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Predictive role of exteroceptive and interoceptive bodily dimensions to schizotypal personality traits

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The phenomenological approach to schizophrenia emphasizes the role of bodily experiences in the onset and manifestation of positive, negative and disorganized psychotic symptoms. According to the dimensional approach to psychosis, there exists a continuum ranging from individuals with low levels of schizotypy to diagnosed schizophrenia patients, with schizotypy encompassing positive-like, negative-like, and disorganized-like symptoms of schizophrenia. Empirical evidence suggests that along this continuum, both exteroceptive (external sensory) and interoceptive (internal bodily) dimensions might be distorted. Understanding the contribution of these bodily dimensions in the manifestation of psychotic symptoms, even in schizotypy, might help target early interventions for individuals at risk of developing psychotic disorders. This study investigated the potential contribution of exteroceptive and interoceptive bodily dimensions to schizotypal personality traits, such as cognitive-perceptual traits (positive-like symptoms), interpersonal traits (negative-like symptoms), and disorganization traits (disorganized-like symptoms). Partial Least Squares Regression was used to integrate several bodily dimensions to understand their impact on schizotypy, revealing specific and non-specific contributions of exteroceptive and interoceptive dimensions to different traits. In particular, exteroceptive bodily dimensions generally predicted all schizotypal traits, with specific associations to positive-like symptoms, while interoceptive dimensions mostly predicted interpersonal-like and disorganized-like symptoms. These results suggest a difference in how exteroceptive and interoceptive bodily dimensions contribute to the three schizotypal traits. This highlights specific aspects of interoceptive and exteroceptive body representations that could serve as targets for early intervention. Particularly, interoception emerges as a potential prodromal marker, suggesting that early intervention in this area could be crucial.

Schizophrenia research has been conducted using two main approaches: cognitive and phenomenological. The former has traditionally focused on analysing mental processes and cognitive distortions central to the disorder, such as deficits in attention, memory, and executive functions. The latter emphasizes the role of bodily experience and the mind–body relationship in the onset and manifestation of psychotic symptoms. Following the phenomenological approach, it has been proposed that the core aspect of selfhood, referred to as the "minimal self", involves automatic, pre-reflective, and implicit bodily functioning. This concept also includes connecting with others at an intracorporeal level[1–3] and experiencing blurred self-other boundaries[4]. According to the continuum hypothesis of schizophrenia, these aspects of the "minimal self" are altered in early schizophrenia and schizotypal conditions[5–8]. Several studies investigating different dimensions of body representations have empirically supported this proposal[5–8].

For instance, disruptions in the representation of the *peripersonal space* have been observed in individuals with schizophrenia and high levels of schizotypy[9]. Similarly, both patients with schizophrenia[10] and individuals with high levels of schizotypy[11] exhibit impairments in the *body structural representation*[11], *body image*[12,13], *spatial tactile acuity*[14,15], and *sensorimotor functions*[16,17]. Body representations are predominantly multisensory, and recent research underscores a crucial connection between deficits in multisensory integration and self-disorders in schizophrenia[18]. For example, De Gelder et al.[19] identified impaired audiovisual integration in schizophrenia patients, while Williams et al.[20] found altered integration of tactile and proprioceptive signals in those with schizotypy. Further investigations have delved into the temporal aspects of multisensory processing, which

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is thought to be the scaffolding for perception and cognition[21]. These studies have revealed altered temporal sensitivity in schizophrenia patients and those with high scores on the Schizotypal Personality Questionnaire (SPQ)[8,11,22,23].

Recently, it has been proposed that a crucial aspect of the human minimal self is interoception and that the developmental trajectory of interoception interacts with exteroceptive minimal-self components. For example, changes in the ability to perceive and identify interoceptive signals coincide with improvements in sensorimotor and multisensory body representations[24,25]. Interoception plays a crucial role in the experience of a unified bodily self[26,27]. Notably, impaired interoceptive representations have been found to contribute to the disrupted sense of bodily self often observed in individuals along the schizophrenia spectrum[28–30]. Garfinkel et al.[31] identified three distinct aspects of interoception: interoceptive accuracy referring to the accuracy in detecting internal bodily sensations, interoceptive sensibility referring to the subjective evaluation of experiencing internal bodily sensations[32], and interoceptive awareness referring to the metacognitive awareness of one's interoceptive ability. The first two aspects have been shown to be reduced in chronic schizophrenia patients[29,30,33]; as well as in youth with psychotic-like experiences[34].

