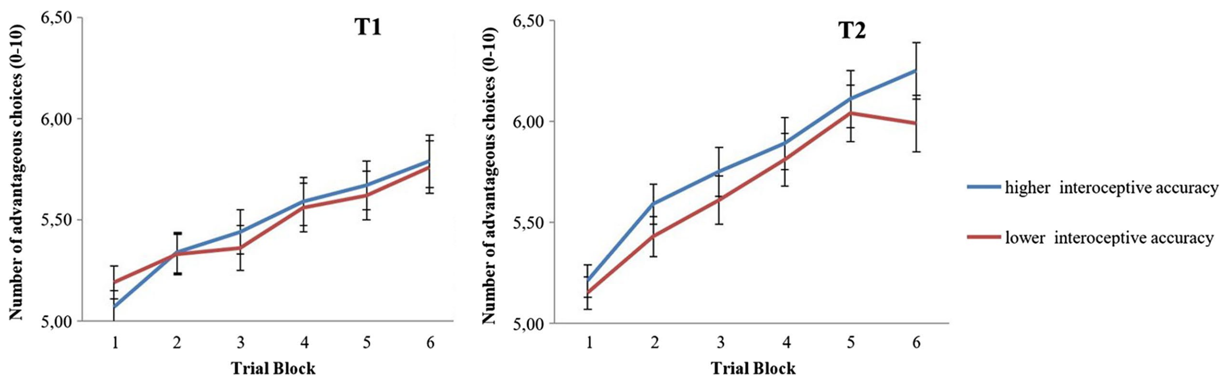

FIGURE 2
IGT performance: Number of advantageous choices (i.e., doors C and D), over 6 blocks of 10 trials each, in children with lower vs. higher interoceptive accuracy at t1 and t2 (error bars represent the 95% confidence interval).

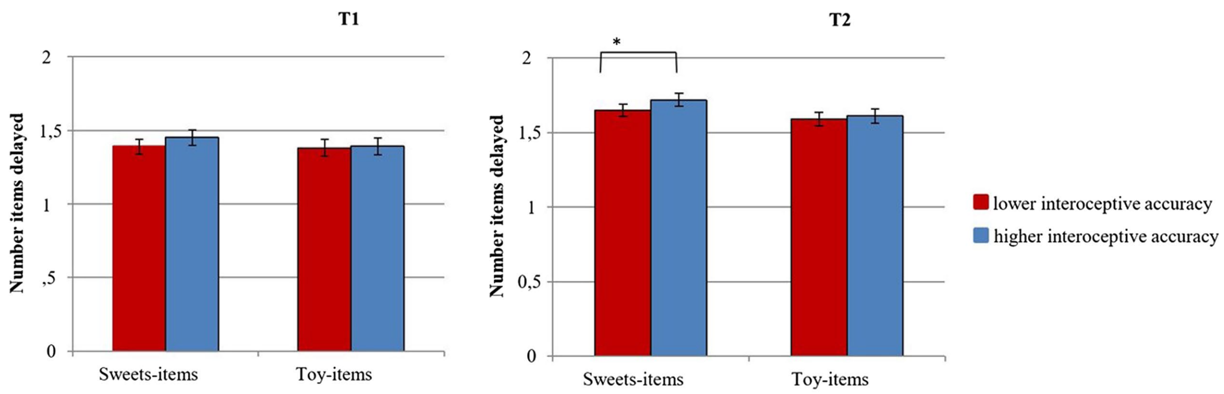

FIGURE 3
DoG performance: Number of sweets-items and toy-items delayed in children with lower vs. higher interoceptive accuracy at t1 and t2 (error bars represent the 95% confidence interval). $*p \leq 0.05$.

We found that first, across the 60 IGT trials, children in both interoceptive accuracy groups learned to select the advantageous doors more often. Additionally, children with higher (as compared to lower) interoceptive accuracy performed better in the IGT at t_2, overall choosing for more advantageous and less risky options at this time point; this is at least partially consistent with our hypotheses. As the groups did not differ in terms of age, this difference cannot be attributed to a developmental advantage. However, neither at t_1 nor at t_2, we found evidence that the magnitude of increase of advantageous choices across trials was influenced by children's interoceptive accuracy. Further subsequent comparisons of age groups at t_1 revealed that all children, independent of age and interoceptive abilities were able to learn to opt for more advantageous choices in the IGT task. Additionally, this learning process was influenced by interoceptive accuracy, but only in the middle age group. Age group further influenced IGT performance, but not interoceptive accuracy.

In contrast to our hypothesis, correlations between the distinct variables were mostly low or non-significant. Furthermore, children with higher (as compared to lower) interoceptive accuracy did not delay more items in the DoG task, neither in general, nor across age groups. A post-hoc analysis revealed more delayed items at t_2 in children with higher interoceptive accuracy, but only when items were food-specific. Unexpectedly, higher versus lower interoceptive accuracy did not predict 1-year-changes in rank percentage of decision-making performance.

The present IGT-results at t2 match the few existing studies showing that higher interoceptive accuracy is related to advanced IGT performance in healthy adults (Werner et al., 2009; Wölk et al., 2014). This is mainly in line with the SMH, which stresses the role of somatic-marker signals in guiding decision-making processes (Damasio, 1994, 1996). Thus, the present study is the first to indicate that already in middle childhood, better access to somatic feedback, in terms of enhanced interoceptive accuracy measured by cardiac-perception, seems to be associated with an enhanced ability to forgo short-term benefit for long-term profit. In line with findings of Werner et al. (2009) in adults, we did not find a significant interaction between interoceptive accuracy and

TABLE 2 Summary of the multiple-regression analyses for the decision-making measures.

Variable	B	SE B	β
IGT at t2			
Step 1			
Constant	23	1.82	
Age t1	0.30	0.19	00.04
IGT t1	0.27	0.03	00.24**
Step 2			
Constant	23.41	1.92	
Age t1	0.30	0.19	00.04
IGT t1	0.27	0.03	00.24**
Interoceptive accuracy t1	−0.25	0.36	−0.02
DoG (sweets-items) at t2			
Step 1[a]			
Constant	1.34	0.14	
Age t1	0.01	0.02	00.01
DoGSweets t1	0.18	0.02	00.22**
Step 2[a]			
Constant	1.33	0.15	
Age t1	0.01	0.02	00.01
DoGSweets t1	0.18	0.02	00.22**
Interoceptive accuracy t1	0.01	0.03	00.01
DoG (toy-items) at t2			
Step 1[b]			
Constant	1.32	0.15	
Age t1	−0.01	0.02	−0.01
DoGToys t1	0.24	0.02	00.28**
Step 2[b]			
Constant	1.27	0.16	
Age t_1	−0.01	0.02	−0.01**
DoGToys t1	0.24	0.02	00.28**
Interoceptive accuracy t_1	0.03	0.03	00.02**

IGT, Child version of the Iowa Gambling Task; DoG, Delay of gratification.
[a]$R^2 = 0.06$ for Step 1, $\Delta R^2 = 0.06$ for Step 2.
[b]$R^2 = 0.08$ for Step 1, $\Delta R^2 = 0.08$ for Step 2.
$^{**}p < 0.001$.

IGT trial block, indicating that although children with higher interoceptive accuracy showed a better overall performance, both groups learned to choose more advantageously over the course of IGT trials. Furthermore, the relatively small effect sizes indicate that much of the variance in decision making is accounted for by variables other than interoceptive accuracy. Thus, although bodily feedback influences decision making, it may not be essential or their relation be mediated by factors not taken into account in the present study. Yip et al. (2020) proposed emotional intelligence as a moderator of the link between bodily responses and decision-making, such that adults with lower emotional intelligence tend toward a maladaptive association of bodily arousal and risky behavior. Accordingly, in children (aged 8–12) emotional intelligence is thought to contribute to IGT performance (Li et al., 2020). Consistently, there is evidence for a positive association between cardiac interoceptive accuracy and interpersonal emotional intelligence (Koch and Pollatos, 2014a) as well as emotion regulation (Opdensteinen et al., 2021). This is in line with the finding that interoceptive accuracy predicts aversion to loss in a gambling task in adults (Sokol-Hessner et al., 2015). Furthermore, it remains possible that in the IGT task, children and adults use forms of bodily feedback other than cardiac interoceptive accuracy. Decision making is probably supported by different systems being active to varying degrees, depending on individual and situational characteristics (Frijda, 2005; Knutson and Bossaerts, 2007; Laird, 2007; Dunn et al., 2010). Thus, future studies would benefit from adopting individual difference approaches to figure out for which individuals decision-making processes are positively influenced by bodily feedback in contrast to other information-processing mechanisms (Wölk et al., 2014; Moccia et al., 2021; Avcu Meriç and Sönmez, 2022). The role of individual differences in this process might be of even further relevance, as interoceptive processes are thought to have extensive bilateral implications for mental health and chronic pain already in children (Hechler, 2021).

To date, studies on the role of somatic markers in decision making have exclusively focused on variants of the IGT, measuring decision-making patterns given incomplete information or ambiguous consequences, respectively. To our knowledge, our study is the first to indicate that children's interoceptive accuracy is also related to decision-making ability in situations that are less complex and ambiguous than the IGT, differing in the time that children need to wait for rewards and in the certainty with which rewards are obtained (i.e., in DoG tasks). However, we found children with higher interoceptive accuracy to show a stronger ability to delay gratification only for sweets-items, but not for toy-items. This finding is particularly interesting given the role of interoception in the regulation of eating and body weight (e.g., Pollatos et al., 2008; Ainley and Tsakiris, 2013; Herbert et al., 2013; Klabunde et al., 2013; Herbert and Pollatos, 2014; Young et al., 2017). In general, an accurate heartbeat perception is linked to a more finely-tuned behavioral self-regulation according to one's bodily needs (Herbert et al., 2007). For example, eating-disordered or overweight individuals exhibit lower interoceptive accuracy than do normal-weight individuals (Herbert and Pollatos, 2014). This was also true for overweight children in the present sample, who exhibited a lower interoceptive accuracy than did normal-weight children at t2 (Koch and Pollatos, 2014b). Furthermore, overweight children tend to have difficulties in delaying gratification, especially when it is food-specific and palatable (Bonato and Boland, 1983). Seeyave et al. (2009) found that, among other factors, the ability to delay gratification in young children (age 4) is related to the likelihood of overweight in adolescence. Thus, the present results point to a possible link between lower interoceptive accuracy, difficulties in delaying food-specific gratification, and the development of overweight. However, these interesting initial findings need to be interpreted with caution because effect sizes were small and only post-hoc analyses turned out to be significant at an alpha-level of 0.05. Additionally, further analyses in the present study indicated that in contrast to our expectations, later decision-making abilities are *not* predicted by early interoceptive accuracy. Further studies are needed to verify those first explorative results examining the relations of these three variables during development in more detail.

In general, the associations between interoceptive accuracy and the two decision-making measures turned significant only at t2 when children were 7 to 11 years old, which might point to a developmental strengthening of the association over time. This was partially reflected by the analysis across age groups: in children of 7–8 years of age, interoceptive accuracy influenced the learning across IGT trials, but not the overall outcome. These results suggest a developmental change in the way children utilize bodily feedback in decision-making processes. However, no significant developmental change was found in the number of delayed items across age groups. During middle childhood, interoceptive accuracy as well as decision-making ability are not yet finally developed (Prencipe et al., 2011; Koch and Pollatos, 2014a), and there is evidence that bodily responses influence decision-making ability more strongly when interoceptive ability increases (Dunn et al., 2010). Thus, with progress in development of both abilities as well as with a consolidation of their linkage based on learning processes, the association between interoceptive accuracy and decision making probably gets increasingly established. However, the absence of similar findings in the youngest as well as the oldest age group indicates that this development is not linear and likely to be influenced by other factors in a complex system. In adults, improvement of interoceptive abilities after a training interval was further correlated with a shift toward rational decision making (Sugawara et al., 2020). Furthermore, the fact that significant associations only occurred at t2 could be taken to indicate that the age of 6 to 7 years might be crucial for consolidating the link between interoceptive accuracy and decision making. This is supported by the difference in interaction of interoception and decision making in the IGT between the youngest and middle-aged group. However, this speculative assumption needs to be further confirmed by future studies examining age effects in more detail. Further studies are required in order to resolve the developmental timetable of interoceptive and decision-making abilities and the role of further factors accompanying the development.

In contrast to our expectations, interoceptive accuracy did not influence subsequent 1-year-changes in rank percentage of decision-making performance, when controlling for age and decision-making performance at t1. This missing longitudinal relation could be explained first, by the influence of third variables (e.g., general cognitive ability or attention). Other studies in adults indicate that higher-order cognitive functions, such as working memory are required in order to mediate decision-making in response to somatic cues (Hinson et al., 2002). If so, higher interoceptive accuracy would simply occur as an epiphenomenon of enhanced decision-making performance, rather than being a preceding factor. Alternatively, interoceptive accuracy might start to influence the subsequent development of decision making only later in development, which would agree with the finding that cross-sectional associations did not occur until t2, when children were aged 7 to 11 years. Furthermore, interoceptive accuracy turned out to be only moderately stable between measurement time points. Thus, assuming that concurrent levels of interoceptive accuracy influence decision making, this finding would provide an additional explanation for the missing longitudinal relationship between both variables. Apparently, interoceptive accuracy cannot yet be seen as a stable trait during middle childhood; interestingly, neither can be decision-making (Smith et al., 2012; Li et al., 2020). It would be interesting for future studies to examine longitudinal relations throughout and later in development, with an assumingly increasing stability of interoceptive accuracy and decision making. Finally, within the 1-year interval of our study, decision making had a limited possibility to change. Thus, future studies would benefit from exploring longitudinal relations of variables over a longer time span.

4.1. Study limitations

The present study is the first to examine the relations between interoceptive accuracy and decision making in children at 6-11 years of age. Its strengths include the examined age group, the assessment of interoceptive accuracy in a large unselected sample of over 1.400 children, the use of a DoG task in addition to the IGT, and the longitudinal perspective across a 1-year period. However, the study has some limitations that need to be acknowledged and that provide directions for future research.

The Heartbeat-Perception Task applied in the present study is commonly used in the assessment of interoceptive accuracy (e.g., Ehlers et al., 2000; Eley et al., 2004; Pollatos et al., 2008; Dunn et al., 2010), and it has been successfully used with children (e.g., Koch and Pollatos, 2014a,b). However, by treating interoceptive accuracy as a dichotomous variable, we applied a rather coarse measure. Given the explorative nature of our research questions and the rather small expected effect sizes, we aimed to maximize the statistical power of our analyses by comparing two equally-sized groups of children that differed significantly with regard to their interoceptive accuracy. A further concern could be that there are a number of factors that might influence the results of Heartbeat-Perception Tasks, such as attentional processes or people's beliefs and expectancies about their heart rates (Knapp et al., 1997; Wiens and Palmer, 2001; Knapp-Kline and Kline, 2005). Nevertheless, different Heartbeat-Perception Tasks lead to congruent results concerning effects of interoception on emotions (Katkin et al., 2001; Pollatos et al., 2005; Wiens, 2005; Pollatos et al., 2007), or concerning localization of relevant brain structures activated during heartbeat perception (Critchley et al., 2004; Pollatos et al., 2007), which supports the validity of such tasks in detecting processes involved in interoception. It might, however, be argued that the Heartbeat-Perception Task is not perfectly valid for children with limited ability to count precisely. This concern is further amplified as no time estimation task was performed as a control condition in order to avoid contamination by simply counting seconds (Desmedt et al., 2020). However, the estimation of heartbeats based on time interval estimation and respective calculations based on prior knowledge is more likely to be a problem in adult rather than in child populations. Furthermore, the Heartbeat-Perception Task was applied in children aged around 8–11 years before without additional control by a time estimation task (Eley et al., 2004; Georgiou et al., 2015). Nonetheless, alternative methods might assess interoceptive accuracy more reliably in children: the jumping jack paradigm is a tool that was designed to assess interoceptive accuracy in preschool-aged children to overcome such methodological limitations (Schaan et al., 2019; Opdensteinen et al., 2021); future research might benefit from sensibly choosing the task and control mechanisms for the assessment of interoceptive accuracy in order to provide even more reliable results. Additionally, future studies might investigate the contribution of cognitive factors such as working memory and their development in the Heartbeat-Perception Task in children in order to further validate the method and properly understand the relationship between the contributing factors.

It could also be criticized that, although both the IGT and the DoG task have been designed in order to mimic real-life decision making, it remains unclear whether results are transferable to a less artificial environment. Thus, future studies would benefit from examining interoceptive accuracy in relation to real-life decision making. Moreover, although we applied a longitudinal design, we only had two waves of data with a distance of a single year. Thus, we cannot completely rule out that task familiarity effects might have occurred. However, given the high complexity of the IGT, it seems very unlikely that children remembered the win/loss contingencies for the door choices, in particular because children were not informed about which doors were advantageous after the first test session.

Our findings indicated that the relation of interoceptive accuracy and decision making may be stronger at t2 (i.e., when children are 7 to 11 years old) than at t1 (i.e., about 1 year earlier). However, it would seem premature to make assumptions concerning a developmental framework on the basis of only two time points in children in this broad age range. In general, correlations between interoceptive accuracy, decision making, and age were low or non-existent, and extensively comparing single age groups was beyond the scope of the current paper.

Yet, while the examined age group can be considered as a strength of this study on the one hand, the age range (6 or 7–11, respectively) is rather broad in terms of development on the other hand, rendering the comparison of children at very different developmental stages rather delicate. While the question of the developmental trajectory of interoceptive abilities throughout childhood remains largely unresolved (Murphy et al., 2017), preschool children (aged 4–6) appear to become more sensitive or even oversensitive toward heart rate change with increasing age (Schaan et al., 2019). Additionally, decision-making abilities are thought to develop with age throughout childhood and adolescence (e.g., Crone and van der Molen, 2007), but not necessarily monotonously (Smith et al., 2012; Li et al., 2020). Thus, future studies might benefit from examining the developmental timetable of interoceptive and decision-making abilities in more detail by comparing single age groups and investigate the association over a longer time span as well as in older children, when both abilities have increasingly developed. Further analyses could also focus explicitly on the effect of age on the relationship between interoceptive accuracy and decision-making performance and the pivotal development at the age of 6–7 that was suggested in the present study.

Additionally, sex-specific differences were not taken into account in the present study, although gender might impact the state of development, particularly in young children. In a previous study with the same sample, Koch and Pollatos (2014a) revealed a male advantage on the Heartbeat-Perception Task. While Almy et al. (2018) did not find a significant effect of gender on IGT performance, other studies suggest that boys outperform girls on the IGT (Crone and van der Molen, 2007; Lensing and Elsner, 2018). Accounting for sex-specific differences exceeded the aims and scope of the present study; however, this might be an interesting subject to future research.

Furthermore, when evaluating the present findings, one should keep in mind that an alpha-level of 0.05 was applied for each hypothesis (for both tasks and measurement time points) and statistical power could be reduced in some cases due to violations of the prerequisites for the respective tests. Therefore, infering an overall relation between interoceptive accuracy and decision making during middle childhood can only be done with caution. Moreover, we cannot completely rule out that third variables, such as general cognitive ability, attention or emotional intelligence, might have affected the detected associations of interoceptive accuracy and decision making at t2. However, there neither is evidence that individuals with good cardiac perception exhibit superior cognitive performance, nor did the decision-making tasks show any associations to a fluid-intelligence measure in the present sample (Groppe and Elsner, 2014). Nevertheless, it would be interesting for future studies to examine the causality of effect in the association between cardiac perception and decision making, or the impact of potential moderators such as gender or cognitive factors.

5. Conclusion

Examining a large sample of children, our results for the first time indicate that individual differences in interoceptive accuracy relate to decision-making abilities in situations of varying complexity as early as in middle childhood, showing that already at the age of 7–11 years, the perception of and sensitivity to somatic feedback in form of cardiac cues may help in forgoing short-term reward for long-term profit, providing valuable contribution to the evidence on the SMH. Furthermore, the association of interoceptive accuracy and the delay of sweets-items might have implications for the regulation of body weight at a later age. These associations did not occur until the second measurement time point, which indicates a probable consolidation of the link between interoceptive accuracy and decision making over the course of development. However, effect sizes were rather small and results did not confirm that interoceptive accuracy could predict changes in rank percentage of decision making across a 1-year-period. Furthermore, the study design does not allow for causal inferences concerning relationships between variables. Thus, future studies are needed to validate these first findings and to investigate the exact role of somatic-marker information for decision making over the course of development in more detail. Such studies should examine the reported associations over a longer time-span with tests specifically adapted for children and should consider other potential intervening variables.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors on request, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by Research Ethics Board at the University of Potsdam; Ministry of Education, Youth and Sports of the Federal State of Brandenburg. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Author contributions

The original paper was written by OP, BE, and KG and updated and revised by KM. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2022.1070037/full#supplementary-material

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Synergistic effects of transcutaneous vagus nerve stimulation and inhibitory control training on electrophysiological performance in healthy adults

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Transcutaneous vagal nerve stimulation (tVNS) is a non-invasive nerve stimulation technique that exerts a positive "exogenous" online neuromodulatory effect on inhibitory control (IC). Additionally, IC training (ICT) is an effective approach for enhancing IC *via* the "endogenous" activation of brain regions implicated in this process. The aim of the present study was to examine the synergistic effects of tVNS and ICT on IC enhancement. For this, we measured the changes in neural activity in frontal, fronto-central, and central regions in the time domain of the N2 component and the frequency domain of alpha power during the stop signal task. A total of 58 participants were randomly divided into four groups that received five sessions of either ICT or sham ICT with either online tVNS or sham tVNS. No differences in N2 amplitude were detected after any of the interventions. However, N2 latency shortened after tVNS + ICT in frontal, fronto-central, and central regions. N2 latency shortened after the intervention of sham tVNS + ICT in frontal region. Moreover, alpha power after tVNS + ICT intervention was larger than those of the other interventions in frontal, fronto-central, and central regions. The obtained electrophysiological data suggested that combining tVNS with ICT has synergistic ameliorative effects on IC, and provide evidence supporting the IC-enhancing potential of tVNS combined with ICT.