Therefore, abnormalities in both exteroceptive and interoceptive body representations play a crucial role in shaping bodily phenomenological experiences across the schizophrenia-schizotypy continuum. Building on this reasoning, we hypothesize that these abnormalities may differentially predict the symptom-like traits observed in schizotypy. In support of the continuum hypothesis of schizophrenia, schizotypy is considered a subclinical expression of schizophrenia symptoms within the general population. Schizotypal traits typically encompass three dimensions[35,36]: cognitive-perceptual traits (positive symptom-like experiences), such as unusual perceptual experiences and odd beliefs, which are analogous to the positive symptoms of schizophrenia (e.g., hallucinations and delusions); interpersonal traits (negative symptom-like experiences), such as social withdrawal and emotional flatness, which correspond to the negative symptoms of schizophrenia (e.g., social dysfunction, diminished motivation, and emotional expression); and disorganized traits (cognitive disorganization-like experiences), such as odd speech and behaviour, which align with the disorganized symptoms of schizophrenia (e.g., disruptions in thought processes and basic cognitive impairments)[37].

The present study tested the hypothesis that different schizotypal personality traits are influenced by different exteroceptive and interoceptive bodily dimensions. To this aim, we administered a behavioral battery designed to assess both exteroceptive and interoceptive body representations, as well as multisensory integration. The specific dimensions and tasks in this battery were selected based on literature concerning body representations and multisensory integration in schizotypy and schizophrenia[38]. Rather than covering every aspect of body awareness, the battery emphasizes those most relevant to the schizophrenia spectrum. The exteroceptive measures focused on body image, body schema (defined as the unconscious mental representation of the body's position, movement, and spatial relations), and abilities related to multisensory integration. The battery's design aligns with the idea that bodily experience arises from continuous interaction between internal and external sensory inputs[39], as supported by theoretical frameworks such as embodied cognition[40] and the body schema model[41].

These theories agree on the idea that exteroception, interoception, and multisensory integration work together to create a unified experience of "being in the body." Accordingly, bodily experience is inherently multifaceted, involving the coordination of sensory, motor, and cognitive systems. This integrated experience enables efficient interaction with the environment, shaping perception, cognition, and behavior. Additionally, different body representations interact with one another and often engage multisensory processes. For instance, spatial tactile acuity and body structural representation provide detailed sensory feedback that refines our understanding of body boundaries and shape, influencing both body image and sensorimotor functions[39]. At the same time, multisensory integration synthesizes information across modalities (e.g., vision, touch, proprioception), facilitating motor actions, particularly within peripersonal space—the immediate area surrounding the body. Temporal tactile acuity and multisensory temporal resolution are crucial for coordinating actions that require rapid, precise sensory-motor interactions. Finally, interoception—the perception of internal bodily states such as heartbeat, hunger, or pain—enriches bodily experience by linking external sensory perceptions to internal sensations, influencing both body image and sensorimotor functions.

To understand this complex interplay, we used Partial Least Squares Regression (PLSR), a supervised learning methodology. PLSR provides a robust approach for examining relationships between multiple predictors and outcomes, making it particularly well-suited for our multidimensional analysis. With this novel approach, we aim to identify both interoceptive and exteroceptive body dimensions that are associated with and differentially predict schizotypal traits, while accounting for interactions between these dimensions. By doing so, this study provides new insights into their specific contributions to schizotypy, advancing our understanding of their role in the risk of psychosis along the schizophrenia continuum.

Methods and materials

Participants

Sixty right-handed, healthy volunteers (36 females, mean age ± SD: 25.71 ± 5.47 years) participated in the study after providing written informed consent. Participants were recruited through an online questionnaire. No participant had a history of neurologic, general medical or psychiatric conditions based on self-reports. No participants reported a family history of psychosis. The experimental protocol was approved by the Institutional Ethics Committee at the University G. d'Annunzio, Chieti-Pescara. All methods were performed in accordance with the ethical committee guidelines and regulations. All participants were assessed for their schizotypal personality traits using the Schizotypal Personality Questionnaire[42].

Schizotypal personality questionnaire (SPQ)
The Schizotypal Personality Questionnaire[42] is a validated questionnaire based on the diagnostic criteria of the DSM-III-R for schizotypal personality disorder. It consists of 74 items that measure the three-factor construct of schizotypy: cognitive-perceptual deficit, interpersonal deficit, and disorganization[7,42]. Responses are dichotomous (yes/no), with one point assigned for each agreement with an item. The total SPQ scores ranged from 0 to 53 (mean ± SD: 22.58 ± 13.37); the cognitive-perceptual scores ranged from 0 to 26 (mean ± SD: 9.56 ± 7.46); the interpersonal scores ranged from 0 to 29 (mean ± SD: 11.3 ± 6.82); the disorganization scores ranged from 0 to 16 (mean ± SD: 4.83 ± 4.08).

Procedure
Each participant completed the entire battery, which comprised tasks and questionnaires evaluating either exteroceptive or interoceptive bodily dimensions (Table 1).