KEYWORDS

transcutaneous vagus nerve stimulation (tVNS), inhibitory control training, EEG, N2, alpha oscillation, inhibitory control enhancement

1. Introduction

Transcutaneous vagus nerve stimulation (tVNS) is a non-invasive brain stimulation technique (Ridgewell et al., 2021) that has been suggested as a potential method by which to modulate inhibitory control (IC) *via* the activation of the locus coeruleus-noradrenergic (LC-NE) pathway (Warren et al., 2019; Rodenkirch et al., 2022). Studies on tVNS have demonstrated widespread activity in expected vagal projection areas (e.g., locus coeruleus, prefrontal cortex) (Rings et al., 2021). Additionally, tVNS was reported to produce a significantly greater BOLD signal in the frontal cortex based on a concurrent tVNS/fMRI analysis (Badran et al., 2018). tVNS can also modulate specific markers of cortical excitability in participants undergoing transcranial magnetic stimulation combined with electroencephalography (TMS-EEG) (Capone et al., 2015; Mertens et al., 2022) and has been associated with increased activity in the frontal lobe, likely as a consequence of vagal afferents transducing signals to higher-order brain centers (Rajiah et al., 2022). Peripheral autonomic nervous system activity and that relative changes in PFC oxygenation contribute to these effects as quantified using functional near-infrared spectroscopy (fNIRS) by the research about tVNS on cognitive function (Hoper et al., 2022). The NE system has been reported to play a varied and complex role in executive function (Usher et al., 1999; Slater et al., 2022; Tomassini et al., 2022). Moreover, recent studies have reported that tVNS can induce remarkable changes in IC, as revealed by electrophysiological data, such as event-related potentials (ERP). For example, tVNS has been found to result in a decrease in the amplitude of N2 (Pihlaja et al., 2020) and an increase in that of P3 (Ventura-Bort et al., 2018), which are markers of cognitive control. tVNS was also reported to induce an increase in the metrics of electroencephalogram (EEG) microstate *A* mean duration (Ricci et al., 2020) and enhance the frontal midline theta power spectrum in a go/no-go task (Keute et al., 2019). These findings demonstrate the potential of tVNS to modulate IC. However, the LC-NE activation-associated increases in brain norepinephrine levels induced by tVNS are transient and return to baseline levels when tVNS is stopped (Van Leusden et al., 2015). These findings may explain why resting beta and gamma oscillations, measured using magnetoencephalography, are not affected by tVNS (Keute et al., 2021). This indicates that tVNS, as "exogenous" online neuromodulation, might facilitate the activation of neural networks that are associated with IC.

Based on the theory of neuroplasticity, cognitive training has been proposed as an effective approach for enhancing IC (IC training; ICT). ICT has been defined as a repeated practice that adapts one or multiple standardized paradigms to specifically target IC in cognitive functioning (Elmasry et al., 2015). Previous research showed that ICT can enhance IC in healthy individuals, which is attributable to the "endogenous" activation of specific brain regions that are closely associated with IC during practice periods (Millner et al., 2012). However, the limitations of ICT include poor transfer to non-trained tasks, a lack of continuous practice motivation, and increased mental workload due to long-term repeated practice.

Given the different neurological mechanisms underlying the effects of tVNS and ICT on IC enhancement, our group developed a novel intervention approach involving tVNS combined with ICT. In a recent behavioral study, we revealed that this approach can cause a training effect and transfer effect and achieve IC enhancement in healthy individuals (Wang et al., 2022). However, the behavioral indicator of IC was not sufficient to evaluate the efficacy of the combined tVNS + ICT intervention, as participants were instructed not to produce a behavioral response to some types of stimuli. ERP research has provided another reliable electrophysiological measure of neural activity associated with IC enhancement.

The amplitude and latency of N2, an early ERP component, have been demonstrated to be associated with IC. Electrophysiological studies using the stop signal task (SST) or the go/no-go task have found a significant fronto-central N2 component in signal or no-go trials compared to go trials (Groom and Cragg, 2015; Dippel et al., 2017). Moreover, the signal- or no-go-N2 component has been reported to reflect an individual's detection (Chmielewski and Beste, 2017) or monitoring of conflict (Raud et al., 2020) and initiated response, which may reflect inhibition processes (Ghin et al., 2022). Anterior fronto-central N2 latency has been reported to be longer in adults with attention deficit hyperactivity disorder (ADHD) (Fisher et al., 2011) and those with sleep deprivation (Kusztor et al., 2019). Additionally, older people with mild cognitive impairment have been reported to have a longer N2 latency than healthy younger people (Chiang et al., 2018; Cid-Fernandez et al., 2019). These findings indicate that N2 latency may serve as a neural marker of IC and that anterior cortex-evoked N2 amplitude is strongly and positively correlated with response inhibition.

In addition to ERP, event-related oscillations (EROs) are a direct measure of neural activity that is time-locked to IC. EROs are typically analyzed by decomposing the event-related EEG signal into phase and magnitude information over a range of frequencies (Pandey et al., 2016). The high spatial and temporal resolution of EROs enables time-frequency analysis of regional brain activity to investigate neural dynamics in cognitive processes (e.g., IC). Cortical neural oscillations in the EEG alpha band (8–13 Hz) have been reported to reflect the most basic cognitive processes (Klimesch, 2012; Foster and Awh, 2019), as well as be linked with the suppression or inhibition of task-irrelevant information (Jensen and Mazaheri, 2010; Wiesman et al., 2019; van Zoest et al., 2021) and increased signal-to-noise ratio of activity within the cerebral cortex (Vaden et al., 2012; Hwang et al., 2016). Several studies have proposed that there exists an alpha-associated inhibitory gating process for interfering information in the frontal cortices. An increase in alpha activity may reflect inhibitory gating processes, whereby increased alpha power-blocking oscillation activity could block interfering or irrelevant signals to improve information processing efficiency and strengthen the dynamic functional responsiveness of brain networks (Konjusha et al., 2022). In cognitive control paradigms such as the SST or the go/no-go task, response inhibition after a stop signal or no-go stimulus has been associated with increased alpha power (Schmiedt-Fehr et al., 2016). However, people with alcohol addiction who have weak IC display significantly lower evoked alpha power compared with healthy adults for the no-go stimulus (Händel et al., 2011; Pandey et al., 2016).

Therefore, the aim of the present study was to investigate changes in neural activity in distinct brain regions following tVNS combined with ICT, including the time domain of ERP (signal-N2) and the frequency domain of EROs (alpha power), which reflect IC performance. We have previously demonstrated that this novel approach of tVNS combined with ICT can improve IC using behavioral analysis (Wang et al., 2022). Here, to further evaluate the synergistic effect of tVNS combined with ICT, we extend this investigation to neurophysiological performance. We hypothesized that IC performance, reflected by frontal and central neural activity, would be enhanced using tVNS combined with ICT.

2. Materials and methods

2.1. Participants

A total of 58 male undergraduate students (M_{age} = 19.5 years, SD = 0.7 years) were recruited *via* leaflets. According to the actual sample size, the *post-hoc* power was calculated as 0.88 using G*Power software (ver. 3.1.9.7.2; Heinrich-Heine-Universität Düsseldorf, Düsseldorf, Germany) (Kang, 2021). All participants were right-handed and had not previously participated in similar cognitive intervention research. Participants underwent a Web-based screening questionnaire before the experiment to ensure that they met the inclusion/exclusion criteria. The exclusion criteria included color blindness, a history of any psychological or neurological disorder, brain trauma or surgery, heart-related diseases, and adult ADHD assessed using the adult ADHD self-reporting scale (Kessler et al., 2005). A total of 60 participants passed the initial screening and were enrolled in the experiment. Two withdrew before completing the experiment due to personal schedule conflicts. The remaining 58 participants were allocated to one of the four following groups using a randomized single-blinded method: A tVNS + ICT group (n = 14), a sham tVNS + ICT group (n = 15), a tVNS + sham ICT group (n = 15), and a sham tVNS + sham ICT group (n = 14). All the participants provided written informed consent before participation and received 100 RMB/h as compensation for completing the experimental tasks efficiently. All procedures in the study were carried out in accordance with the Declaration of Helsinki and were approved by the Medical Ethics Committee of the Air Force Medical University (NO.KY20213079-1).

2.2. Apparatus and procedure

Each participant was required to complete three sequential experimental phases, including a pre-test, a five-session training, and a post-test. The experimental schedule of each participant (**Figure 1**) lasted for approximately two weeks. The pre-test was completed 1–2 days before the experiment began. The post-test was completed 1–2 days after the training phase. The five-session training phase consisted of five sessions of combined simultaneous tVNS (or sham tVNS) and ICT (or sham ICT). The training frequency was once a day, and each training session lasted approximately 60 min, during which each participant was required to complete four sets of combined simultaneous tVNS (or sham tVNS) and ICT (or sham ICT). Each ICT (or sham ICT) set comprised 240 trials, with a 5-min rest period between training sets. tVNS applied during ICT also included five sessions. The frequency of tVNS was the same as that for ICT, and the duration of each set of tVNS was equal to the duration of each set of ICT, which was approximately 60 min.

2.3. Intervention protocol

During the tVNS, two electrodes were placed at the cymba concha of the left ear. Based on previous tVNS studies, the parameters of the stimulation device (tVNS501, Rishena, Changzhou, China) were set to continuously deliver electrical stimulations with a pulse width of 200–300 µs at 25 Hz and a biphasic pulse interval of 30 s ON and 30 s OFF. The stimulus intensity of the tVNS varied between individuals and was set to the average level, which was defined by the level above the detection threshold but below the pain perception threshold (Ellrich, 2011; Pihlaja et al., 2020). All participants reported a strong "tingling" sensation to the stimulation condition but no uncomfortable feelings. For the sham tVNS, the electrodes were placed on the left earlobe. Except for the different electrode positions, all parameters were identical between the tVNS and sham tVNS groups.

Each set of the SST was adapted to the ICT paradigm and included 180 go trials and 60 stop trials. The time of stop-signal delay (SSD) in the SST was adjusted according to the performance of the participants on the stop trials; the initial SSD was 250 ms, and after reacting correctly to a stop trial, the SSD increased by 50 ms, whereas after reacting incorrectly to a stop trial, the SSD decreased by 50 ms. The SSD ranged from 0 to 750 ms. Performance on the SST was assessed using the stop-signal reaction time, which was calculated as the average difference between the reaction time (RT) of go trials and the SSD. A lower stop-signal reaction time reflected stronger response inhibition. The exclusion criteria in the SST analysis included a RT of less than 150 ms or more than 1000 ms on go trials or stop-failure trials, and a mean RT of stop-failure trials longer than the mean RT of go trials and $p_{(respond|signal)}$ lower than 0.25 or higher than 0.75 (Congdon et al., 2012; Verbruggen et al., 2019). All participants were required to complete 5 sessions of ICT. For the sham ICT paradigm, the simple reaction task of each set comprised 240 trials, and trials of the "training session of sham ICT" with an accuracy level below 90% were excluded. Other parameters of the simple reaction task were the same as those of the SST.

2.4. Electrophysiological recording and data analysis

During the SST at both the pre- and post-test phases, continuous EEG data were recorded using a 32-channel Grael EEG amplifier (Compumedics Germany GmbH, Germany) that was configured according to the international 10–20 placement system with the midline reference located at the vertex between Cz and CPz, and the grounding electrode located near the area of Fz. The electrooculogram was recorded *via* two bipolar electrodes placed at the lateral canthus of each eye (horizontal electrooculogram) and above and below the left eye (vertical electrooculogram). The EEG data were sampled at 1024 Hz using Curry 8.05 Recorder software (Compumedics Neuroscan, Germany), and the impedance of each electrode was kept below 20 kilohms.

The recorded EEG data were preprocessed offline using the EEGLAB toolbox (v. 14.1.1) in MATLAB R2020b (The MathWorks, Inc., MA, USA). Preprocessing included removing non-brain and invalid EEG channels from subsequent analysis, re-referencing to the average of left and right mastoids, band-pass filtering (1–30 Hz), down-sampling to 128 Hz, and removing eye blinks, saccades, muscle artifacts, swallowing, or other noise artifacts using independent component analysis-based correction. Epochs of 1000 ms were extracted from -200 to 800 ms relative to

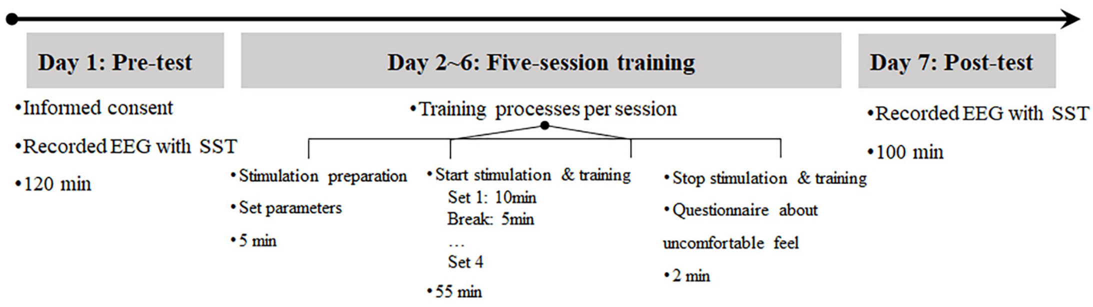

FIGURE 1
Overview of the experimental procedure and timeline in the study.

stimulus onset for each trial, followed by baseline correction to a pre-stimulus interval of 200 ms, and epochs exceeding the voltage threshold of ±80 μV in amplitude at any channel were excluded from subsequent analysis.

In the present study, frontal (F11, F7, F3, FZ, F4, F8, F12), fronto-central (FC3, FCZ, FC4), and central (C3, CZ, C4) regions were the regions of interest (ROIs). The peak amplitudes and latencies of the N2 based on stop signal trials of the SST (signal-N2) were defined as the peak negative signal. The corresponding peak latency in the time windows from 100 to 300 ms after stimulus onset, and the power spectral density (PSD) of the alpha band with time-locking events (stop signal trials of the SST) were calculated using fast Fourier transform in the 800-ms time window after stimulus onset in the ROIs (frontal, fronto-central, and central regions).

2.5. Statistical analysis

The ERP parameters (N2 amplitude and latency) and EROs parameter (PSD of the alpha power) were analyzed separately using repeated measures analysis of variance (rmANOVA), executed in SPSS 25 (IBM Inc., New York, NY, USA) with 2 phases (pre- and post-test), 4 groups (tVNS *vs.* sham tVNS, ICT vs. sham ICT) in each ROI (frontal, fronto-central, and central regions). The main effects of phase and group and the interaction effects were analyzed. To further explore the within-group (pre- and post-test) and between-group differences at each phase, simple effects analysis with *post-hoc* Bonferroni correction was performed. Additionally, between-group differences in baseline variables, such as age and years of education, were assessed using one-way ANOVA.

Significance was set at a value of α of 0.05. The effect size was estimated using partial eta-squared (η_p^2). Data were analyzed using SPSS software (version 25, IBM Inc., New York, NY, USA). Descriptive statistics are reported as means ± standard deviation.

3. Results

3.1. Baseline parameters

Descriptive statistics, including the means and standard deviations, are reported in Table 1. There were no significant between-group differences in age [$F_{(3,54)}$ = 0.44, p = 0.73] or years of education [$F_{(3,54)}$ = 0.11, p = 0.95] (Table 1). ERP and EROs data in each ROI are presented in Table 1 and the results are shown in Table 2. For the frontal region, the results revealed a significant main effect of phase on signal-N2 latency and amplitude as well as alpha power. There was no significant main effect of group and no phase × group interaction effect on signal-N2 latency and amplitude. However, there was a significant main effect of group and a significant phase × group interaction effect on alpha power. For the fronto-central region, the results revealed a marginally significant main effect of phase on signal-N2 latency and alpha power, a marginally significant main effect of group on alpha power, and a significant phase × group interaction effect on signal-N2 latency and alpha power. For the central region, there was a significant phase × group interaction effect on alpha power.

3.2. N2 component

ERP are depicted in Figures 2, 3. The results of simple effect using *post hoc* Bonferroni tests indicated that the tVNS + ICT group had significantly shorter signal-N2 latency at post-test than pre-test in frontal, fronto-central, and central regions (frontal: p = 0.007; fronto-central: p = 0.001; central: p = 0.044). Additionally, the sham tVNS + ICT group exhibited a significantly shorter signal-N2 latency at post-test than pre-test in the frontal region (p = 0.041). However, there was no significant difference between pre- and post-test in the tVNS + sham ICT or sham tVNS + sham ICT groups in frontal, fronto-central, and central regions. Additionally, the sham tVNS + ICT group exhibited a significantly shorter signal-N2 latency at post-test than at pre-test in the frontal region (p = 0.04). However, there was no significant difference between pre- and post-test in the tVNS + sham ICT or sham tVNS + sham ICT groups in frontal, fronto-central, and central regions.

3.3. Alpha power

As shown in Table 2, the rmANOVA of alpha power based on PSD revealed significant main effects of phase and group and a phase × group interaction effect in the ROIs.

To further explore the intervention effects between groups, we performed a simple-effect analysis using *post-hoc* analysis

TABLE 1 Mean (standard deviation) of baseline variables including age and years of education, N2 component, and alpha power in ROIs during pre- and post-test.

Group	Age (years)	Edu (years)	Region	Phase	N2-Lat (ms)	N2-Amp (μ V)	PSD-alpha (db)
tVNS + ICT (n = 14)	19.50 (0.65)	13.60 (0.27)	*F*	*Pre-*	235.89(39.59)	−3.67(3.78)	17.23(0.80)
				Post-	215.00(25.45)**	−3.89(1.93)	18.62(0.88)**
			FC	*Pre-*	217.26(43.52)	−5.13(7.32)	19.18(1.38)
				Post-	189.36(18.11)**	−5.19(3.37)	20.36(0.97)**
			C	*Pre-*	217.45(35.05)	−4.49(7.09)	18.70(1.61)
				Post-	199.78(24.20)*	−5.78(3.35)	19.88(1.17)**
sham tVNS + ICT (n = 15)	19.53 (0.83)	13.62 (0.30)	*F*	*Pre-*	232.51(28.89)	−3.17(3.08)	17.51(1.41)
				Post-	217.34(27.13)*	−4.03(2.68)	17.11(1.38)$^+$
			FC	*Pre-*	206.60(33.02)	−3.62(4.43)	19.09(1.34)
				Post-	204.86(21.67)	−4.99(3.20)	18.71(1.26)
			C	*Pre-*	209.20(26.37)	−3.12(4.66)	18.69(1.28)
				Post-	206.25(19.96)	−4.93(3.34)	18.47(1.29)
tVNS + sham ICT (n = 15)	19.33 (0.72)	13.54 (0.51)	*F*	*Pre-*	229.09(29.41)	−3.35(3.07)	16.86(1.42)
				Post-	227.98(23.16)	−5.27(2.84)*	16.20(0.80)**
			FC	*Pre-*	201.74(35.76)	−4.49(5.67)	18.96(1.56)
				Post-	195.31(18.93)	−6.25(5.47)	18.22(0.82)**
			C	*Pre-*	213.72(39.59)	−4.06(5.93)	18.73(1.70)
				Post-	198.26(18.59)$^+$	−5.05(5.94)	17.72(0.81)**
Sham tVNS + sham ICT (n = 15)	19.64 (0.75)	13.57 (0.53)	*F*	*Pre-*	233.58(19.21)	−5.03(3.52)	16.82(1.24)
				Post-	229.03(26.37)	−5.45(3.21)	17.57(1.21)**
			FC	*Pre-*	202.57(26.46)	−8.42(5.01)	18.73(1.33)
				Post-	206.47(29.70)	−8.18(4.02)	19.61(1.25)**
			C	*Pre-*	202.94(26.15)	−8.16(4.74)	18.26(1.19)
				Post-	207.03(26.08)	−7.57(3.93)	18.78(1.35)*

Edu, years of education; N2-Lat, N2 latency; N2-Amp, N2 amplitude; PSD-alpha, PSD of alpha power; F, frontal region; FC, fronto-central region; C, central region. $^{**}p < 0.01$, $^{*}p < 0.05$, $^{+}p < 0.08$.

TABLE 2 Summary of rmANOVA results for signal-N2 latency and amplitude, alpha power in ROIs.

Effect	N2-Lat			N2-Amp			PSD-alpha		
	F	FC	C	F	FC	C	F	FC	C
	$F(\eta_p{}^2)$	$F(\eta_p{}^2)$	$F(\eta_p{}^2)$	$F(\eta_p{}^2)$	$F(\eta_p{}^2)$	$F(\eta_p{}^2)$	$F(\eta_p{}^2)$	$F(\eta_p{}^2)$	$F(\eta_p{}^2)$
phase	7.98** (0.13)	3.95$^+$ (0.07)	3.62 (0.06)	4.15* (0.07)	1.25 (0.02)	1.99 (0.04)	6.05* (0.10)	3.49$^+$ (0.06)	0.92 (0.02)
group	0.22 (0.01)	0.23 (0.01)	0.07 (<0.01)	1.14 (0.06)	2.34 (0.12)	2.10 (0.11)	3.97* (0.18)	2.65$^+$ (0.13)	1.95 (0.13)
phase × group	1.54 (0.08)	2.87* (0.14)	1.49 (0.08)	0.83 (0.04)	0.54 (0.03)	0.68 (0.04)	18.83** (0.51)	14.17** (0.44)	15.74** (0.47)

N2-Lat, N2 latency; N2-Amp, N2 amplitude; PSD-alpha, PSD of alpha power; F, frontal region; FC, fronto-central region; C, central region. $^{**}p < 0.01$, $^{*}p < 0.05$, $^{+}p < 0.08$.

with Fisher's LSD correction (Figure 4). We found no significant difference in alpha power between the four groups at baseline (in the pre-test phase). However, there was a significant difference in alpha power between the four groups in the post-test phase. The post-test results showed a significantly larger alpha power in the tVNS + ICT group than the sham tVNS + ICT group (frontal: $p < 0.001$; fronto-central: $p < 0.01$), the tVNS + sham ICT group (frontal: $p < 0.001$; fronto-central: $p < 0.001$), and the sham tVNS + sham ICT group (frontal: $p = 0.01$; fronto-central: $p = 0.01$) in frontal and central regions. Additionally, we found a significantly

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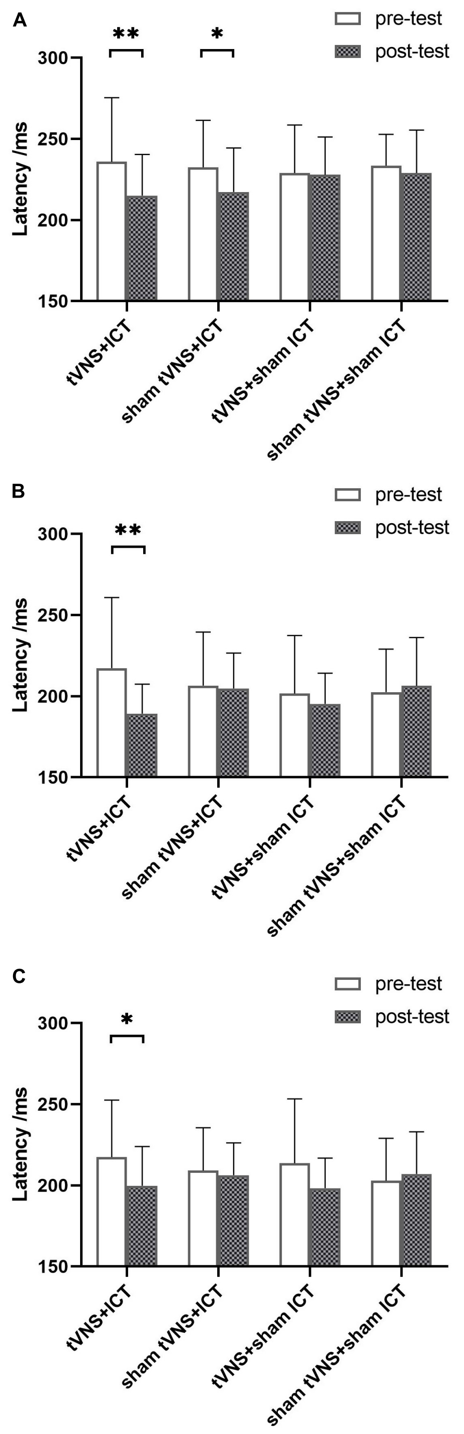

FIGURE 2
Summary of signal-N2 latency in SST. **(A)** Signal-N2 latency between pre- and post-test for each group in frontal region. **(B)** Signal-N2 latency between pre- and post-test for each group in fronto-central region. **(C)** Signal-N2 latency between pre- and post-test for each group in central region. Error bars represent the standard deviation of the mean. $^*p < 0.05$, $^{**}p < 0.01$.

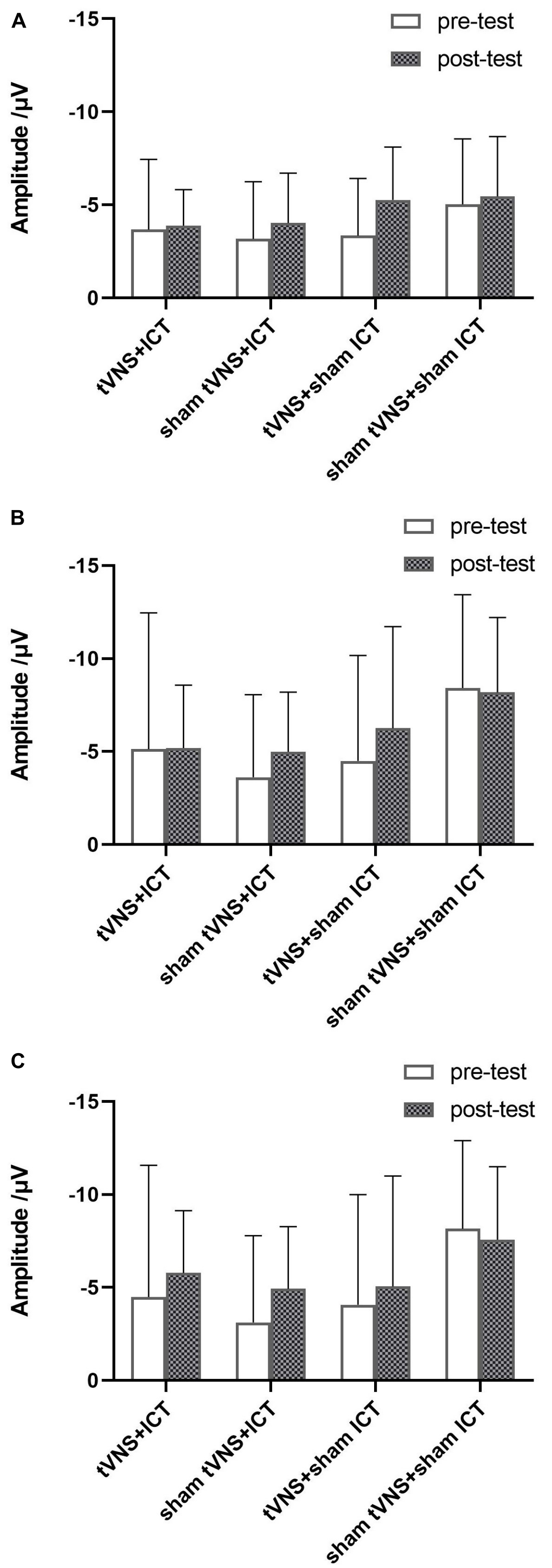

FIGURE 3
Summary of signal-N2 amplitude in SST. **(A)** Signal-N2 amplitude between pre- and post-test for each group in frontal region. **(B)** Signal-N2 amplitude between pre- and post-test for each group in fronto-central region. **(C)** Signal-N2 amplitude between pre- and post-test for each group in central region. Error bars represent the standard deviation of the mean.

larger alpha power value in the tVNS + ICT group than in the sham tVNS + ICT ($p < 0.001$) and tVNS + sham ICT ($p < 0.001$) groups, and marginally significantly larger alpha power in the tVNS + ICT group than in the sham tVNS + sham ICT group ($p = 0.077$) in the fronto-central region.

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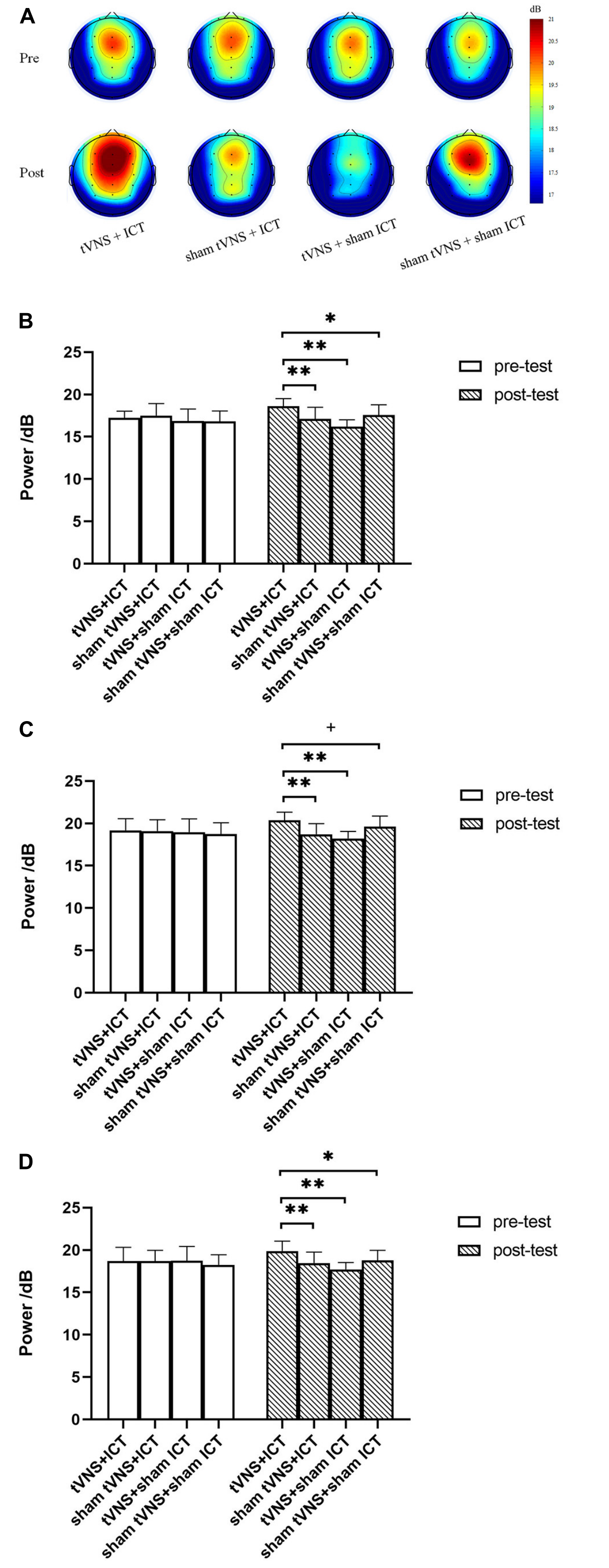

FIGURE 4
Summary of alpha power in SST. **(A)** Topography of alpha power spectrum density between the four groups during pre- and post-test phases. **(B)** Alpha power between groups, during pre- and post-test phases in frontal region. **(C)** Alpha power between groups, during pre- and post-test phases in fronto-central region. **(D)** Alpha power between groups, during pre- and post-test phases in central region. Error bars represent the standard deviation of the mean. $^{**}p < 0.01$, $^{*}p < 0.05$, $^{+}p < 0.08$.

4. Discussion

In the present study, we investigated whether tVNS and ICT exert a synergistic effect on IC enhancement and further investigated the enhancement effect in healthy adults according to cortical electrophysiological performance in selected ROIs. To our knowledge, this is the first study to demonstrate the synergistic effect of tVNS combined with ICT on electrophysiological brain activity in healthy adults. As hypothesized, we found that signal-N2 latency was significantly shorter and alpha power was significantly greater after the combined intervention with tVNS and ICT. Concerning the N2 component results, the tVNS + ICT and sham tVNS + ICT groups exhibited a shorter signal-N2 latency in the frontal region, which indicated that the timing of conflict monitoring in response inhibition was faster in healthy adults who had received ICT than in those who had not. This finding is consistent with those of previous studies on IC practice manifesting the frontal N2 latency modulation on the temporal dynamics (Millner et al., 2012), and subjects exhibited faster N2 latency after inhibition training (Schroder et al., 2020). In addition, our findings on the signal-N2 latency in the frontal region are in line with the effects of ICT on behavioral performance, whereby subjects who have undergone ICT obtained a faster stop-signal reaction time (Wang et al., 2022).

Furthermore, the signal-N2 latency was also shorter after the combined tVNS with ICT intervention in fronto-central and central regions, and this effect was not seen in the sham tVNS or sham ICT groups. This is consistent with the hypothesis that tVNS exerts a positive synergistic effect on IC enhancement, which, in turn, produces an accelerating effect of automatically generated response tendencies (Grützmann et al., 2022). This has been corroborated by findings from Pihlaja et al. (2020) who suggested that a change in the frontal N2 component is a neural marker of cognitive control.

By contrast, the signal-N2 latency did not differ significantly between the pre- and post-tests in the tVNS + sham ICT intervention group. tVNS has shown potential for benefiting cognition in healthy adults, such as modulating conflict monitoring in IC processes (Pihlaja et al., 2020). However, it is reportedly difficult to maintain the modulatory effect once tVNS has stopped (Van Leusden et al., 2015), which could explain why we found no difference in signal-N2 latency after the tVNS + sham ICT intervention.

Interestingly, we found no significant difference in signal-N2 amplitude between pre- and post-tests in the tVNS + ICT intervention group. In line with our previous results, where we found that $p_{(\text{respond}|\ \text{signal})}$ in the SST did not differ significantly between the pre- and post-tests with tVNS + ICT intervention (Wang et al., 2022), the present finding on signal-N2 amplitude seems to demonstrate that N2 amplitude could be a marker with which to assess the ability of processing conflict signals monitored in IC. Additionally, the ceiling effect of response inhibition (Bürki et al., 2014) in the SST might be the main reason why there were no significant behavioral [$p_{(\text{respond}|\ \text{signal})}$] or electrophysiological (signal-N2 amplitude) performance changes indicative of IC enhancement in the tVNS + ICT group.

For alpha power in the SST, the tVNS + ICT group obtained stronger alpha-band PSD compared with the sham tVNS + ICT, tVNS + sham ICT, and sham tVNS + sham ICT (placebo intervention) at the post-intervention phase in frontal, fronto-central, and central brain regions. Given that alpha power is thought to be associated with inhibition (Händel et al., 2011), the finding of larger alpha power after the tVNS + ICT intervention suggests that this combination can improve IC performance. Moreover, alpha oscillations have been linked to mechanisms underlying IC, such as the suppression of irrelevant or interfering information (Vaden et al., 2012). Our findings also support work showing a stronger power of frontal and central alpha oscillations when performance in inhibition tasks increases, via top-down inhibitory strategic processes (Hwang et al., 2016; Konjusha et al., 2022). Additionally, our findings on the change in alpha oscillations support reports that tVNS can activate endogenous neuromodulatory signaling, such as LC-NE activity, which is correlated with increased arousal (Sharon et al., 2021); this, in turn, improves the ability to overcome the interfering effects of irrelevant information in the prefrontal cortices.

One limitation of the present study was that we could not determine how the ability of tVNS + ICT to induce stronger alpha power in the selected ROIs influenced IC performance. We can speculate that the increased alpha power seen following the tVNS + ICT intervention may have a far transfer effect on cognitive functions (e.g., shift of attention task, multitasks in IC), including IC. Additionally, we did not investigate the optimal sessions of tVNS combined with ICT, which might produce greater IC enhancement. It is also unclear how long IC enhancement is maintained after the tVNS + ICT intervention. Accordingly, future research should focus on investigating the transfer effects, the optimal protocol, and the duration of the IC-enhancing effect of tVNS + ICT intervention. Although Results regarding alpha power in fronto-central region showed marginally significant difference between the tVNS + ICT group and the sham tVNS + sham ICT group, these results should be taken with caution. Thus, these findings with statistically marginal significance in present study also require further validation by expanding the sample size. Finally, due to the small sample size, the clinical implications of these findings in present study should explored by expanding the sample size in different participant populations in future research. To investigate the transfer effects and the optimal protocol of tVNS on brain activity, the evaluation of neural effects of tVNS by neuroimage techniques (e.g., TMS-EEG, fNIRs, fMRI) should be studied in future research.

5. Conclusion

In the present study, we demonstrated that tVNS combined with ICT shortens the signal-N2 latency and that increased alpha power in the SST is closely associated with IC enhancement. These findings provide neurophysiological evidence to suggest that tVNS combined with ICT may be a valuable method for enhancing IC, and may represent a novel and feasible approach for improving IC in adults with ADHD, those addicted to alcohol or drugs, people with obesity, and individuals who require a high inhibitory capacity, such as healthcare and military personnel, pilots, and astronauts.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by the Medical Ethics Committee of the Air Force Medical University. The patients/participants provided their written informed consent to participate in this study.

Author contributions

CW, LZ, and ZW designed and conducted the study. XC, HW, LY, and ZW contributed to the study design. CW, YQ, ZG, YL, and JD contributed to recruitment of participants, data collection, and data analysis. CW and LZ were responsible for writing of the manuscript. HW, LY, and ZW contributed to review the literature and interpret the results. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fnins.2023.1123860/full#supplementary-material

SUPPLEMENTARY TABLE 1
The original data of **Figure 3A**.

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Sex differences in functional brain networks involved in interoception: An fMRI study

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Interoception can be described as the ability to perceive inner body sensations and it is different between biological sex. However, no previous research correlated this ability with brain functional connectivity (FC) between males and females. In this study, we used resting-state functional magnetic resonance imaging to investigate FC of networks involved in interoception among males and females in a sample of healthy volunteers matched for age. In total, 67 participants (34 females, mean age 44.2; 33 males, mean age 37.2) underwent a functional MRI session and completed the Self-Awareness Questionnaire (SAQ) that tests the interoceptive awareness. To assess the effect of sex on scores obtained on the SAQ we performed a multivariate analysis of variance. A whole-brain seed-to-seed FC analysis was conducted to investigate the correlation between SAQ score and FC, and then to test differences in FC between males and females with SAQ score as a covariate. MANOVA revealed a significant difference in SAQ scores between males and females with higher values for the second ones. Also, significant correlations among interoception scores and FC in Salience network and fronto-temporo-parietal brain areas have been detected, with a sharp prevalence for the female. These results support the idea of a female advantage in the attention toward interoceptive sensations, suggesting common inter-network areas that concur to create the sense of self.

KEYWORDS
interoception, fMRI, SAQ, functional connectivity, sex differences

1. Introduction

Interoception is a multi-faced process that reflects the capability in perceiving inner body signals (e.g., Craig, 2002). It is also an umbrella term for the phenomenological experience of the body state, an experience which is ultimately a product of the central nervous system, regardless of what information the brain uses and does not use to construct this experience (Ceunen et al., 2013). Interoceptive sensibility, namely, the self-evaluation of subjective interoceptive information (Garfinkel et al., 2015), is different and less distinct than exteroceptive somatosensory stimulus (e.g., self-perceiving touch, pain or temperature; Craig, 2008). Interestingly, paying attention to one's own bodily states is different between females and males and has been demonstrated in several independent samples (Longarzo et al., 2021). Specifically, women show higher attention to visceral states but reduced interoceptive accuracy, and this may affect how they report their own body-related sensations (e.g., Garfinkel et al., 2015; Grabauskaitė et al., 2017). These biological sex differences might be due to hormonal and physical changes experienced by women during lifespan, which reflects in the experiences of menstruation, pregnancy and menopause (e.g., Murphy et al., 2019). Visceral sensations are part of the interoceptive awareness, which is generally assessed by using the Self Awareness Questionnaire (SAQ; Longarzo et al., 2015).

Most recent research highlighted associations between brain structures and biological sex, which might be linked to different degree of interoceptive awareness. In particular, neuroimaging studies found differences in brain cytoarchitecture between females and males. For instance, Goldstein et al. (2001) reported that male brains are ten percent larger than female brains, even after intracranial volume adjustment (Cosgrove et al., 2007), this result is confirmed in a study of brain volume over the entire lifespan (Coupé et al., 2017). Also, cytoarchitectonic differences according to sex are present in brain regions such as the amygdala, hippocampus and insula (e.g., Ruigrok et al., 2014). Frontal and medial paralimbic brain areas are larger in women, while the hypothalamus, amygdala and angular gyrus appear to be larger in men (e.g., Rezzani et al., 2019). In the female population, the volume of both corpus callosum and language-related temporo-parietal regions is comparatively larger than males, whereas males have larger parietal cortical areas (Grabowska, 2017), which are linked to the visuospatial and sensorimotor function (Federico et al., 2022).

Differences between brain functional connectivity and biological sex have also been reported in literature. Resting state fMRI studies, which use the temporal correlation between fluctuations in different brain regions as a measure of intrinsic functional connectivity (FC), report stronger FC in the Default Mode Network (DMN) for females within wide brain networks, which include the posterior cingulate cortex, the precuneus and the medial prefrontal cortex bilaterally (e.g., Bluhm et al., 2008). Stronger intra-network FC in females and stronger inter-network FC in males are reported (Allen et al., 2011; Zhang et al., 2018). Also, a mixture FC differences between females and males has been reported in lobar regions (Filippi et al., 2013). Crucially, similar results were found by using Diffusion Tensor Imaging in a pediatric sample (Ingalhalikar et al., 2014), but over the healthy adults structural connectivity didn't seem to correlate with FC (Tsang et al., 2017). Finally, FC differences among sex has been reported, with males which exhibit a greater right-brain-lateralized short-range FC as compared to females (Tomasi and Volkow, 2012).

An interesting research question is whether the above-mentioned sex-related structural/functional differences in the brain may reverberate in terms of interoceptive awareness. For instance, neuroimaging studies linked the insula and cingulate cortices to interoceptive awareness. Specifically, the anterior insular cortex has been considered as an hub which encodes and represents interoceptive information, and for this reason it has been also defined as an interoceptive cortex (Critchley et al., 2004; Craig, 2009). Notably, by adopting a microstructural point of view, the insula has reciprocal neural link with the anterior cingulate cortex (ACC), which is related to physiological information and provides autonomic responses (Craig, 2009). These regions are functionally linked within the salience network (SN), namely, a brain network critically involved in integrating highly processed sensory information with visceral, autonomic, and hedonic markers, to guide the own behavior. Such a network involves the bilateral anterior insular cortices and dorsal ACC, as well as the prefrontal cortex (PFC), supramarginal gyrus (SMG), striatum/basal ganglia, thalamus, and cerebellum (Seeley et al., 2007; Guo et al., 2012). All these sensory-related processes exhibit a decrease with aging. Indeed, numerous studies demonstrated age-related decreases in primary somatosensory cortex (Good et al., 2001; Sowell et al., 2003), insular cortex (Good et al., 2001; Resnick et al., 2003), and SN connectivity (Onoda et al., 2012).

Taking together all the above-mentioned evidence, the general picture which emerges is that very little is known about how sex-related differences in the brain may generate different levels of interoceptive awareness. Studying such differences may allow researchers to expand knowledge about how our brain perceives inner-body signals and to target specific populations in order to understand what makes them more susceptible. Therefore, the present study aims at exploring sex differences in functional brain networks involved in interoception in a large sample of healthy participants.

2. Materials and methods

The sample of our study includes 67 healthy subjects (34 females, mean age 44.2 ± 14.5; 33 males, mean age 37.2 ± 12.4) enrolled at the IRCCS SYNLAB SDN, and performing both an extensive neuropsychological assessment and magnetic resonance imaging (MRI). All the subject that participated in this research protocol were recruited if they met the following criteria: (i) lack of actual or past history of alcohol or drug abuse, (ii) lack of current or past history of major psychiatric illnesses, (iii) lack of history of brain injury, stroke, or any other major clinical condition, (iv) lack of current or past use of psychoactive medications. The eligibility criteria to define the participants "healthy subjects" were assessed through a brief clinical interview performed by an expert neuropsychologist. Each subject provided written informed consent that was previously approved by the local Ethics Committee of IRCCS Pascale and performed according to the ethical standards laid down in the 1964 Helsinki Declaration and its later amendments. All individuals were naïve to the scope of the study and gave their written informed consent to participate without any reward.