Exteroceptive bodily dimensions
Body image Body Image refers to our subjective experience of the physical structure of our body in terms of its size, shape, and physical composition[43]. This dimension was evaluated through both a task, the *Photographic Figure Rating Scale (PFRS) task,* and a questionnaire, the *Body Uneasiness Test (BUT).*

The PFRS, adapted from the study by Naor-Ziv et al.[44], was used to assess participants' body image perception and body shape dissatisfaction. From this task, we quantified the following variables: the mean Body Mass Index (BMI) reflecting each participant's actual physique (A), ideal body image (I), and perception of how others perceive their body (O). Furthermore, we calculated the discrepancies between these means and the participants' actual BMI (R), denoted as ΔAR (A-R), ΔIR (I-R), and ΔOR (O-R). These differences provided insights into the participants' levels of misperception regarding their current physique, dissatisfaction with their ideal body image, and inaccurate beliefs about how others view their bodies. See Supplementary Material for a detailed description of the task.

The Body Uneasiness Test is a questionnaire designed to assess individuals' attitudes towards their own body image. Developed by Cuzzolaro et al.[45], the BUT[46–48] consists of 34 items and a list of 37 body parts, characteristics, or functions. Participants rate each item on a scale ranging from "Never" (0) to "Always" (5), with higher scores indicating a greater level of impairment or uneasiness. The BUT calculates measures of overall severity and distress related to body uneasiness. These include the Global Severity Index (GSI), defined as BUT A score, and Positive Symptom Total (PST) defined as BUT B.

Spatial tactile acuity Spatial Tactile Acuity refers to the ability to precisely perceive the location and quality of touch[49]. This dimension was evaluated through the two-point discrimination (2PD) task, which assesses the ability of participants to identify two closely spaced points on a small area of the skin and measures the accuracy of their discrimination skills[50]. We compared two body parts chest and thigh used as targets with the neck used as reference[51]. From this task, we quantified the following variables: the correct response for the two target body parts, chest (C-che) and thigh (C-thi); the overestimation for both chest (O-che) and thigh (O-thi) calculated by the errors and overestimation of the body parts compared to the reference and similarly, the underestimation for chest (U-che) and thigh (U-thi) calculated by errors and underestimation of the body parts. See Supplementary Material for a detailed description of the task.

Dimensions	Assessment	Variables
Exteroceptive		
Body Image	PFRS—photographic figure rating scale task BUT A B—body uneasiness test (A & B)	BMI (R), A(ctual), I(deal), O(ther), ΔAR, ΔIR, ΔOR Pt. tot. A, Pt. tot. B
Spatial tactile acuity	TPD—Two-point discrimination task	C-che, O-che, U-che, U-thi, O-thi, C-thi
Body structural representation	FL—Finger localization task	HIT
Multisensory integration (MI)	MSI—Multisensory integration task	AUC-av, AUC-at, AUC-vt
Multisensory temporal resolution	SJ—Simultaneity judgments task	PSE-sj, JND-sj
Peripersonal space	PPS—PeriPersonal space task	PSE-pps
Temporal tactile acuity	TOJ-u—Temporal-order judgment task (uncrossed)	JND-toju,
Sensorimotor functions	TOJ-c—Temporal-order judgment task (crossed) LJ—laterality judgement task	JND-tojc, SC-toj MRE-lh, MRE-rh
Interoceptive		
Interoceptive accuracy	HBDT—heart beat detection task HBCT—heart beat counting task	Acc(uracy)-d Acc-c
Interoceptive sensibility	HBDT—heart beat detection task HBCT—heart beat counting task BPQ—body perception questionnaire MAIA—multidimensional assessment of interoceptive awareness	Con(fidence)-d Con-c Subscales: BOA-SUP-BOA/SUB Subscales: 1 M–8 M
Interoceptive awareness	HBDT—heart beat detection task HBCT—heart beat counting task	Aw(areness)-d Aw-c

Table 1. Tasks and questionnaires evaluating either exteroceptive or interoceptive bodily dimensions.

Body structural representation Body structural representation (BSR) refers to knowledge about the topological organization of bodies, outlining how different body parts interrelate within a spatial configuration, focusing on the spatial positioning of each body part related to others[43]. This dimension was evaluated through the Finger Localization Task[52], which requires participants to identify and differentiate stimulated fingers in three different conditions. We focused on the third condition in which participants had to identify which two fingers were simultaneously touched. We calculated the accuracy and included the score of correct responses (HIT) as a variable. See Supplementary Material for a detailed description of the task.