2.1. Neuropsychological assessment

All participants in the study completed the Self-Awareness Questionnaire (SAQ), a self-report tool devised to evaluate the perception of a wide range of bodily sensations and, in particular, investigate the frequency of perceiving signals from volunteer's own body (Longarzo et al., 2015). The SAQ is composed by 28 items to be rated on a 5-point Likert scale (0 = never; 1 = sometimes; 2 = often; 3 = very often; 4 = always). The total score ranges 0–112 with higher scores represent higher interoceptive awareness. The SAQ has a bi-factorial structure; the first factor (F1)

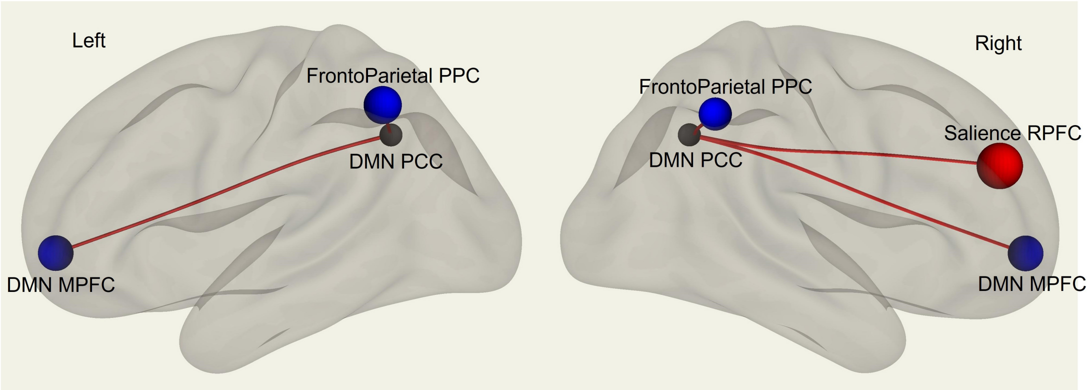

FIGURE 1
fMRI seed-to-seed three dimensional representation showing FC differences between males and females' subjects with SAQ and age as covariates.

TABLE 1 Whole-brain seed-to-seed FC differences analysis between males and females' subjects with SAQ and age as covariates.

Seed	Targets	T-score	p-FDR
DMN PCC	Salience RPFC right	4	0.005
	Frontoparietal PPC left	−3.4	0.018
	DMN (MPFC)	−3	0.042
	Frontoparietal PPC right	−2.8	0.050

Positive T-scores represent FC hyperconnectivity, while negative T scores represent FC hypoconnectivity. p-FDR, *p*-value corrected for multiple comparisons (Benjamini and Hochberg, 1995).

included items related to visceral sensations, whereas the second one (F2) is related to somatosensory sensations (Longarzo et al., 2015). In our research, we performed a multivariate analysis of variance (MANOVA) in order to assess the effect of biological sex, demographics parameters and SAQ scores, with a Wilks' lambda (λ) statistic. SPSS (IBM Corp., Released 2016. IBM SPSS Statistics, Version 24.0) were used to perform statistical analyses.

2.2. MRI functional connectivity

A Biograph mMR 3T scanner (Siemens Healthcare, Erlangen, Germany) with a 12-channel head coil were used to acquire MR images. The MR acquisition protocol included structural and functional sequences: (1) 3D T1-Magnetization Prepared Rapid Acquisition Gradient Echo (MPRAGE), voxel size 0.8 × 0.8 × 0.8 mm^3, Field of View (FOV) 214 × 214 mm, TR/TE/TI = 2,400/2.25/1,000 ms, scan time 5:03; and (2) Resting-state fMRI, Echo Planar Imaging-Gradient Echo sequence (EPI-GRE), voxel-size 4 × 4 × 4 mm^3, TR/TE = 1,000/21.4 ms, 350 measurements, bandwidth: 2,230 Hz, multiband factor: 2 (Auerbach et al., 2013), scan time 6:02. fMRI data were analyzed with Functional Connectivity Toolbox (CONN v. 20b; Whitfield-Gabrieli and Nieto-Castanon, 2012) and Statistical Parametric Mapping (SPM v. 12). Both CONN and SPM were executed on MATLAB (v. 2021b). Pre-processing of fMRI data were performed with CONN using a pipeline that includes realignment, slice-timing, functional-image normalization in the Montreal Neurological Institute (MNI) space, outlier detection with ART-based scrubbing smoothing, and physiological denoising (Alfano et al., 2021). A statistical data analysis was devised to assess differences in functional connectivity (FC) between male and female participants after controlling for age, SAQ, F1 and F2 covariates. We evaluated FC differences between these two sub-groups by performing CONN-based seed-to-seed analyses, which were conducted by adopting cortical and subcortical ROIs (FSL Harvard-Oxford maximum likelihood cortical and subcortical atlas, dividing bilateral areas into left/right hemisphere for a total of 106 ROIs). Then, a regression-based inter-network FC analysis was conducted to investigate correlations between brain networks FC and SAQ, F1 and F2 scores (networks from CONN's ICA analyses of HCP dataset for a total of eight networks with 32 subnetwork ROIs; Bar-Joseph et al., 2001). An alpha level of 0.05 was used with false discovery rate (FDR) correction for multiple comparisons (Benjamini and Hochberg, 1995) for both the seed-to-seed and network-to-network comparisons.

3. Results

Multivariate analysis of variance (MANOVA) showed significant differences between males and females on SAQ total score (λ = 0.03, F(hypothesis-DOF 64, error-DOF 64) = 4.5; $p = 0.005$), and on both factors, F1 (λ = 0.05, F(hypothesis-DOF 44, error-DOF 84) = 5.8; $p = 0.002$) related to visceral sensations and F2 (λ = 0.08, F(hypothesis-DOF 40, error-DOF 88) = 4.1; $p = 0.036$) related to somatosensory sensations, with females showing higher values of SAQ, F1 and F2 than males. Mean age did not differ between the two groups. By using SAQ and age as covariates, results of the whole-brain seed-to-seed network analysis showed significant differences between male and female participants (**Figure 1** and **Table 1**). The following pattern of seed-to-seed network FC hypoconnectivity (males with a lower FC than females) was found: DMN posterior cingulate cortex (PCC) - left and right Frontoparietal network PPC (T(64) = −3.4; p-FDR = 0.018 and T(64) = −2.8; p-FDR = 0.05, respectively), DMN MPFC (T(64) = −3; p-FDR = 0.042). The following pattern of seed-to-seed hyperconnectivity (males with a higher FC than females) was found: DMN PCC - right Salience RPFC

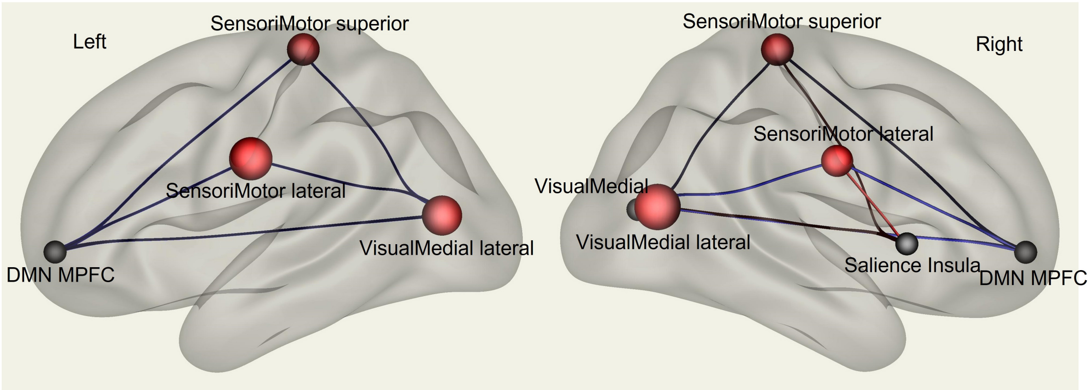

FIGURE 2
fMRI seed-to-seed three dimensional representation showing FC analysis with the SAQ considered as a continuous regressor and age as covariate.

TABLE 2 Whole-brain seed-to-seed FC analysis with the SAQ considered as a continuous regressor and age as covariate.

Seed	Targets	T-score	p-unc	p-FDR
DMN (MPFC)	SensoriMotor superior	3.3	0.0015	0.045
Salience (insula right)	SensoriMotor lateral left	−3.2	0.0023	0.050
Visual medial	Visual lateral right	3.6	0.0006	0.018
	Visual lateral left	3.3	0.0018	0.025
	SensoriMotor lateral left	2.9	0.0047	0.045
	Visual occipital	2.8	0.0063	0.046
	SensoriMotor lateral right	2.7	0.0083	0.048

P-FDR, *p*-value corrected for multiple comparisons (Benjamini and Hochberg, 1995).

(T(64) = 4; p-FDR = 0.005). Following, the SAQ was considered as a continuous regressor and age as covariate (**Figure 2** and **Table 2**). A moderate positive correlation among the SAQ score and the following network seeds were found: DMN (peak seed: MPFC) and the superior SensoriMotor network (T(64) = 3.3; r = 0.38 p-FDR = 0.045); Salience network (peak seed: right insula) and the left lateral SensoriMotor network (T(64) = −3.2; r = −0.37; p-FDR = 0.05); visual medial network and left and right visual lateral network (T(64) = 3.3; r = ; p-FDR = 0.025 and T(64) = 3.6; r = 0.39; p-FDR = 0.018, respectively), left and right sensorimotor lateral network (T(64) = 2.9; r = 0.34; p-FDR = 0.045 and T(64) = 2.7; r = 0.35; p-FDR = 0.048, respectively), visual occipital network (T(64) = 2.7; r = 0.34; p-FDR = 0.046). FC analyses with F1 and F2 scores, confirm and reflect the results and the brain areas obtained with SAQ score described above.

4. Discussion

In the present study we aimed to investigate the functional brain networks involved in interoceptive awareness in a sample of healthy males and females. To measure interoceptive awareness, we used the SAQ, namely, a neuropsychological test which measures subjective interoceptive sensibility (Longarzo et al., 2015). Behaviorally, our results highlight that females have significantly higher SAQ scores as compared to males. Specifically, females obtained higher scores than males in the SAQ total score and on both SAQ sub-factors, namely, visceral and somatosensory sensations. Then, we investigated differences in brain FC between the two groups (female vs. males), by including age and SAQ scores as covariates. Finally, we analyzed whether there were correlations between FC measures and interoceptive awareness (i.e., SAQ scores). FC results showed significant correlations among SAQ score, the right insular cortex (part of the SN) and left lateral sensorimotor network, including the somatosensory cortex. We found FC sex-related differences in interoception awareness in PCC, which is part of DMN, and in the RPFC, which is part of the SN, with males' participants exhibiting higher FC.

Consistently with our results, most recent research underlined how the cingulate, together with the insula, contributes to elaborate interoceptive awareness, particularly in choosing the most appropriate response to perceive inner-body stimuli. Also, from a functional perspective, the cingulate showed sex differences in studies on emotional processes, which might be related to interoception (Mann et al., 2011). In particular, our findings seem to support the Critchley et al.'s (2001) two-processes hypothesis, which highlights how changes in self-perceiving bodily states may be seen as a function consisting of two hierarchical processes, namely, a first-order context-independent autonomic representational process, within the insular and somatosensory cortices, and a second-order context- and experience-dependent representational process, within the cingulate and ventromedial prefrontal cortices.

Kircher et al. (2000) reported that self-descriptive traits activate a network which includes the precuneus, superior parietal lobe, prefrontal cortex, and cingulate cortex. Coherently, our results showed that the prefrontal cortex and cingulate cortex have stronger FC in males. Also, Gusnard et al. (2001) attributed to the precuneus, cingulate and medial prefrontal areas the role of engaging continuous information and representation of the self when a person is awake and alert (Cavanna and Trimble, 2006). Sevinc et al. (2017) showed that the SN is implicated in the coordination of executive control and associative processes. Consistently with this evidence, our results suggest that the RPFC, the insular cortex, ACC/PCC, and orbitofrontal cortex may represent a crucial interoceptive hub for the human adults.

A positive correlation between SAQ scores and the FC of sensorimotor network and visual network bilaterally were found in our study. The sensorimotor network, also known as somatomotor or somatosensory network, is a large-scale brain network that primarily includes somatosensory (post-central gyrus) and motor (precentral gyrus) regions and extends to the supplementary motor areas (Smitha et al., 2017). Neural networks involved in interoceptive awareness may, therefore, extend beyond primary interoceptive regions, hence broadening somatosensory areas in order to include the posterior cingulate and hippocampus (Eckert et al., 2009). These brain regions, as well as the paracentral cortex, are critical for the representation of broader contextual information and sensorimotor engagement with the environment (Vogt et al., 2006; Jantzen et al., 2007). Coordinated neurocognitive processing among salience, visual and sensorimotor networks is important for maintaining interoceptive accuracy in older adults (Ueno et al., 2020). This evidence is in line with our pattern of positive correlation between SAQ scores and FC of sensorimotor and visual networks, by excluding sex differences from the analyses. A limitation of our study is the replicability since the SAQ as a neuropsychological test is not as spread in resting-state fMRI studies as other neuropsychological assessments more often used in neurocognitive imaging studies. Moreover, neuropsychological assessments tend to have small effect sizes (Owens et al., 2021).

To sum up, our results depict a complex framework, which concerns the interaction of multiple large-scale functional brain networks (i.e., the salience, somatosensory, and visual network) in generating interoceptive awareness. All these brain networks may concur to create a personal perspective of the own bodily status, with females showing a stronger attitude in self-perceiving and self-recognizing their internal body states. Conversely, males may pay less attention toward their body as an effect of their attitude to integrate more general, less fine, body states (Sun et al., 2015). Thus, according to this line of evidence, one may speculate that interoceptive awareness may involve more detailed, fine information processing, which is not globally distributed in the cortex. There are several potential applications of the study like considering different cut offs in calculating SAQ scores taking into account of sex and age (higher cut offs should be considered for women given their higher pre-disposition). Future research could consider a different scoring of questionnaires related to anxiety disorders if there was reported a prevalence of anxiety disorders in males or females (Jalnapurkar et al., 2018) with a link to interoceptive aspects (Pollatos et al., 2007). Sex differences in interoceptive awareness may, therefore, emerge as an effect of differences in FC of specific brain regions, which may exhibit different developmental trajectories. The following stage could calibrate interoception-related tools considering the sex differences and relying on their neuroimaging data. Future research may involve participants with mood disorders in order to investigate how interoception and neuroimaging are involved in the occurrence of such disorders and better characterize those neurocognitive processes.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by the IRCCS Pascale Naples Ethics Committee. The patients/participants provided their written informed consent to participate in this study.

Author contributions

GF, CC, and VA conceived the study. VA, AD, and GC acquired the behavioral and fMRI data and conducted the study. GF and VA analyzed the data. VA wrote the manuscript's first draft. GF, AD, GC, MA, MS, and CC revised the manuscript and provided the critical comments and theoretical contributions. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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Feeling of hand deformation as a monkey's hand: an experiment on a visual body with discomfort and its algebraic analysis

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While there are many studies in which body ownership can be transferred to a virtual body, there are few experimental studies of how subjects feel about their own bodies being deformed since a real body cannot be deformed. Here, we propose such an experimental setup, in which a twisted hand is diagonally viewed from behind, which is called a "monkey's hand." Although the subject cannot see the thumb hidden behind his or her arm, he or she feels that the monkey's hand has an ambiguous thumb that functionally never exists but structurally exists. This ambiguity is consistent with experimental results on proprioceptive drift, by which the deformation of the hand is measured. The ambiguity of the presence and absence of the thumb is finally analyzed with a specific algebraic structure called a lattice. This can help us understand disownership as being different from the absence of ownership.

KEYWORDS

sense of ownership, body image, body deformation, rough set, lattice

1. Introduction

The body is considered to play a positive and active role in interfacing between consciousness and the world surrounding a subject. In that sense, we can utilize the body to explore the environment. However, the body can also show the negative and passive implications, such as when it is injured or paralyzed. Since such feelings are destined to be accepted even if they are not preferable, these feelings are passive and negative. In this study, we focus on negative and passive feelings in the body.

The demand for active and positive implications for the body is also found in the study of bodily sensations. An active and positive implication is defined as a feeling that the subject can use the body to explore the environment and that this body is consistent with the subject's own healthy body. Research on bodily sensations has been broadly divided into a sense of ownership (SoO) and sense of agency (SoA) (Gallagher, 2000; Botvinick, 2004; Haggard and Eltam, 2010; Tsakiris, 2010). SoO is the feeling that the body is certainly one's own, and SoA is the feeling that the cause of the movement of the body is certainly one's own. However, SoO is not considered to be a single basic sensation but a comprehensive judgment (similar to the taste of wine) for various afferent signals (Ehrsson, 2020). In these studies, the subject may feel that his or her hand moves freely and is no longer his or her own; this research began with conventional research on alien hands (Hassan and Josephs, 2016). The question of how bodily sensations are formed is based on the two speculations that having bodily sensations has active and positive implications and that the formation of bodily sensations requires the integration of multiple sensations. These ideas have emerged as important to the intelligent body as a system that deals with the real world. The positive and active implication of the body is consistent with a healthy body that a subject can move as his or her own body. In that sense, the positive and active implication of the body is directly related to the sense of agency. Whether the virtual body can be moved or not, the subject is a healthy person who can move his or her own part of the body and that implies that the sense of ownership is also related to the positive and active implication of the body. The seminal experiment on this question is the rubber hand illusion (Botvinick and Cohen, 1998).

A rubber left-hand model is placed in front of the subject, and the subject's left hand is placed to the left of the rubber hand, occluded by a screen. The subject is instructed to gaze at the rubber hand. In this situation, the rubber hand and the subject's hand, in the same position, are simultaneously rubbed by a paintbrush. After that, the subject answers a subjective questionnaire. The subject is asked to indicate the position of his or her left hand before and after the stimulation, and the proprioceptive drift is calculated as the difference between these measurements. While this drift is frequently considered to be correlated with the sense of ownership, it has also been reported that subjective ratings and drift are dissociated (Rohde et al., 2011). It was concluded that the sense of ownership of the hand results from the integration of visual and tactile sensations. This has been verified in accordance with the principle of unity in space (Stein and Stanford, 2008).

The results of the asynchronous condition were examined in more detail, and it was reported that the sense of ownership decreased significantly when the time lag between the visual and tactile sensations exceeded 300 ms (Shimada et al., 2014) and was almost lost when it reached 500–1,000 ms. Spatial deviations also have tolerances that give subjects a sense of ownership (Tsakiris and Haggard, 2005), and such deviations have been reported to exist both horizontally and vertically (Lloyd, 2007; Kalckert and Ehrsson, 2014a). In addition, the direction of the brush is the same (Gentile et al., 2013), the position of the rubber hand is in a position that is not unreasonable for rotation (Ide, 2013), and there are congruent orientations and identical types of tactile sensation (Ward et al., 2015). It has also been experimentally clarified that such factors are conditions for acquiring a sense of ownership. There is also an allowable range of sense of ownership related to the deformation of the hand itself.

It has been found from various experiments that the important point is not the material, such as wood or metal, but the outer shape (Kalckert and Ehrsson, 2014a,b). Hand deformation can be dealt with in various ways by using VR with a head-mounted display (HMD). Stretched arms in VR are known to result in feelings of ownership that exceed spatial tolerance, which is interpreted as the brain being plastic enough to cope with slow arm stretching (Kilteni et al., 2012). It has been experimentally found that it is possible to acquire a sense of ownership of an invisible hand (Guterstam et al., 2013). In this case, a movement that traces the contour of the outer shape of the hand is needed, and it should not deviate from the permissible range regarding the outer shape.

In addition, experiments with a rubber hand can be extended to the whole body; subjects can feel a sense of ownership of a mannequin and a virtual body in VR, and a sense of ownership can also be obtained for an entire body that is a transparent human (Slater et al., 2010; Preston et al., 2015). It is thought that the sense of ownership is acquired not only through the integration of the visual sense and tactile sense but also through the integration of the tactile sense and proprioceptive sense or the integration of the visual sense and kinesthetic sense (Ehrsson, 2020).

Electrophysiological studies in macaque monkeys reveal the presence of single neurons in the prefrontal cortex and parietal cortex, especially in the cortex that lines the premotor cortex and intracranial groove, in response to all visual, tactile, and proprioceptive sensations (Graziano et al., 2004). Macaque monkeys are considered candidates for the integration of multisensory stimuli. In humans, studies using fMRI have found regions in the frontal and parietal lobes that respond to both visual and tactile stimuli. The hypothesis that the acquisition of physical ownership is due to the integration of multisensory stimuli is further supported (Makin et al., 2007; Gentile et al., 2013).

The above findings regarding the sense of ownership of the hand reveal the following. First, there is an acceptable range in the conditions for acquiring a sense of ownership. Second, when all or multiple parts, such as tactile, visual, proprioceptive, and kinesthetic sensations, are integrated, it is easy to obtain a sense of ownership even for things that are not an actual physical body. Third, even for deformations of objects such as hands realized in VR, humans will become accustomed to these deformations as long as sufficient time is taken for the deformations. The above three points indicate that the sense of ownership is flexible, and physical sensations can be transferred to other things, although there are restrictions.

The notion of an embodied mind (Clark, 1998; Varela et al., 2017) reveals that the body acts as an interface between logical intelligence and the real world since the body can realize what is called morphological computing (Pfeifer and Bongard, 2007). When the rubber skin of a robot's hand can contribute to grasping an egg without breaking the egg, one can say that the body as the skin morphologically, rather than logically, computes the degree of power needed to grasp the egg, that is, morphological computing plays an essential role in embodied intelligence.

The neurocognitive model of body ownership (Tsakiris, 2010; Ehrsson, 2020) is consistent with the notion of the embodied mind. They are both based on optimization in a world consisting of repeated experiences (i.e., a stationary world). Discomfort deviating from the experienced world is excluded from that framework. In the sense of optimization, constructed body ownership has active and positive implications. On the other hand, discomfort with body image must sometimes be accepted for one's own body, that is, there are negative and passive implications of body ownership. Discomfort does not imply a lack of body ownership. While body ownership is reduced for incongruent rubber hands (Ehrsson, 2020), that situation never reveals discomfort. In contrast, if the subject's own real hand is incongruent, there is discomfort and disownership notwithstanding the presence of the sense of agency (Nishiyama et al., 2015) that is not a lack of body ownership (de Vignemont, 2011).

People with autism spectrum disorder (ASD) often consider themselves abstract. They have a weak sense of the body. A hug machine that tightens the body on the left and right is known to be effective in giving a sense of security to people with ASD, but this may be because the physical inconvenience of an immobile body makes it possible to feel the existence of the body for the first time (Minoura et al., 2019, 2020b).

Discomfort contributes to both body ownership and disownership. Since there is discomfort if a subject's own hand is movable but incongruent, this can lead to disownership accompanied by a sense of agency (Nishiyama et al., 2015). If the rubber hand is replaced by the experimenter's real hand in the rubber hand illusion paradigm, a subject can experience a movable but uncontrollable hand with discomfort, which leads to body ownership with discomfort (Minoura et al., 2020a). These experiments are set up by using a real hand. In these studies, subjects feel disownership, in the sense that the body ownership carried by the subject's own body is totally different from body ownership in everyday life and/or that body ownership is maintained notwithstanding real hand discomfort. In addition, there are reports of paralyzed bodies and bodies with disabilities that clearly indicate the existence of the body due to their discomfort (Giummarra et al., 2012). This is also true for the real body.

In contrast, body discontinuity in VR space leads to the situation that a subject does not experience body ownership despite experiencing a sense of agency (Tieri et al., 2015). A lack of experience of ownership does not imply the experience of loss of ownership. In this sense, this is not disownership. The extreme case of body ownership accompanied by discomfort is the phantom limb case (Nikolajsen and Christensen, 2015). Synchronous touching of the ear and a paralyzed arm can lead to much more body ownership in paralyzed bodies (Pazzaglia et al., 2019). This implies the recovery of body ownership accompanied by discomfort. This case also involves the real body. It is very difficult to detect discomfort that is not in a real body but in a virtual body.

Our key idea is the significance of discomfort (i.e., passive and negative implications). In fake bodies such as rubber hands or VR hands, body ownership never involves discomfort. If a subject feels discomfort, he or she cannot acquire body ownership of a fake body. Otherwise, he or she can acquire body ownership. In that scheme, discomfort and body ownership never coexist. In contrast, a subject's own hand that is movable but incongruent (Nishiyama et al., 2015), real hand illusions (Minoura et al., 2020a), and body ownership of paralyzed bodies (Pazzaglia et al., 2019) involve discomfort, whether body ownership is acquired or not. Strictly speaking, a subject feels not loss of ownership but disownership in his or her own hand if it is movable but incongruent (Nishiyama et al., 2015). Since disownership is neither ownership nor loss of ownership, it is a feeling of a body with a kind of discomfort. Because that feeling is different from ordinary body ownership, a subject frequently claims that he or she does not feel body ownership. Disownership generated in a real body is different from the loss of ownership; rather, it reflects ambiguity regarding the dualism of ownership and loss of ownership. In this study, we propose an approach to the sense of body ownership that is based on passive and negative implications, using a case in which the feeling that a part of the body is missing and deformed can be instantly induced. This will be discussed in the next section.

To evaluate body ownership with discomfort and/or ambiguity regarding the absence or presence of the thumb, we introduce a lattice derived from rough set theory that enables data analysis based on discernibility, which is taken as an equivalence relation (Pawlak, 1981, 1982; Polkowski, 2002). In rough set theory, a regularity called a decision rule is obtained for data in the form of a decision table, and the relative reduct is one of the most important regularities. Although a relative reduct cannot be obtained (Skowron and Rauszer, 1992), many algorithms have been proposed to obtain candidates for the relative reduct (Hu et al., 2000, 2008; Tan et al., 2005; Xu et al., 2007). In addition, there are many generalizations of rough sets in data analysis (Ziarko, 1993; Yao and Lin, 1996; Greco et al., 2001; Zhu, 2007). Recently, rough sets have been developed in the field of three-way decision-making (Yao, 2010, 2012, 2018).

Rough sets are applied not only to data mining but also to logic. In particular, the relationship between modal logic and rough set theory has been researched (Orlowska, 1984; Vakarelov, 1989; Järvinen, 2007a,b), and the relationship between a rough set and a lattice has been studied with a fixed point of the composition of lower and upper approximations (Yao, 2004a,b; Yao and Chen, 2006; Li et al., 2017). Independently of these studies, one of the authors found a lattice construction based on rough sets and proposed a representation theorem (Gunji and Haruna, 2010). In this study, we discuss various techniques of lattice theory (Davey and Priestley, 2002); in the preliminary section, we discuss lattices along with easily accessible citations.

2. Research objective: passive attitude

Here, we conducted an experimental study on the deformation of the hand as a pure illusion, called a "monkey's hand" in this study, without using HMD. This illusion can be achieved by simply turning the inside of the palm toward the outside of the body, extending the arm, and hiding the thumb in the shadow of one's arm while looking at the moving hand. The subject should judge whether the thumb is only hidden and is visually determined to have disappeared or deformed (Figure 1).

The monkey's hand illusion was found by one of the authors ~10 years ago, and Gunji (2013), which was published in Japanese, referred to it without experimental evaluation. Thus, the experimental study of the monkey hand illusion is first described in this study. In addition, we explain why we call this illusion the "monkey's hand illusion." Compared to those of humans, the thumbs of apes and monkeys are far from the other four fingers, which are adapted to grasp trees. Only humans have a thumb close to the other four fingers, which constitute an organ dedicated entirely to manipulation (Marzke, 1992). Although the thumbs of apes and monkeys have a structural similarity with those of humans since the thumb is one of five fingers, there is little functional similarity. From the human point of view, monkeys and apes have a thumb with respect to structure but not with respect to function. This ambiguous status of the thumb is intrinsic to the monkey's hand illusion. We feel as if the palm were extended and deformed like that of a monkey in the monkey's hand illusion, and we feel as if the thumb were (functionally) lost and (structurally) exists. That is why we call this illusion the monkey's hand illusion.

The illusion of a monkey's hand is that it is one's own hand, so it is possible to move the finger freely, and the sensation of moving the finger and the visual sense are completely synchronized.

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FIGURE 1
Various postures of the "monkey's hand."

As a result, it feels as if the thumb were lost as an element of the hand but as if the thumb exists somewhere far from the palm. Although such a feeling is somewhat confusing, the illusion seems to reflect that the hand is similar to a monkey's hand, where the monkey's thumb is both present (since it is structurally similar to the human thumb) and absent (since it is not functionally similar to the human thumb; Figure 1). This illusion of the body does not indicate the freedom to transfer the sense of possession to an unknown deformed object but conversely has the negative implication that the thumb disappears and the palm deforms slightly.

Although it is difficult to accept that the subject's own hand is deformed to the monkey's hand, the deformation can be accepted along with strange and negative feelings. However, the effect of the illusion depends on the subject.

How will this finding change by creating an experimental system of approaches that give passive and negative implications to the sense of ownership? The objective of this study was to propose such a model experiment and determine the direction of the study. Since the palm illusion proposed here relies on vision, the way vision affects proprioceptive sensations is evaluated. In addition, since the active/passive approach "creates" a place/object to which the sense of ownership shifts, the possessed body or a part thereof is always treated as a dualistic evaluation of "existence/non-existence." In contrast, in this experiment, the defect of the thumb is perceived in comparison with the five-fingered hand, and the reality of the deformed hand is felt. It should be possible to handle not only the dualistic evaluation of "existence/non-existence" but also absence, such as the judgment that "it should exist but not here." Thus, whether the absence of the thumb is perceived is evaluated by a subjective questionnaire, and how it affects the illusion of the palm is discussed through a mathematical structure (lattice) (Davey and Priestley, 2002; Yao, 2004a; Gunji and Haruna, 2010).

3. Materials and methods

3.1. Participants

This experiment was conducted at Waseda University Nishi-Waseda Campus from June 11 to July 8 in 2021. The subjects were 32 healthy men and women aged 18–25 years, including 18 men and 14 women. The average age was 21.1 years. The subjects were recruited with a reward; the experiment was conducted after giving an overview in advance, and consent was obtained. The data for all 32 subjects were used as valid data for the analysis. We only experimented with the right hands (32 participants) regardless of the participant's dominant hand. We did not find any difference between the groups.

3.2. Experimental apparatus

The experimental equipment was set up as shown in Figure 2A. The equipment used in the experiment was as follows: a tripod, a plastic board, two cloths, a stopwatch (iPhone7plus), a video camera (Everio GZ-MG740, Victor), a cotton stick, a wire, a ruler, and a blue sticker. In the experiment, the experimenter sat on the left and the subject sat on the right, and the experiment was photographed from the front of the subject with a video camera.

3.3. The "monkey's hand" illusion

Here, we explain the illusion of the "monkey's hand" used in this experiment. If one twists one's left arm as shown in Figure 2B and takes a position where the thumb is hidden behind the arm and the four fingers and palm are visible, it is as if the thumb were lost. This can create the illusion that one has only four fingers. Since the hand looks like a monkey's or chimpanzee's hand (although monkeys and chimpanzees have five fingers), this hand state is named the "monkey's hand." In each experiment, the subject creates this "monkey's hand" state and performs tasks.

Although there are individual differences, many of the subjects can easily feel that "the palm has become four fingers" rather than "the thumb is hidden and invisible," as described below. Through the "monkey's hand," the absence of the thumb and the deformation of the palm can be felt while ensuring a sense of ownership. Additionally, to clarify the meaning of the absence of the thumb, the "hidden thumb hand" was used as a control experiment for the "monkey's hand." The "hidden thumb hand" was set as shown in

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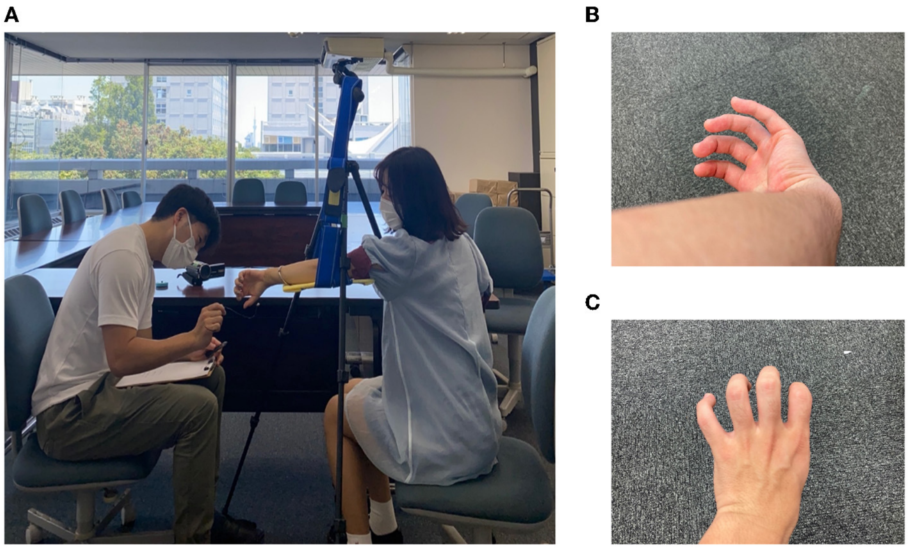

FIGURE 2
(A) Experimental setup. **(B)** Monkey's hand condition. **(C)** Hidden thumb hand condition.

Figure 2C. This is the state of the hand seen from the back side of the hand with the thumb folded inward. The "hidden thumb hand" is similar to the monkey's hand in that only the thumb is hidden, but it seems difficult to perceive the deformation of the hand here. By comparing the "monkey's hand" with the "hidden thumb hand," we experimented with differences in subjective images and the structural significance of the absence of the thumb, and we quantified the results. In addition, by comparing the "monkey's hand with open eyes" with "that with closed eyes," the drift of proprioceptive sensation was measured.

3.4. Experimental procedure

In the whole experiment, the subjects were divided into Groups A and B, and the order of the experiments was changed between Groups A and B, where the content of the experiments and tasks were the same. The way we separated the participants into Groups A and B was completely random. All the conversations were in Japanese. The time required for all the experiments was ∼40 min. The flow of the experiments is shown in Table 1, which describes the experimental procedure. For instance, in Group A, first, the subject was asked to answer the preexperimental questionnaire. Second, the subject was asked to put his or her hand in the monkey's hand position and move his or her own fingers freely and then was asked to answer the subjective questionnaire. This is the main experiment (condition). Third, the subject was asked to make the folding thumb position and move his or her own fingers freely and then was asked to answer the same subjective questionnaire as used in the main experiment. This is the control experiment (condition). Fourth, the subject was asked to perform Experiment 1, which was conducted to measure the illusion of palm extension. Experiment 1 was performed in the monkey's hand position with open eyes (main condition) and with closed eyes (control condition). After a series of performances, the subject was asked to answer the postexperiment questionnaire for the normal monkey hand position. Fifth, the subject was asked to perform Experiment 2, which was conducted to measure the illusion of

TABLE 1 Experimental flow.

Group A	Group B
Preexperiment questionnaire	Preexperiment questionnaire
↓	↓
Subjective task (main)	Subjective task (control)
↓	↓
Subjective questionnaire A	Subjective questionnaire B
↓	↓
Subjective task (control)	Subjective task (main)
↓	↓
Subjective questionnaire A	Subjective questionnaire B
↓	↓
Experiment 1 (a→ b)	Experiment 1 (b→ a)
↓	↓
Postexperiment questionnaire A (main)	Postexperiment questionnaire B (main)
↓	↓
Experiment 2 (a→ b)	Experiment 2 (b→ a)
↓	↓
Postexperiment questionnaire A (control)	Postexperiment questionnaire B (control)

Blanks in purple: experimental task; blanks in blue: questionnaire. The symbol a→ b (b→ a, respectively) represents the order of the task from a to b (from b to a, respectively) (a: monkey's hand position with open eyes; b: monkey's hand position with closed eyes).

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the hidden thumb extension. Experiment 2 was also performed in the monkey's hand position with open eyes (main condition) and with closed eyes (control condition). After a series of performances, the subject was asked to answer the postexperiment questionnaire for the reversed monkey hand position, which was different from the questionnaire used in Experiment 1. The difference between Groups A and B was simply the order of the experiments under the main condition and the control condition.

3.4.1. Preexperimental questionnaire

First, the subjects were asked to answer the preexperimental questionnaire as shown in Table 2. This questionnaire investigated the subject's attributes, such as gender, age, dominant hand, and sports history, to determine whether they were related to the experimental results. The same questionnaires were used for Group A and Group B.

TABLE 2 Contents of the "preexperiment questionnaire."

Age	__ years old
Gender	
Dominant hand	Right·Left
Longest participation in a sport	Preschool/elementary school/junior high school/high school/university/____
	Period: ___ year
	item:
Most recent sport	Period: ___ ___~___ ___ _____Years
	item:
Frequency of regular exercise	Never·less than once a week·2–4 times a week·more than 5 times a week

3.4.2. Experimental subjective questionnaire

After answering the preexperiment questionnaire, the subjects sat in a predetermined position and performed each experiment. First, the subjects were asked to perform a subjective task. In Group A, the left arm was placed on a hanging board, as shown in Figure 3A, for the main experiment to create a "monkey's hand" state. Then, the four fingers were moved freely for 20 s while looking at the hand. We aimed to establish the illusion through visual short-term memory in these 20 s (Atkinson and Shiffrin, 1968). After that, the subjects were asked to answer "Subjective Questionnaire A," as shown in Table 3.

Next, the subjects performed a control experiment, as shown in Figure 3B. With the back of the hand and four fingers visible in the "hidden thumb hand" state, the four fingers were moved freely for 20 seconds in the same way, and "subjective questionnaire A," as shown in Table 3, was answered again. Group B performed the subjective tasks of the control experiment before those of the main experiment. This is the difference between Group A and Group B. The order of the questions in "Subjective Questionnaire B" was changed from that in "Subjective Questionnaire A," but the questions themselves were the same.

Regarding Subjective Questionnaire A, Q1 is intended to examine the degree of the illusion, such as whether one's hand feels like four fingers in the state of a monkey's hand, and Q2 is intended to determine whether it feels as if the thumb is gone. Additionally, Q3, Q5, Q6, and Q7 are intended to confirm

FIGURE 3
Subjective task **(A)** in the main experiment and **(B)** in the control experiment.

whether each finger other than the thumb can be recognized as that finger independently of the other fingers. Q4 and Q8 are dummy questions used to detect an answer that does not meet the research aims. We designed the questions to test the feasibility of the experiment.

3.4.3. Experiment 1

After answering the "subjective questionnaire," Experiment 1 was performed. In this experiment, while the subject looked at the palm and four fingers in the state of the monkey's hand, as shown in Figure 4A, the experimenter touched a number written on the subject's hand with a cotton swab. Then, the subject was asked to guess what number was touched and gave the answer (Figure 4B). The number was selected at random, and it depended on the size and shape of the subject's hand. The subject responded by looking at a preprinted photograph of his or her hand with numbers written on it and comparing it with the tactile sensation when touched.

In the control experiment, the same operation as that in the monkey's hand position was performed with the subject closing his or her eyes, and the setup of the experiment was the same as that shown in Figure 4A. The aim was to estimate how the degree of illusion in terms of deformation of the palm is achieved visually. The number touched was randomly determined for each subject in advance.

TABLE 3 Contents of "subjective questionnaire A."

Q1	Because it looks like a four-fingered hand, I realize that I don't have a thumb
Q2	I feel that my thumb doesn't exist
Q3	Being able to see the middle finger has nothing to do with being able to see the other fingers
Q4	I feel that the index finger does not exist
Q5	Seeing the ring finger is sufficient to notice the existence of the ring finger
Q6	Fingers other than the visible index finger are independent of seeing the index finger
Q7	The existence of the little finger is noticed only by seeing the little finger
Q8	I can see my thumb

In Experiment 1, the deviation between the actual touched position and the position where the subject felt touched was measured. This deviation indicates the proprioceptive drift regarding the body position, especially the deformation of the palm. The main experiment and the control experiment were performed alternately 10 times each, for a total of three sets (60 times in total). However, Group A started with the main experiment, and Group B started with the control experiment. Additionally, the four fingers were moved for 7 s between sets to recreate the illusion state to clear the illusion and reset the device (this operation was similar to the subjective task under the main experiment). After Experiment 1 was completed, the subject was asked to answer Postexperiment Questionnaire A (Table 4) for the normal monkey eyes position. In Group B, after Experiment 1 was completed, the subject was asked to answer Postexperiment Questionnaire B (Table 5) for the reversed monkey hand position mentioned in the next section.

3.4.4. Experiment 2

Subsequently, Experiment 2 was performed. In this experiment, the subject touched the tip of the thumb of the left hand with the index finger of the right hand while looking at the palm and

TABLE 4 Contents of "postexperiment questionnaire A (main)."

Q1	After moving my four fingers freely, I felt like my thumb wasn't there
Q2	I felt that the hand was originally a four-fingered palm, rather than a five-fingered hand with the thumb missing
Q3	I felt that the four-fingered palm was my palm
Q4	I felt that my four fingers were free to move
Q5	I felt that the arm with the palm and four fingers was newly added
Q6	I felt that my invisible thumb had moved somewhere else on my body
Q7	I felt that the skin of my four fingers had a different texture than my palms
Q8	I felt that my palm was covered with a four-fingered palm
Q9	In Experiment 1, I felt that I was touching something other than my own hands
Q10	I felt pain when I touched my hand in Experiment 1

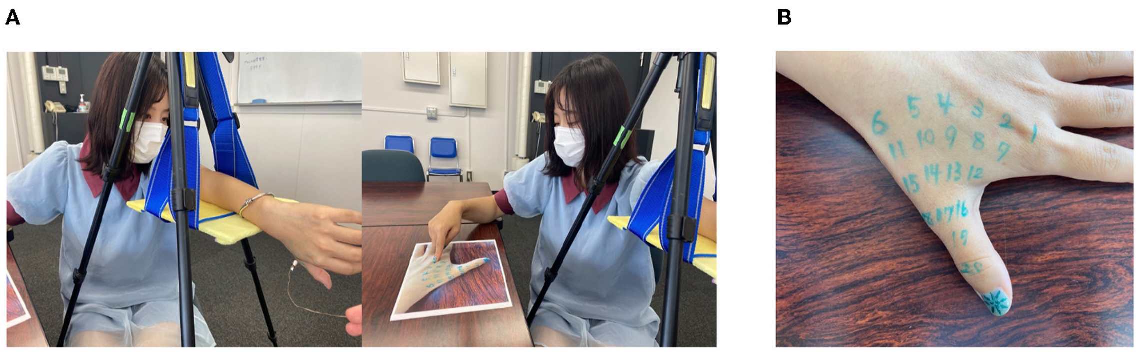

FIGURE 4
(A) Experiment 1 (main experiment). **(B)** Numbers written on the back of the hand.

four fingers in the state of the "monkey's hand" (Figure 5A). Before starting Experiment 2, we placed a small blue dot sticker on both the tip of the index finger of the right hand and the tip of the thumb of the left hand. During Experiment 2, the subject tried to use the right-hand dot sticker to touch the left-hand dot sticker. We measured the distance between the two dots.

The subject stopped his or her hand by saying "yes" at the moment when he or she thought they were touching, and the experimenter measured the distance between the tip of the index finger of the right hand and the tip of the thumb of the left hand. In the control experiment, the subject performed the same operation with eyes closed to determine the sense of body ownership (SoO) without the visual sense. However, in the control experiment, the starting position was with the index finger of the right hand placed on the third joint of the middle finger of the left hand (Figure 5B).

TABLE 5 Questionnaire content of "postexperiment questionnaire A (control)."

Q1	After moving my four fingers freely, I felt like my thumb wasn't there
Q2	I felt that the hand was originally a four-fingered palm, rather than a five-fingered hand with the thumb missing
Q3	I felt the four-fingered palm was my palm
Q4	I felt that my four fingers were free to move
Q5	I felt that the arm with the palm and four fingers was newly added
Q6	I felt that my invisible thumb had moved somewhere else on my body
Q7	I felt that the skin of my four fingers had a different texture than my palms
Q8	I felt that my palm was covered with a four-fingered palm

The main experiment and the control experiment were performed alternately, three times each (six times in total). However, Group A started with the main experiment, and Group B started with the control experiment.

After Experiment 2 was over, in Group A, the subjects answered Postexperiment Questionnaire B (Table 5). The subjects responded by taking a position in which all five fingers and the palm could be seen, as shown in Figure 6 below. That position is called the reversed monkey hand position. In Group B, after Experiment 2 was completed, the subject was asked to answer Postexperiment Questionnaire A (Table 4) for the normal monkey hand position.

3.5. Lattice analysis

Although the monkey's hand illusion in this manuscript is presented in the literature for the first time, our analysis is strongly connected with the property of the illusion itself. The illusion is not so simple that it can be verified whether the modified hand is the subject's own or not. While the illusion involves contradictory properties, the illusion is genuine. It feels as if the thumb exists and does not exist. An illusion with contradictory properties is normally regarded as a non-well-defined illusion that cannot be verified. However, properties that are contradictory in normal classical logic do not imply a contradiction in alternative logic. Therefore, we analyzed the logical structure of the illusion indicated in our manuscript and showed that contradictory properties can be allowed in that logic. One reviewer who stated that he or she was a mathematician said that the application of lattice theory and algebra was adequate. In fact, showing a strong connection

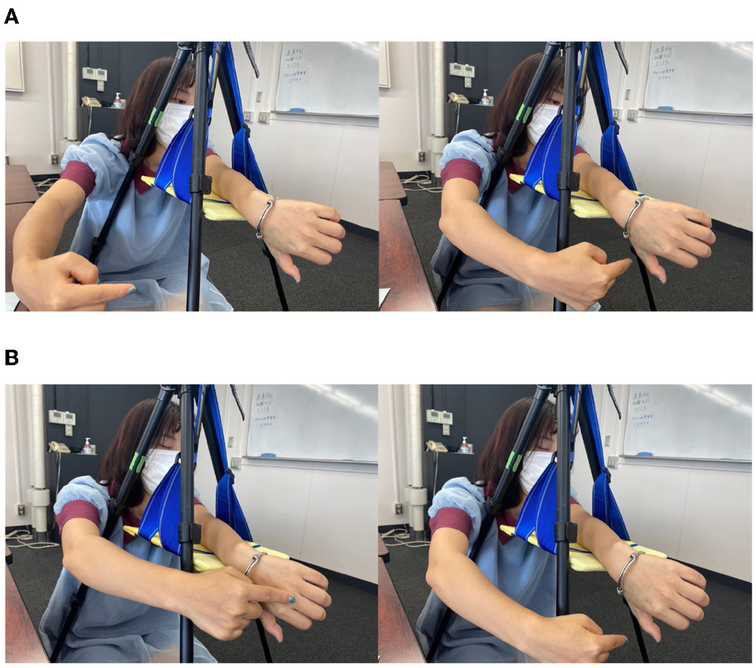

FIGURE 5
(A) Experiment 2 (main experiment). **(B)** Experiment 2 (main experiment).

FIGURE 6
Posture when responding to the postexperiment questionnaire (control).

between phenomena and analytical methods can play an essential role in neuroscience.

In this study, we analyze the logical structure of the hand by using a subjective questionnaire. Therefore, we first explain the lattice and then describe how to use it for analysis.

Before providing a detailed definition, we start with a brief short history of lattice theory. Algebraic logic was proposed by George Boole (Boole, 1847, 1854) and was completed by Birkhoff's lattice theory (Birkoff, 1940). A lattice is an ordered set that is closed with respect to specific binary operations, join and meet (Davey and Priestley, 2002). Although elements in a set have no structure, elements in an ordered set have a specific structure called an order. While there are various sets equipped with structures called groups, rings, and fields, lattices are the simplest structured set (Passman, 2011). A lattice called an orthomodular lattice was developed not only for Boolean algebra but also for quantum logic (Birkhoff and von Neumann, 1936; Greechie, 1971; Maeda, 1980; Kalmbach, 1981, 1983; Khrennikov, 2001). Since quantum mechanics is used as information science to explain decision-making and cognitive illusions (Khrennikov, 2001, 2010; Aerts, 2009; Busemeyer and Bruza, 2012; Aerts et al., 2019; Ishwarya and Cherukuri, 2020), the way quantum logic is derived in cognition has recently been studied (Gunji and Haruna, 2022; Gunji and Nakamura, 2022a,b). Lattice theory has also been developed in programming and computation to analyze programming (Scott, 1972, 1976; Nielson et al., 2005).

3.5.1. Definition of a lattice

A collection of elements that are distinct from each other is a set, but in a set, there is no relationship between the elements. In mathematics, a relationship is introduced between these elements to allow the structure to be considered. The simplest structure is an ordered set that introduces an order between elements (Davey and Priestley, 2002).

We first define an order. A subset of the direct product set is called a relation for the set S, and a relation that satisfies specific conditions is an order. The direct product of S is a set consisting of all pairs of elements of S. If $S = \{a, b\}$; then, we write the direct product of S as $S \times S = \{(a, a), (a, b), (b, a), (b, b)\}$. A relation R is any subset of the product and is called the relation R on S. For example, as one of the relations of $S \times S = \{(a, a), (a, b), (b, a), (b, b)\}$, $R = \{(a, a), (a, b), (b, a)\}$, which is a relation on $S = \{a, b\}$. If the element (a, b) is an element of the relation R, this is written as aRb. In the above example, we can write aRa, aRb, and bRa. A relation on S that satisfies conditions (1) to (3) below is called an ordered relation or simply an order. That is, for any $x, y, z \in S$,

$$xRx \tag{1}$$

$$xRy \text{ and } yRx \implies x = y \tag{2}$$

$$xRy \text{ and } yRz \implies xR \tag{3}$$

An order is often represented by $\leq$. That is, xRy is written as $x \leq y$. A set in which any elements satisfy (1) to (3) is called an ordered set.

For any two elements x, y of the ordered set P, the join of x and y is represented as $x \vee y$ and is defined by conditions (4) and (5).

$$x \leq x \vee y,\ y \leq x \vee y, \tag{4}$$

$$x \leq z \text{ and } y \leq z \implies x \vee y \leq z. \tag{5}$$

Similarly, the meet operation represented by $x \wedge y$ is defined by conditions (6) and (7).

$$x \wedge y \leq x,\ x \wedge y \leq y, \tag{6}$$

$$z \leq x \text{ and } z \leq y \implies z \leq x \wedge y. \tag{7}$$

An ordered set P in which any two elements $x, y \in P$, $x \vee y$ and $x \wedge y$ are also elements of P is called a lattice. In this case, join and meet can be considered (binary) operations similar to addition and multiplication. A lattice is an algebra in the sense that it is closed for this operation (the result of the operation is also an element of it).

Figure 7 is a diagram called a Hasse diagram that illustrates an ordered set. A Hasse diagram is used to illustrate the structure of a lattice. In the Hasse diagram, the elements are drawn in circles so that they do not overlap; if $x \leq y$, the circle representing y is drawn above the circle representing x, and those two circles are connected by a line. However, if $x \leq y$, and if there is another element z such as $x < z < y$, the circles representing x and y are not connected by a line. In Figure 7, the left Hasse diagram is not a lattice, although the right diagram is a lattice.

A lattice L is defined as a distributive lattice if and only if for any $x, y, z \in L$, $x \wedge (y \vee z) = (x \wedge y) \vee (x \wedge z)$. A lattice L is defined as a complemented lattice if and only if for $\forall x \in L$, $\exists x^c \in L$ such that $x \wedge x^c = 0$ and $x \vee x^c = 1$, where 0 and 1 represent the least and the greatest values of L, respectively. A Boolean lattice (algebra) is defined by a complemented distributive lattice (Davey and Priestley, 2002).

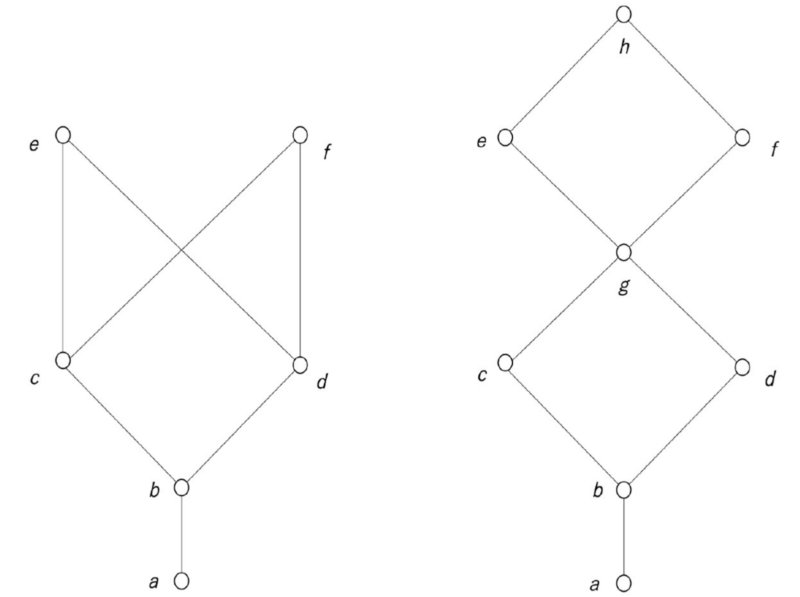

FIGURE 7
Non-lattice ordered set **(left)** and a lattice **(right)**.

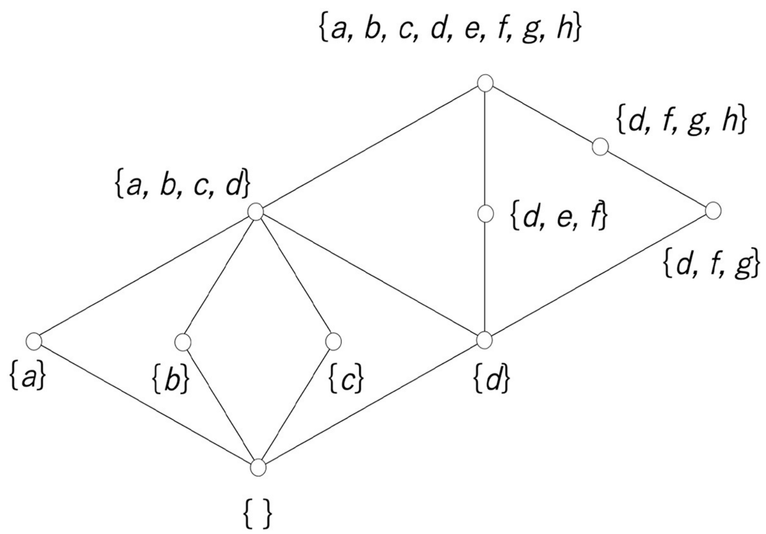

FIGURE 8
Example of a lattice whose elements are sets.

3.5.2. A lattice whose elements are sets

An element of the lattice used in the analysis of this study is a set of elements. When the elements are a set, the order relation is defined by the inclusion relation. If any element of set A is an element of set B, A is included in B, which is expressed by $A \subseteq B$. This inclusion relation clearly satisfies (i) $A \subseteq A$; (ii) $A \subseteq B$ and $\subseteq A \Longrightarrow A = B$; and (iii) $A \subseteq B$ and $B \subseteq C \Longrightarrow A \subseteq C$, which correspond to conditions (1) to (3). The join and meet operations, $A \vee B$ and $A \wedge B$, are also defined, and they satisfy conditions (4) to (7). Figure 8 shows an example of a lattice whose elements are sets. The symbol {} with no elements indicates the empty set.

3.5.3. Rough set lattice

When applying a rough set to a lattice, we use a map, kernel, and equivalence relation. Therefore, we first define these notions. A set is defined as a collection of elements that are distinct from each other. There is no structure other than discernibility. Given a pair of sets, a map is defined from one set, called the domain, to the other, called the codomain, such that for any element of the former set, there is a unique element in the latter set.

Suppose that the sets S and M and a map from S to , φ, are given. Here, if S is interpreted as the set of real phenomena and M as the set of representations that are the result of cognition, the

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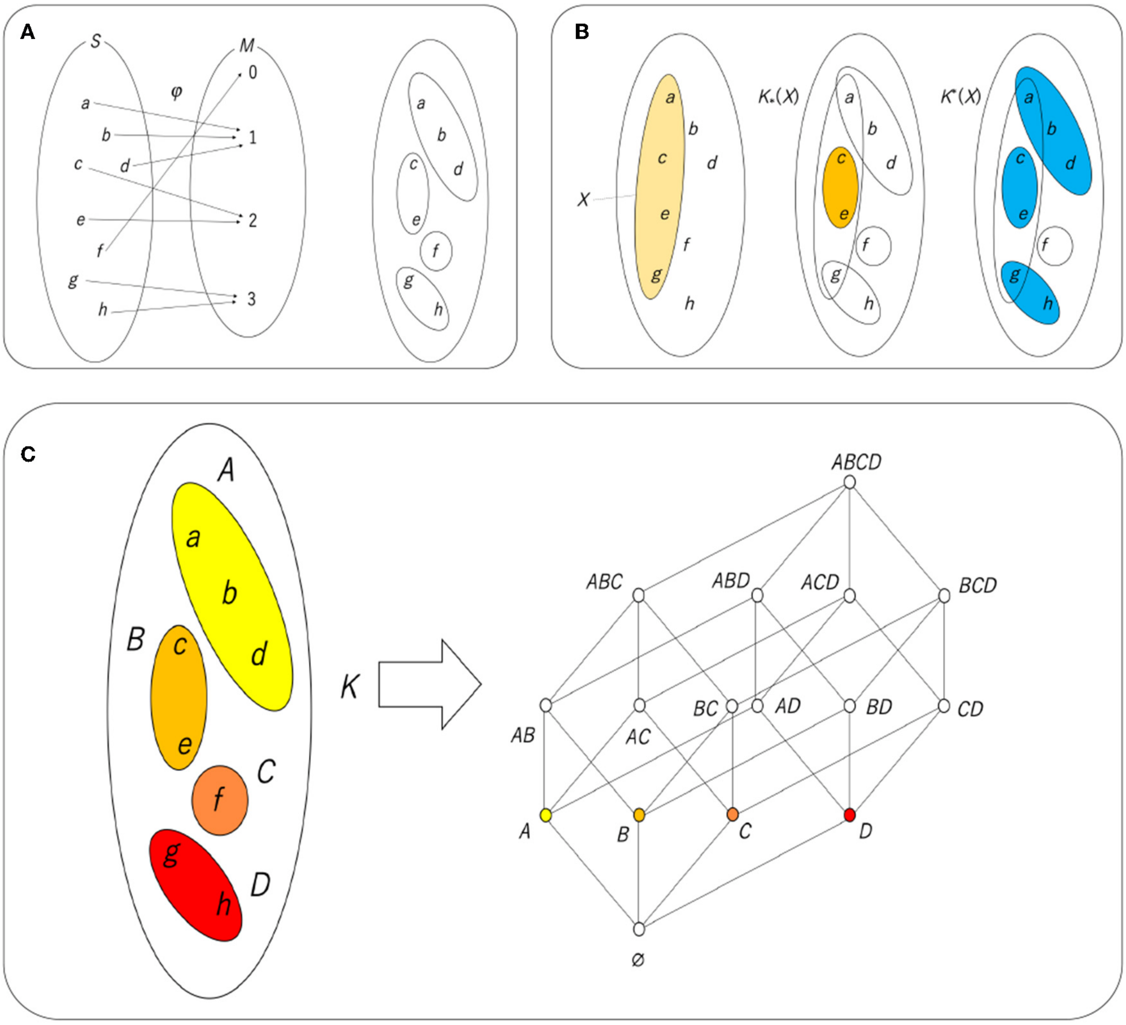

FIGURE 9
(A) Cognitive process φ and the equivalence class derived from it. **(B)** X (left), $K_*(X)$ (center), and $K^*(X)$. **(C)** Hasse diagram of a lattice resulting from $K^*(K_*(X)) = X$. An equivalence class with a certain color corresponds to an atom with the same color. Note that *AB* in the Hasse diagram is an abbreviation of $A \cup B$.

mapping φ is cognition. Let us assume that this cognitive process is defined as shown in Figure 9. Figure 9A shows that a, b, and d, which are distinct phenomena, are perceived as the same value, 1. To summarize all the cognitive situations, $\varphi(a) = \varphi(b) = \varphi(d)$, $\varphi(c) = \varphi(e)$, $\varphi(f)$, $\varphi(g) = \varphi(h)$. This means that a, b, and d are the same with respect to φ and are called the kernel of φ in universal algebra. Strictly speaking, the kernel is defined by $\mathrm{Ker}\varphi = \{(x, y) \in S \times S | \varphi(x) = \varphi(y)\}$. The kernel can allow an equivalence relation. Given a set S, a subset of $S \times S$ is called a relation. The relation $K \subseteq S \times S$ is an equivalence relation if and only if K satisfies, for any $x, y, z \in S$, (i) xKx, (ii) $xKy \Rightarrow yKx$, and (iii) xKy and $yKz \Rightarrow xKz$. Note that xKy implies $(x, y) \in K$. It is straightforwardly verified that $\mathrm{Ker}\varphi$ is an equivalence relation, and it is replaced by K here.

A mapping defines a destination for all the elements of a set of domains and is not allowed if there are multiple destinations for an element. Therefore, by mapping, the set of domains is divided into subsets that are disjoint (no overlap). Each of these divided groups is called an equivalence class (Figure 9A). Given an equivalence relation K, an equivalence class is defined by $[x]_K = \{y \in S | xKy\}$. In using this notation, $[a]_K = \{a, b, d\}$. The division using the obtained equivalence class as a unit can be said to be a set that is coarse-grained with respect to the set of original phenomena. In that sense, a set whose unit is this equivalence class is called a rough set. Fuzzy sets and fuzzy logic are known from the perspective of coarse-grained sets and the logic derived from them, but fuzzy sets aim for coarse-grained continuous quantities, and for that purpose, it is necessary to arbitrarily define the membership function. On the other hand, a rough set can derive all approximations from one map, and the method used in the phase structure can be used as it is (Pawlak, 1981, 1982; Polkowski, 2002). Therefore, in recent years, rough sets have been widely used in the field of soft computing instead of fuzzy sets.

The method used in the topological structure is "approximation." Similar to considering a set of interior points or the closure of a set, it is possible to define lower and upper approximations for equivalence relations and perform approximate calculations. Figure 9B shows an example of lower approximation and upper approximation by the equivalence relation K obtained in Figure 9A. Here, X is given as a subset of the set S. If the recognizing agent can directly recognize all the elements of X, then X will be recognized as X. However, here, the agent can only recognize the equivalence class of K and can only recognize a subset of S as a combination of equivalence classes. In other words, X is approximated as a combination of equivalence classes. There are two types of approximation. The first is a lower approximation, represented as $K_*(X)$, which is a collection of elements in equivalence classes of K contained in X. The second is the upper approximation, represented as $K^*(X)$, which is a collection of equivalence classes of K having non-empty intersections with X. They are formally defined by the following equations:

$$K_* (X) = \{x \in S|\ [x]_K \subseteq X\}, \tag{8}$$

$$K^* (X) = \{x \in S|\ [x]_K \cap X \neq \varnothing\}. \tag{9}$$

In Figure 9B, $K_* (X)$, which is a union of the equivalence classes included in X, is represented by $\{c, e\}$, and $K^* (X)$, which is a union of the equivalence classes that have non-empty intersections with X, is represented by the union of $\{a, b, d\}$, $\{c, e\}$, and $\{g, h\}$, that is, $\{a, b, c, d, e, g, h\}$. By definition, $K_* (X)$ is contained in X and X is contained in $K^* (X)$, so $K_* (X)$ is a sufficient condition for X, and $K^* (X)$ is a necessary condition for X. In that sense,

$$K_* \left(K^* (X)\right) = X \tag{10}$$

implies a necessary and sufficient condition for X. It is easy to see that any combination of equivalence classes can satisfy Equation (10), as shown in Figure 9C. This ordered set is a lattice since the meet of two elements is expressed as the intersection of the two elements and the join is expressed as the union; this is a Boolean lattice or Boolean algebra.

There are two cognitive processes, namely visual and tactile, and it is thought that the way each phenomenon is received is different. Potatoes and pebbles look the same visually, but the difference can be determined by touching them. On the other hand, frog skin and the surface of jelly feel the same, but the difference is immediately visible. Since the cognition and perception of the phenomena differ depending on the sensory mode, it is concluded that the division of a world with such phenomena as elements differs depending on the sensory mode. Figure 10A illustrates this situation. It is assumed that the two divisions placed on the left and right are the divisions obtained from two different cognitive processes. Here, for convenience, let us assume that the left side is divided by sight (equivalence relation K) and the right is divided by tactile sensations (equivalence relation T). A relation I can be defined from these two divisions. In Figure 10A, the central 3×4 matrix takes four equivalence classes of visual sensation in the vertical direction and three equivalence classes of tactile sensation in the horizontal direction. If an equivalence class of K is represented by x and an equivalence class of T is represented by y, then xIy (presence of a relation; blue cell) is defined by common elements that exist in both x and y, and the absence of a relation (blank cell) is defined by no element existing in both x and y. For

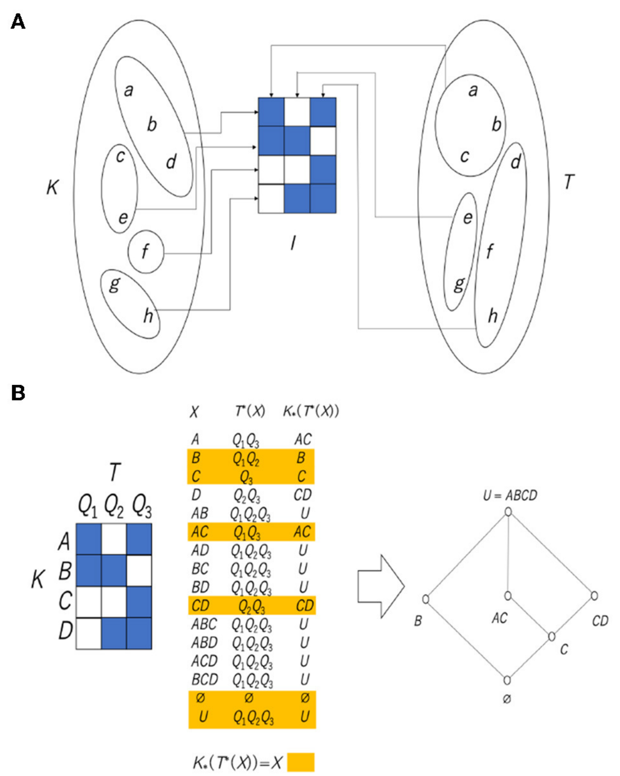

FIGURE 10
(A) Relation obtained from two types of cognition. **(B)** Rough set lattice derived from the relationship between two types of equivalence classes. Note that *AC* in the central table and the Hasse diagram is an abbreviation of $A \cup C$.

example, since a cell at (1, 2) indicates a pair of a visual equivalence class $\{c, e\}$ and a tactile equivalence class $\{a, b, c\}$, there exists a common element, c, and this cell is colored blue.

In the case of one equivalence relation, the necessary and sufficient condition is given by $K_* (K^* (X)) = X$, but in the case of two equivalence relations, one equivalence relation is used as a necessary condition. By using the other as a sufficient condition, an equation that satisfies the necessary and sufficient conditions can be obtained as follows:

$$K_* \left(T^* (X)\right) = X. \tag{11}$$

Including Equation (11), four types of necessary and sufficient conditions can be obtained, such as $T_* (K^* (X)) = X$, $K^* (T_* (X)) = X$, and $T^* (K_* (X)) = X$, and it is known that the set of all X is a lattice and they are all isomorphic (structurally the same) to each other (Gunji and Haruna, 2010). Since the set obtained through the upper approximation and the lower approximation is at most the union of the equivalence classes, the lower approximation and the upper approximation can be calculated by considering only the compositions of the equivalence classes. The relationships obtained from the two equivalence classes directly implement this.

Figure 10B shows how to construct a rough set lattice derived from Equation (11). We assume that there is a relation I between a set of equivalence classes A, B, C, D with respect to the equivalence

TABLE 6 Comparison of average values and t-tests for each question in the subjective questionnaire.

No.	Contents of question	Average value (main experiment)	Average value (control experiment)	Difference in means	p-value (two-sided t-test)
Q1	Because it looks like a four-fingered hand, I realize that I don't have a thumb	0.61	−0.45	1.06	0.006
Q2	I feel that my thumb doesn't exist	0.06	−0.84	0.90	0.027
Q3	Being able to see the middle finger has nothing to do with being able to see the other fingers	0.23	0.77	−0.55	0.071
Q4	I feel that the index finger does not exist	−2.10	−2.58	0.48	0.053
Q5	Seeing the ring finger is sufficient to notice the existence of the ring finger	0.65	1.13	−0.48	0.047
Q6	Fingers other than the visible index finger are independent of seeing the index finger	0.58	0.94	−0.35	0.152
Q7	The existence of the little finger is noticed only by seeing the little finger	1.32	1.13	0.19	0.837
Q8	I can see my thumb	−2.74	−2.45	−0.29	0.095

relation K and a set of equivalence classes Q_1, Q_2, Q_3 with respect to the equivalence relation T. The central table shows the calculation of X, $T^*(X)$ and $K_*(T^*(X))$. After that, we collect the X satisfying $K_*(T^*(X)) = X$ (highlighted in the table in Figure 10B), and we can obtain a rough set lattice, as shown in the right Hasse diagram in Figure 10B.

3.5.4. Analysis in this study

In this study, we consider representations and objects as two types of equivalence classes, obtain a relationship between them using the results of subjective questionnaires, and obtain a rough set induction lattice from them. We evaluate the algebraic structure from the structure of the lattice.

4. Results

4.1. Subjective task

From the preexperimental questionnaire, regarding factors such as gender, age, dominant hand, and sports history, no significant differences were found.

The results of the questionnaire after performing the subjective task are shown in Table 6 and Figure 11. In Q1 and Q2, the difference in the subjective intensity of the main experiment with respect to the control experiment is larger than that of the other questions. The subjects could feel as though the thumb had disappeared, and the illusion of a four-fingered hand was induced when the monkey's hand was held. Additionally, when viewed individually, the main experiment had stronger results than the control experiment in Q1. There were 17 people who had more intense feelings, 10 people with the same intensity, and five people who had less intense feelings. In Q2, the main experiment had stronger results than the control experiment. There were 18 people who had more intense feelings, seven people with the same intensity, and seven people who had less intense feelings. There were seven answers that did not fit the survey intention, but when the subjects were asked the reason for each answer, they gave responses such as "I didn't know which one was the index finger and it was like I had no index finger (main Experiment Q4)" and "Since the first part of the thumb (trapezium) was visible, it was interpreted as the thumb (control Experiment Q8)"; therefore, we did not exclude the data of these respondents.

A t-test was performed on the mean values of the experiment and the control experiment. The results are shown in the rightmost row of Table 6. Q1 has a p-value of $\approx 0.006 < 0.05$, Q2 has a p-value of $\approx 0.027 < 0.05$, Q5 has a p-value of $\fallingdotseq 0.047 < 0.05$, and it can be said that there is a significant difference between them.

4.2. Experiment 1

In Experiments 1a (main experiment; open eyes condition) and 1b (control experiment; closed eyes condition), the total deviation distance [mm] between the position that was actually touched and the position identified by the subject was normalized by dividing it by the length of the subject's nail (the length of the center of the nail). The value of Experiment 1a was 27.24, and the value of 1b was 24.18 (Figure 12A). When the significance of the difference was examined using the t-test, a p-value of $\fallingdotseq 0.023 < 0.05$ was obtained, and it was found that there was a significant difference.

From this result (Figure 12), we conclude that the deviation could be felt as larger when looking at the four-fingered hand than when the eyes were closed. Additionally, when viewed individually, 1a is more misaligned than 1b. There were 21 people with a large total value and 11 people with a small total value.

4.3. Experiment 2

In Experiments 2a (main experiment; open eyes condition) and 2b (control experiment; open eyes condition), the total distance

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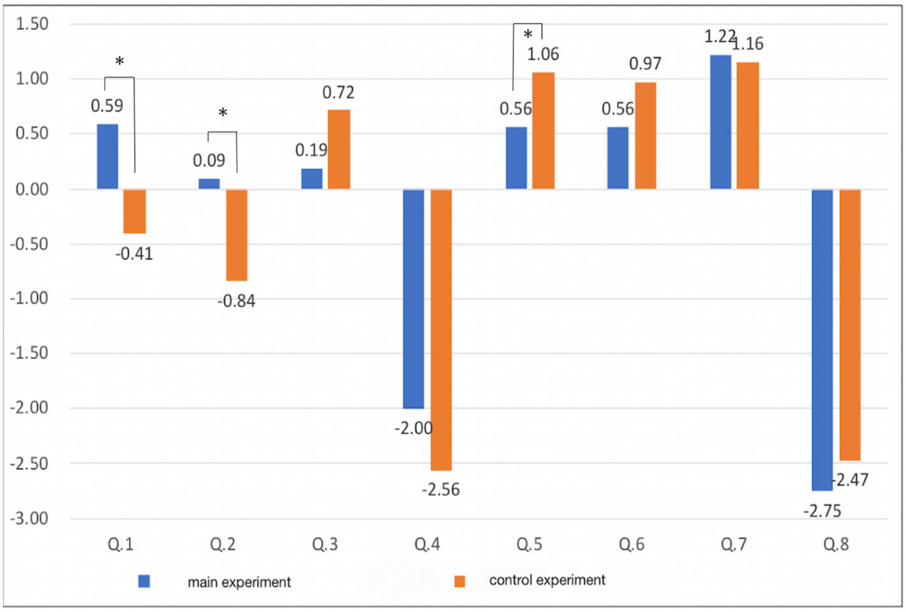

FIGURE 11
Subjective questionnaires and averages for each question. *$p < 0.05$.

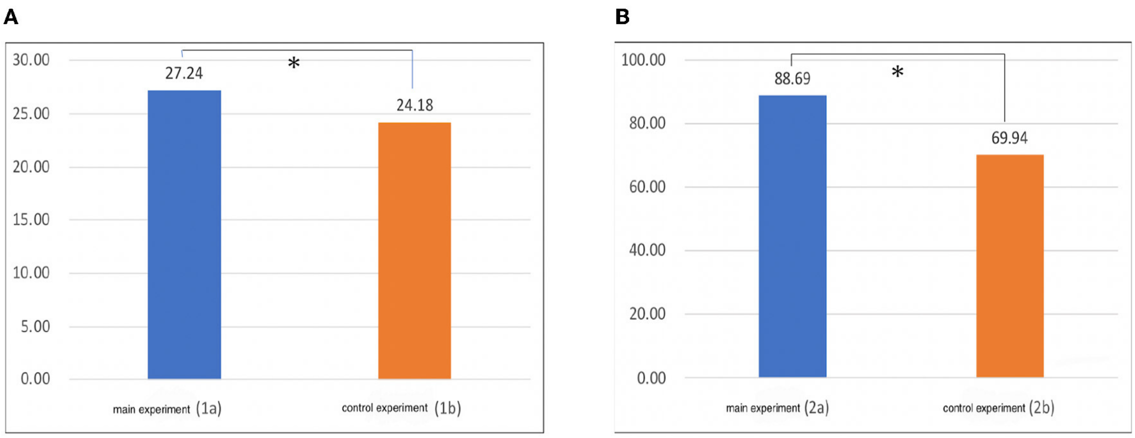

FIGURE 12
(A) Results of Experiment 1. **(B)** Results of Experiment 2. The vertical axis represents the drift (mm). *$p < 0.05$.

[mm] between the tip of the index finger of the right hand and the tip of the thumb of the left hand at the position where the subject stopped was calculated. The graph in Figure 12B shows the average value for all subjects. The value of Experiment 2a was 88.69, and the value of 2b was 69.94. When the significance of the difference was examined using the t-test, a p-value of ≒ 0.006 < 0.05 was obtained, and it was found that there was a significant difference. From this result, as in Experiment 1, the deviation was larger when looking at the four-fingered hand than when the eyes were closed. When viewed individually, 20 people had a larger total deviation than 2b in 2a, and 12 people had a smaller deviation.

4.4. Correlation between the experimental values and subjective reports

It was investigated whether there was a correlation between the intensity of the subjective illusion that the thumb was lost and the magnitude of the deviation in Experiments 1 and 2. The formula used in the correlation analysis is as follows. The correlation between Experiment 1 and the subjective questionnaire (this experiment; Q1, Q2 average) is plotted as y against x, where x = {[subjective questionnaire Q1 (main experiment)] + [subjective questionnaire Q2 (main experiment)]}/2 and y = [total value in Experiment 1a (mm)] – [total value in Experiment 1b (mm)]. The

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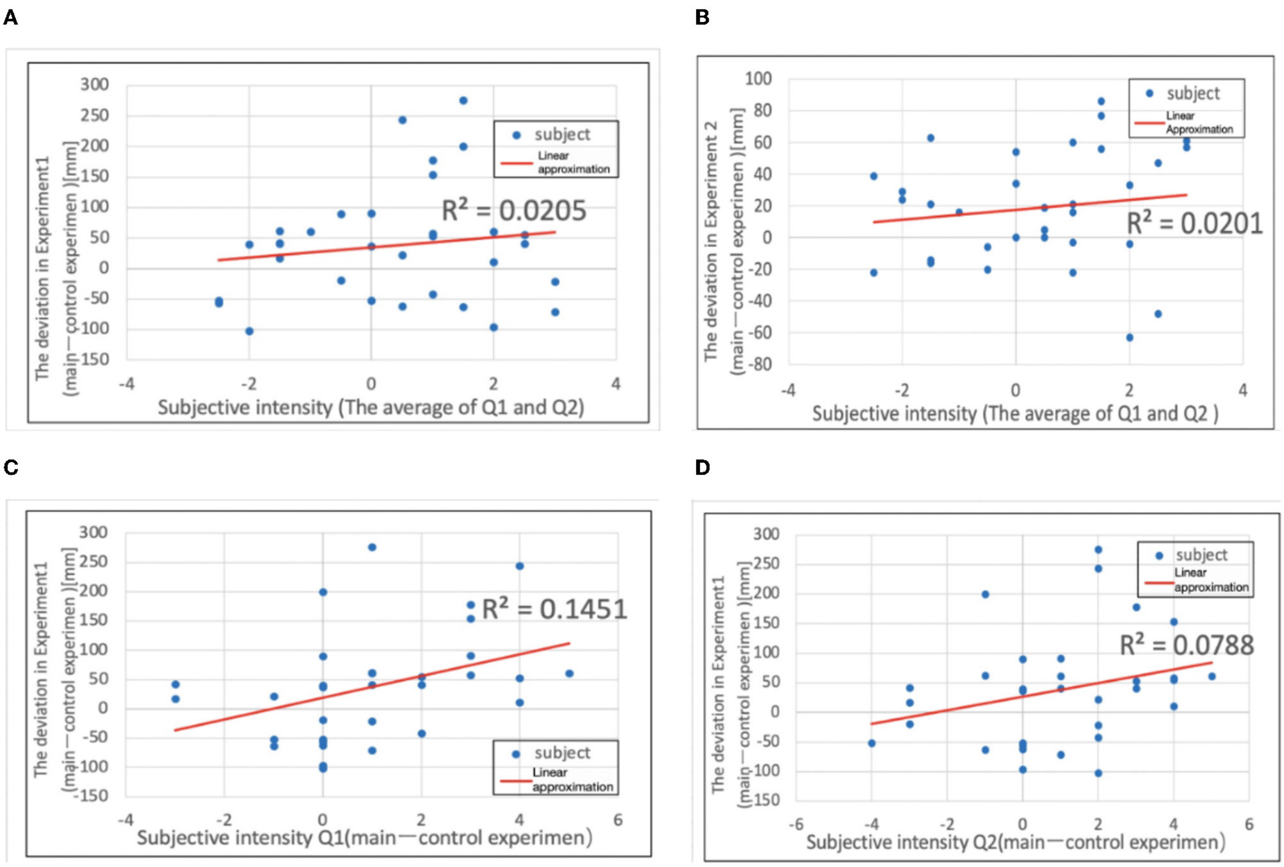

FIGURE 13
(A) Deviation in Experiment 1 plotted against subjective intensity. **(B)** Deviation in Experiment 2. **(C)** Deviation in Experiment 1 plotted against subjective intensity (Q1). **(D)** Deviation in Experiment 2 plotted against subjective intensity.

correlation between Experiment 2 and the subjective questionnaire (this experiment; Q1, Q2 average) is plotted as y against x, where x = {[subjective questionnaire Q1 (main experiment)] + [subjective questionnaire Q2 (main experiment)]}/2 and y = [total value in Experiment 2a (mm)] – [total value in Experiment 2b (mm)]. Note that Q1 is "Because it looks like a four-fingered hand, I realize that I don't have a thumb" and Q2: "I feel like my thumb doesn't exist." Figures 13A, B shows the results of the analysis using the above formula.

When the approximate curves were calculated, the slope of Experiment 1 was 8.285, and the slope of Experiment 2 was 3.129, both showing gentle positive slopes. However, from the correlation analysis, the correlation coefficient was $r \fallingdotseq 0.143$ for Experiment 1 and $r \fallingdotseq 0.142$ for Experiment 2, and there was almost no correlation. Furthermore, when the correlation with Experiment 1 was examined separately for the subjective questionnaires Q1 and Q2, a stronger correlation was obtained than before. The correlation between Experiment 1 and subjective questionnaire Q1 is plotted as y against x, where x = [subjective questionnaire Q1 (main experiment)] [subjective questionnaire Q1 (control experiment)] and y = [total value in Experiment 1a (mm)] [total value in Experiment 1b (mm)]. The correlation between Experiment 1 and subjective questionnaire Q2 is also plotted as y against x, where x = [subjective questionnaire Q2 (main experiment)] – [subjective questionnaire Q2 (control experiment)] and y = [total value in Experiment 1a (mm)] – [total value in Experiment 1b (mm)]. Figures 13C, D shows the results of the analysis using the above formula.

When the approximate curves were calculated (Figure 13), the slope of Experiment 1 was 18.57, and the slope of Experiment 2 was 11.58, both showing positive slopes. Furthermore, from the correlation analysis, Experiment 1 had $r \approx 0.381$. In Experiment 2, $r \approx 0.281$, and it was found that both had a low correlation. We investigated Experiment 2 in the same way, but there was no correlation (Experiment 2 and subjective Q1: $r = 0.118$, Experiment 2 and subjective Q2: $r = 0.184$).

4.5. Postexperiment questionnaire

Table 7 below shows the results of the postexperiment questionnaire (normal monkey hand position) conducted after Experiment 1 and the postexperiment questionnaire (reversed monkey hand position) conducted after all experiments were completed. The purpose of this experiment was to investigate how the subjects felt while performing the experimental task, but as seen from the comparison in each question, the intensity of the illusion of having four fingers was greater in the main questionnaire.

TABLE 7 Comparison of mean values and *t*-tests for each question in the postexperimental questionnaire.

No.	Contents of question	Average value (normal monkey hand)	Average value (reversed monkey hand)	Difference in means	*p*-value (two-sided *t*-test)
Q1	After moving my four fingers freely, I felt like my thumb wasn't there	0.03	−1.56	1.59	0.0003
Q2	I felt that the hand was originally a four-fingered palm, rather than a five-fingered hand with the thumb missing	−0.28	−1.84	1.56	0.0001
Q3	I felt that the four-fingered palm was my palm.	1.50	0.53	0.97	0.0393
Q4	I felt that my four fingers were free to move	2.13	1.69	0.44	0.2250
Q5	I felt that the arm with the palm and four fingers was newly added	−2.28	−2.41	0.13	0.3795
Q6	I felt that my invisible thumb had moved somewhere else on my body	−2.13	−2.38	0.25	0.3399
Q7	I felt that the skin of my four fingers had a different texture than my palms	−1.03	−1.44	0.41	0.3525
Q8	I felt that my palm was covered with a four-fingered palm	−1.97	−1.97	0.00	1.0000
Q9	In Experiment 1, I felt that I was touching something other than my own hands	−1.78			
Q10	I felt pain when I touched my hand in Experiment 1	−2.88			

However, few respondents answered "applicable" to the question asking whether there was an extremely strong illusion in Q5–Q9 (10.8% of the respondents answered "1" or higher in Q5–Q9). Q9 and Q10 can only be answered by a subject in the normal monkey hand position, so they are omitted from the questions for the reversed monkey hand position. Q1 has a p-value of $\fallingdotseq 0.0003 < 0.05$, Q2 has a p-value of $\fallingdotseq 0.001 < 0.05$, and Q5 has a p-value of $\fallingdotseq 0.0393 < 0.05$; there is a significant difference between them.

4.6. Recognition of the absence of the thumb and its corresponding lattice

Here, the results of the "monkey hand" condition and the "hidden thumb hand" condition in the subjective report questionnaire are analyzed with respect to a lattice structure, which is an algebraic structure. The structure is clarified, especially the significance of the hidden thumb.

First, let us describe how to express the relationship between an object and its representation. Here, instead of recognizing and representing the so-called "raw" object, we consider that the object is also an equivalence class that targets the "raw" phenomenon. Even when one identifies an animal as a cat, "cat" is not the name of a specific object but the name of a set consisting of various concrete individuals, such as tabby cats and black cats. This is nothing but an equivalence class, all elements of which are equivalent with respect to the character of the cat.

Here, the object is an element of the world that is recognized as an individual, and the representation is a system element that is forced to have a relationship with the other elements as a system. Additionally, the object and the representation consist of the same element, and it is assumed that the relationship between them is symmetric. The meaning of symmetry is shown in Figure 14. Here, only the hands, feet, and eyes are considered; the representation is in Chinese characters, Kanji, and the object name is written in English. There is a relationship between the object and the representation when the object to be represented exists. In that sense, if an object exists and is recognized in each representation, the relationship exists only in the diagonal components of the relation (Figure 14, upper left diagram). The corresponding rough set lattice is shown in the lower left figure of Figure 14. Note that this is also a Boolean algebra. Of course, if we try to represent a hand but it is lost in an accident, there is no relationship between the representation of the hand and the object. Such a case is possible. Figure 14, upper right diagram, shows that the eye to be represented is related not only to the eye as the object but also to the hand as the object. In this case, from the assumption of symmetry, the eyes as objects are also related to both the eyes and hands as representations. This means that the eyes and hands work together, for example, when playing table tennis, and the hands can react quickly to visual information. In the case of Figure 14, upper right diagram, the legs are isolated. Symmetry also means that relationships between different parts (equivalence classes) of representations are possible only through the object, which allows the objects to be interlocked. Therefore, the relationship between objects is realized symmetrically through the representation. The rough set lattice obtained from the relationship between the eyes and hands is shown in the lower right diagram of Figure 14. This is also a Boolean algebra.

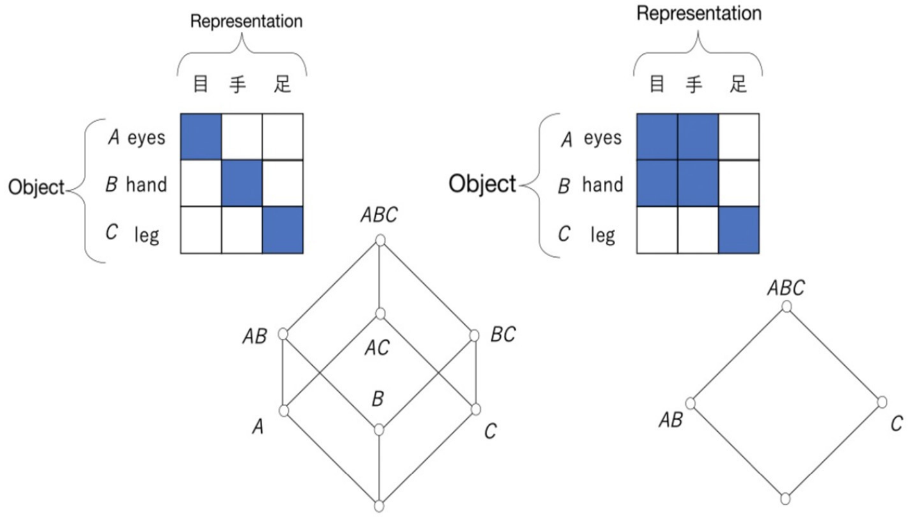

FIGURE 14
Two relations between objects and representations and their corresponding rough set lattices.

Using this relationship between objects and representations, we analyze the "monkey's hand" and "hidden thumb hand." There is a statistically significant difference between affirming and denying the question content only in Q1 and Q2 between the "monkey hand" condition and the "hidden thumb hand" condition. There is a significant difference in Q5, but both are affirmed under the two conditions, and there is no difference between affirmation and denial, that is, in the "monkey hand" state:

> Attribute 1: "Visible four-fingered hands" and "absence of a thumb" coexist;
> Attribute 2: The thumb does not exist;
> Attribute 3: Each of the four fingers other than the thumb can be recognized independently of the other fingers.

As mentioned in Sections 1 and 2, we concentrate on "discomfort" in body ownership, which leads to the feeling of the monkey hand. Since the monkey hand carries an ambiguous feeling of the presence of the thumb (in terms of structure) and absence of the thumb (in terms of function), we choose an attribute to abstract that ambiguous feeling. We prepared the subjective questionnaire to manifest this. Since Q1, "Because it looks like a four-fingered hand, I realize that I don't have a thumb" is positive and significantly different from the result of the control experiment, we can choose Attribute 1. Since Q2, "I feel that my thumb doesn't exist," is positive and significantly different from the result of the control experiment, we can choose Attribute 2. Finally, the results for questions Q3, 5, 6, and 7 are positive, and they lead to the independence of the four fingers, that is, Attribute 3.

In Attribute 1, the condition "absence of a thumb" implies not simply that the thumb does not exist but that there is a feeling of not having a thumb that should exist. This implies that the non-existent thumb can be recognized as an illusion and that the illusion can be related to the other fingers. In contrast, Attribute 2 simply implies that the thumb as represented in the brain does not exist as an object and that an object that should be in the hand is not represented in the brain. The diagram in the upper right inner square in Figure 15 shows Attributes 1–3 as relations between objects and representations. The blank cell (i.e., no relation) in the relation at (Thumb, Thumb) simply implies Attribute 2. The blue cells (i.e., presence of a relation) in the relation at (Index finger, Thumb), (Middle finger, Thumb), (Ring finger, Thumb), and (Little finger, Thumb) and the blank cell at (Thumb, Thumb) imply a coexisting relation between the index, middle, ring, and little finger and the absence of the thumb, which implies Attribute 2. The assumption of a symmetry relation is expressed as the blue cells at (Thumb, Index finger), (Thumb, Middle finger), (Thumb, Ring finger), and (Thumb, Little finger, Thumb), and the blank cell at (Thumb, Thumb). Attribute 3 is expressed as the blue cells that are found only at the diagonal cells for the fingers other than the thumb. This implies that the fingers other than the thumb exist without a relation to other fingers (i.e., they are recognized independently of the other fingers).

On the other hand, Attributes 1 and 2 are denied under the "hidden thumb hand" condition. Since "visible four-fingered hands" and "absence of a thumb" are denied, one obtains the following:

> Not ("visible four-fingered hand" and "absence of a thumb")
> = (Not "visible four-fingered hand") or (not "absence of a thumb")
> = "I cannot see my four-fingered hand" or "I have a thumb."

The statement "*A* or *B*" implies "only *A* is established, only *B* is established, or both *A* and *B* are established." Therefore, denial of Attribute 1 in the "monkey's hand" condition is divided into three attributes in the "hidden thumb hand" condition, such as Attributes 1′-1, 1′-2, and 1′-3. Other attributes corresponding to Attributes 2 and 3 in the "monkey's hand" condition are expressed as Attributes

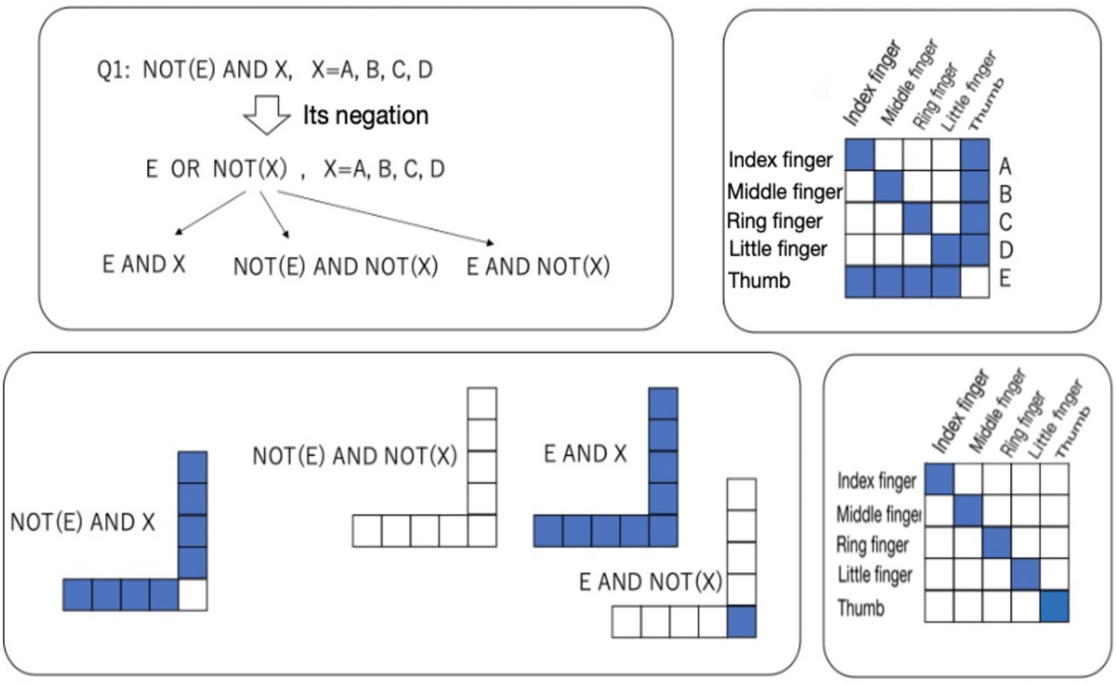

FIGURE 15
Affirmation and negation of Q1 **(upper left)** and their relations **(lower left)**; a relation between representations and objects satisfying Attributes 1 to 3 **(upper right)**; and a relation satisfying Attributes 1′-3, 2′, and 3′ **(lower right)**.

2′ and 3′ in the "hidden thumb hand" condition. Under the "hidden thumb hand" condition, the following attributes are obtained:

Attribute 1′-1: "I cannot see the four-fingered hand" + "I do not have a thumb"
Attribute 1′-2: "I can see the hands of four fingers" + "There is a thumb"
Attribute 1′-3: "I cannot see the four-fingered hand" + "There is a thumb"
Attribute 2′: There is a thumb.
Attribute 3′: Each of the four fingers other than the thumb can be recognized independently of the other fingers (the recognition of each finger is independent).

The negation of Attribute 1 leading to Attributes 1′-1 to 1′-3 mentioned above is shown as a diagram in the upper left inner square in Figure 15. The relations representing Attributes 1′-1 to 1′-3 are shown as the diagrams in the lower left inner square in Figure 15, where E and X represent Attribute 1′-2, NOT(E) and NOT(X) represent Attribute 1′-1, and E and NOT(X) represent Attribute 1′-3 under the "hidden thumb hand" condition. The relationship between objects and the representation corresponding to each attribute is expressed as a relation in the lower left inner square in Figure 15. In contrast to the relation in the "monkey's hand" condition, the "normal hand" in which all fingers including the thumb are recognized independently is given as a diagonal relation in the lower right inner square in Figure 15.

From the above, considering all the attributes, the object–representation relation and the rough set lattice, as shown in Figure 16, can be obtained in the "monkey's hand" and "hidden thumb hand" conditions. The relation at the left end of Figure 16 represents Attributes 1 to 3 under the "monkey hand" condition, and the Hasse diagram below it shows the rough set lattice obtained from that relation. The three conditions on the right are a combination of Attributes 1′-1 to 1′-3 and Attribute 3′, but Attribute 2′ is not added, and they are recognized under the "hidden thumb hand" condition. All of them have different numbers of elements, but the number of equivalence classes, which is the basic unit of recognition, is different from 4 and 5, and they all cover all combinations of equivalence classes. This implies that any phenomenon of fingers is reducible to a single finger. On the other hand, in the lattice of the "monkey hand" condition, the four fingers other than the thumb form a Boolean algebra, and the thumb that is supposed to exist is "absent."

One can check the rough set lattice corresponding to NOT(E) AND X in Figure 16 as follows. In calculating $K_*(T^*(X)) = X$, we assume that the equivalence classes of T and K are assigned with the same symbols and the same order, such as A (little finger), B (ring finger), C (middle finger), D (index finger), and E (thumb), and that the union of equivalence classes is represented by removing the union symbol, for example, representing $A \cup B$ as AB. If $X = A$, then $K_*(T^*(A)) = K_*(AE) = A$. This implies that A is an element of a rough set lattice. It is easy to see that any other fingers, including the thumb, can be an element of a rough set lattice since $K_*(T^*(D)) = K_*(DE) = D$ and $K_*(T^*(E)) = K_*(ABCD) = E$. It is also easy to check that any other combination of fingers except the thumb can be an element of a rough set lattice since $K_*(T^*(AB)) = K_*(ABE) =$

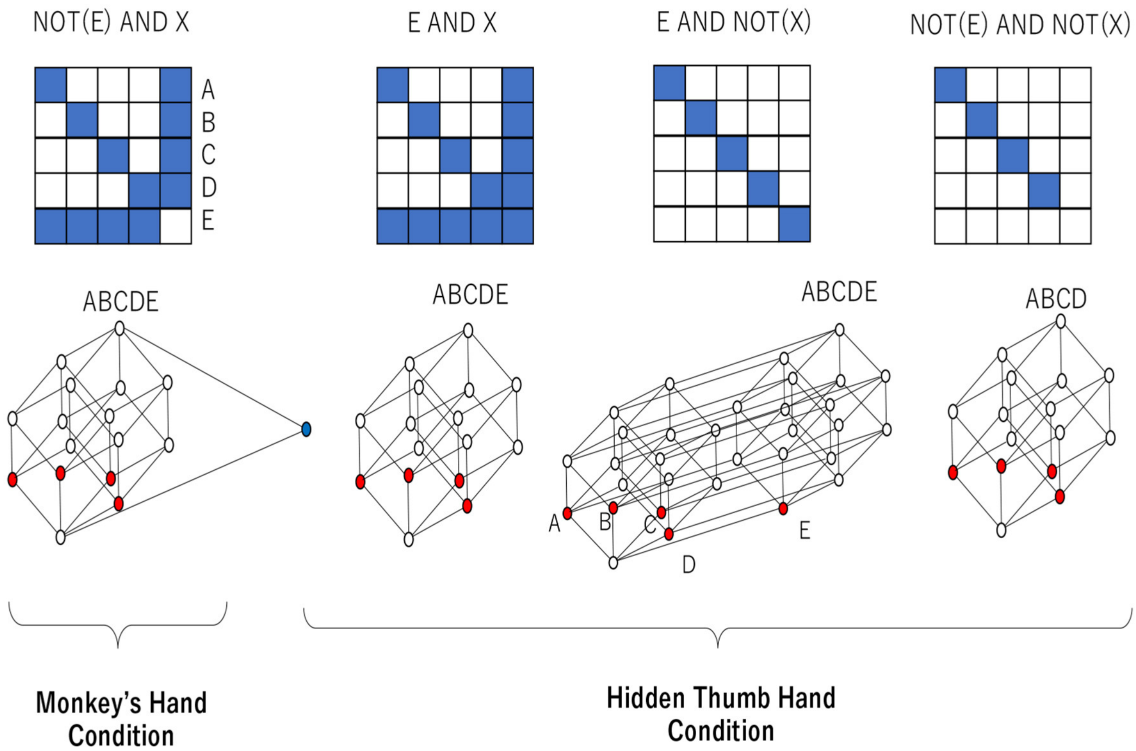

FIGURE 16
Representation/object relations and corresponding lattices in the "monkey's hand" and "hidden thumb hand" conditions.

AB and $K_*(T^*(ACD)) = K_*(ACDE) = ACD$. However, the combination of equivalence classes containing the thumb (E) is not an element of a rough set lattice since $K_*(T^*(AE)) = K_*(ABCDE) = ABCDE$ and therefore $K_*(T^*(AE)) \neq AE$. Finally, one can obtain a set of all elements of the rough set lattice as $\{\emptyset, A, B, C, D, E, AB, AC, AD, BC, BD, CD, ABC, ABD, ACD,\}$ $\{BCD, ABCDE\}$. In contrast, the rough set lattice corresponding to E AND X in Figure 16 never contains the thumb (E) as an element since $K_*(T^*(E)) = K_*(ABCDE) = ABCDE$. In the Hasse diagram, elements of a lattice are linked to other elements by a line, which implies an inclusion relation.

In the Hasse diagram corresponding to NOT(E) AND X, all fingers except the thumb are represented by red circles. This implies that the little, index, middle, and ring fingers are recognized as basic units of recognition (i.e., atoms) and are recognized independently. The elements above the atoms are linked to the atoms, which shows that any combination of atoms can be recognized. On the other hand, the thumb is represented by a blue circle, which intersects only the least and the greatest elements of the lattice. There is no element between the least element and the thumb (blue circle), which implies that the thumb is also a basic unit of recognition. There is no element between the greatest element and the thumb (blue circle), which implies that the thumb cannot form combinations with any other finger. Thus, the lattice structure shows that the thumb is isolated from the other fingers. If the thumb is recognized as a real object, it can entail any component of any other finger, and vice versa. Therefore, if there is no possibility of combinations with the thumb, this implies that the thumb is recognized as an illusion. This implies that the thumb virtually exists but does not truly exist. This is an intrinsic property of the monkey's hand condition, showing the ambiguity of absence and presence.

In the Hasse diagram corresponding to E AND X, all fingers except the thumb are represented by red circles and are recognized as basic units of recognition. They are recognized independently, and any combination is possible. Although the thumb is not recognized independently, it is recognized that the thumb is contained in the set of all fingers. Thus, in this situation, the thumb is simply forgotten. In the Hasse diagram corresponding to E AND NOT(X), all fingers, including the thumb, are represented by red circles and are recognized as basic units of recognition. This is the same as the normal situation in which any finger can be recognized independently. In the Hasse diagram corresponding to NOT(E) AND NOT(X), all fingers except the thumb are represented by red circles and are recognized independently. It is clear that the thumb (E) is not contained in the set of all fingers. This implies that the thumb is recognized as lost.

Through a rough set lattice analysis of the subjective questionnaires, we obtain the essential difference between the "monkey's hand" condition and the "hidden thumb hand" condition. Under the hidden thumb hand condition, regardless of whether the thumb is recognized, any event can be recognized as a combination of basic units of recognition (i.e., atoms). In contrast, the thumb in the monkey's hand condition has a special status in which the thumb can be recognized but cannot be combined with any other fingers. This implies that the thumb is not lost and is recognized but is recognized as an illusion. What does one consider such an illusionary thumb? As a real object, it is recognized that four fingers without the thumb can constitute a whole hand and that the absence of the thumb does not imply that the thumb is something that should exist. In other words, the absence of the thumb is not recognized as a case of a missing thumb. This specific status of the thumb implies that the monkey's hand is naturally recognized as whole, with no parts missing. The monkey hand is passively accepted as a naturally deformed hand.

5. Discussion

In our monkey's hand experiment, the subjects sometimes felt discomfort. The results of Experiments 1 and 2 show that the palm of the subject's hand is expanded outward, which leads to the thumb being far from the other four fingers. This results in discomfort in the subject's thumb, since the thumb is located in a peculiar position, as if the hand were a monkey's hand. Therefore, the subjects feel as if the thumb is functionally lost and structurally present. This leads to the ambiguous feeling that the thumb is lost and present somewhere. Such ambiguity in body ownership reflects a lattice structure in which the thumb exists somewhere in the whole structure but the thumb has no relation to the other four fingers.

Our estimation of drift is different from the drift measurement in the rubber hand illusion. Compared to the drift in the rubber hand illusion, which is the distance between the subject's real hand and the rubber hand, the drift in our experiment has no pair of real and fake hands because the illusion is acquired only for a subject's own real hand. In this condition, the drift in our experiment measures the deformation of the subject's own real hand. Although the control experiment also makes the subject unable to see his or her own thumb, this condition never leads to the illusion of the deformation of the palm and thereby to the illusion of the monkey's hand. It does not result in the illusion of the ambiguity of the thumb in terms of (structural) presence and (functional) absence.

First, we will discuss the results of the subjective questionnaire. As seen from result 4-1, when looking at the hand in the monkey's hand condition, it feels as if one's hand has four fingers. In other words, it is possible to feel the transformational sensation that a part of one's body is absent only by a visual illusion, while the sense of ownership (SoO) is maintained. Typical impressions of the subjects regarding the subjective questionnaire include the following: "I had a strong feeling of not pointing at four," "I felt the illusion of the monkey's hand," and "I gradually began to accept the state of having no thumb in the subjective task." It was concluded that after looking at the monkey's hand for some time, the subject felt that his or her thumb was originally absent and was not lost and that the condition was accepted as his or her own body image.

Next, we discuss proprioceptive drift as objective data. From Experiment 1, one can estimate the deformation of the surface of the palm as a whole. On the other hand, from Experiment 2, one can estimate the location of the thumb itself. While there was a possibility of thumb extension alone without deformation of the palm, the results show that the palm was expanded outward, which led to an extension of the thumb.

Experiments 1 and 2 evaluated how proprioceptive sensations are affected by the illusion. The following hypothesis was established. When looking at the "monkey's hand," the visual stimulus is predominant due to the illusion, the proprioceptive sensation is weakened, and the position recognition shift is larger. In contrast, when the eyes are closed, it is hypothesized that the deviation of position recognition decreases because the judgment is made from the proprioceptive sensation alone. Therefore, as seen from results 3-2 and 3-3, the deviation is larger when looking at the "monkey's hand" in both Experiments 1 and 2. The validity of the hypothesis was verified by the fact that there was a significant difference between this experiment and the control experiment.

Next, we discuss the correlation between subjective data and objective data. After finding that the illusion of the loss of the thumb can be obtained from the monkey's hand position, the correlation between the intensity of the illusion and the magnitude of position recognition deviation in Experiments 1 and 2 was investigated. When examining the correlation with Experiments 1 and 2 using the average of Q1 and Q2, the subjective questions that examine the presence or absence of a four-finger sensation, there was no correlation and only a gentle positive slope. However, there was a weak correlation between Experiment 1 and each of Q1 and Q2 individually. From this, it can be concluded that at least in Experiment 1, a person who strongly felt the illusion had a larger deviation in position recognition. In addition, the fact that no correlation was found for Experiment 2 may have been affected by an error when the subjects measured the distances between fingers. More accurate analysis results could be expected if measurement methods such as laser distance meters were used instead of manual measurement.

Finally, we discuss the recognition of the thumb. Through the analysis of the lattice, the thumb hidden by the "monkey's hand" state is not simply hidden, nor is the concept of the thumb itself lost; it was considered a case in which the thumb cannot be recognized but exists somewhere. Although the body image in conventional studies is limited to the dualistic values of "existence/non-existence," a third kind of value, "absence," is found in our "monkey's hand" study. The image of the monkey's hand is consistent with experimental results on proprioceptive sensation. The deformation of a hand to the monkey's hand is naturally accepted by the participant, and the deviation is large under the monkey's hand condition.

Our results clarify that the illusion of the monkey's hand involves discomfort as there is ambiguity of the presence or absence of the thumb. Previous studies have assumed that discomfort as a conflict between body image and the corresponding real body is correlated with the absence of body ownership. In contrast, we assume that the discomfort is independent of body ownership. In that sense, we predict body ownership with discomfort. However, since discomfort frequently reveals the ambiguity of body ownership and disownership, which could lead to few clear experimental results, it is very difficult to clarify this illusion. After the analysis was conducted with a lattice structure, body ownership with conflict in the form of the monkey's hand illusion was clarified.

It is also reported that patients with spinal cord injury had vivid tactile sensation in their previously numb fingers, during synchronous stroking in the classical rubber hand illusion setup.

It supports that subjective tactile sensation can reemerge during a simple multisensory stimulation paradigm, despite a long period of massive deafferentation (Leggenharger et al., 2013). Such recreation of a coherent mental representation of one's own body ownership might lead to compensation even for the complete absence of proprioceptive input by visual image (Fuentes et al., 2013).

Contradictory feeling of existence of absence thumb in our monkey hand's illusion is strongly relevant to the tactile sensation in numb fingers. These feeling and sensation result not from matching the vision with tactile sensation, but from the impossible matching, since thumbs in the monkey hand's illusion are not seen, and since the tactile sensation in numb fingers is lost. Even if still speculative, it suggests that bodily ownership could result not from the matching between different modalities but from compensation for the gap between the different modalities.

This is the first step toward clarifying body ownership with discomfort in the form of the deformation of body image. While clarifying a body illusion with discomfort requires lattice analysis, the data in the experiment were obtained from a subjective questionnaire. This is a limitation of our research. If the logical structure is obtained from objective data, our research can be developed further.

6. Conclusion

We investigated body ownership accompanied by the feeling of body deformation. Rather than a VR hand, the subject's own real hand was used for the experiment, and the body deformation led to discomfort with body ownership. Since the deformed body looks as if it were a monkey's hand, in which the thumb is far from the other four fingers, the logical status of the thumb hidden from the subject's view is ambiguous between presence and absence. Such an ambiguous feeling of body ownership is clearly seen in our lattice analysis. Most participants felt that the absence of the thumb coexisted with the other four fingers. This does not imply a simple lack of body ownership of the thumb but implies disownership of the thumb. It can be considered that the thumb does not exist in the same way as the other four fingers but exists in a specific form different from that of the other four fingers.

From the lattice analysis, it can be concluded that four fingers, namely the small, ring, middle, and index fingers, are regarded as independent fingers that can form all possible combinations. In contrast, only the thumb is separated from the other four fingers, and a pair of the thumb and other fingers cannot be imagined. This shows that the thumb is not regarded as an element of the hand but exists somewhere, and this implies the ambiguous logical status of the thumb as present and absent.

The ambiguity of the presence and absence of the thumb found in the lattice analysis is consistent with the results of Experiments 1 and 2, which show that participants felt that the palm of the hand was expanded toward the thumb and the position of the thumb was far away from the other four fingers. Thus, the illusion of the hand made it feel as if the thumb were structurally present as one element of the five fingers but functionally absent because of the small possibility of collaborating with the other four fingers. It is also shown that the stronger the illusion, the greater the deformation of the palm.

Through this research, we demonstrate the significance of discomfort accompanied by body ownership, which cannot be analyzed until the lattice structure is estimated.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving human participants were reviewed and approved by Ethics Review Committee on Research with Human Subjects, Waseda University. The patients/participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

Y-PG produced the overall design of the experiment. YR and HS conducted the experiments and analyzed the statistical tests. YR and Y-PG analyzed the experimental results in terms of the rough set lattice. YR, HS, and Y-PG wrote the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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