Multisensory integration Multisensory integration refers to the process by which inputs from two or more sensory modalities are combined by the nervous system to form a stable and coherent percept of the world[53]. This dimension was evaluated through the Multisensory Integration (MSI) task aiming at investigating the integration of visual, auditory, and tactile stimuli in participants' perception. The task focused on evaluating their response speed in relation to the presentation of these stimuli[54,55]. For each multisensory pair—audio-visual (av), audio-tactile (at) and visuo-tactile (vt)—the analysis involved calculating the area-under-the-curve (AUC) subtended by the distribution of reaction times to multisensory stimuli as compared to the distribution of reaction times to unimodal stimuli. Hence, AUC-av, AUC-at and AUC-vt represent a proxy of the magnitude of multisensory integration for audio-visual, audio-tactile and visuo-tactile stimuli, respectively[56]. See Supplementary Material for a detailed description of the task.

Multisensory temporal resolution Multisensory temporal resolution refers to the principle that optimal multisensory integration occurs when stimuli from different senses are presented closely in time, diminishing as the temporal gap increases. This principle highlights the critical role of temporal proximity in influencing the nervous system's integration of diverse sensory information[57].

This dimension was evaluated through the Simultaneity Judgment (SJ) task, which aims to measure temporal sensitivity in the integration of multisensory stimuli. Specifically, we focused on auditory and tactile stimuli (A-T). Two parameters are usually derived from this task: the point of subjective equality (PSE), providing an estimate of the interval between stimuli at which there is the highest probability of the perception of simultaneity and the 'just noticeable difference' (JND-sj), reflecting the subject's sensitivity to changes in temporal intervals between the stimuli. The JND value denotes the minimal temporal interval at which the change between the perceived temporal relation stimuli can be observed[58]. See Supplementary Material for a detailed description of the task.

Peripersonal space Peripersonal Space refers to the space surrounding the body where the integration of stimuli on the body and from the external environment is facilitated[59].

This dimension was evaluated through the Peripersonal Space (PPS) task[9,60,61], which allows evaluating the individual's boundaries of the peripersonal space by assessing the optimal temporal interval for the integration of tactile and auditory stimuli[62,63]. To this aim, a psychometric function is fitted to the RT data. The PSE of the psychometric function is taken as a proxy of the peripersonal space boundary. See Supplementary Material for a detailed description of the task.

Temporal tactile acuity Temporal tactile acuity refers to the ability to perceive and discriminate temporal aspects of tactile stimuli. It involves the capacity to detect and distinguish temporal characteristics of sensations related to touch[64]. This dimension was evaluated through the Temporal Order Judgment. In a typical Temporal-Order Judgment (TOJ) task, participants are tasked with determining the order of two tactile stimuli presented sequentially to their left and right hands. When the hands are in an "uncrossed" position (toju), participants can rely on tactile and proprioceptive cues related to their body posture, utilizing a body-centred reference frame[65]. From this task, we quantified the JND (JND-toju), as a measure of precision, and the proportion of correct responses[66]. The JND-toju represents the smallest interval at which the participants can reliably decide which sensory input of the two presented was first[67]. See Supplementary Material for a detailed description of the task.

Sensorimotor functions *Touch remapping* To perceive the location of touch in space, the brain combines information about touched skin location with information about the location of that body part in space. When the two hands are crossed, this integration is impaired, affecting the ability to judge the order of touches on both hands[66]. This crossed-hand posture creates a conflict between how tactile senses represent external space. Consequently, the same cues must be remapped using an external reference frame. This remapping process becomes necessary to accurately judge the temporal order of the tactile stimuli in the crossed-hand condition (tojc)[17].

From this task, we measured the following variables: the JND (JND-tojc), which represents the smallest interval at which participants can reliably determine which of the two presented sensory inputs came first[67] and the Sum of Confusions (SC-toj), that indicates the sum of differences in the response functions between crossed and uncrossed conditions[17]. SC-toj is a global indicator of differences, which provides an overarching measure of the divergence between the two conditions and assess increases in judgment reversals resulting from the arm-crossing manipulation[68]. See Supplementary Material for a detailed description of the task.

Laterality judgment task The laterality judgement task (LJT) is designed to assess participants' ability to mentally rotate the presented hand images and accurately judge the lateral orientation of presented hand images[69]. We calculated slopes, which reflect the efficiency of the neural mechanism underlying the mental rotation process: a smaller slope indicates higher neural efficiency in mental rotation[70]. We quantified slopes for both hands, indicated as Mental Rotation Efficiency for the left hand (MRE-lh) and the right hand (MRE-rh), illustrating the efficiency of the respective mental rotation processes[71]. See Supplementary Material for a detailed description of the task.

Interoceptive bodily dimensions

Interoceptive accuracy Interoceptive accuracy refers to the accuracy in detecting internal bodily sensations[31]. Two tasks determined cardiac interoceptive accuracy: the Heartbeat Detection task, also known as the Tapping or Tracking task[72,73], and the Heartbeat Counting task[74]. In the Heartbeat Detection task (d) participants were instructed to focus their attention on their bodily sensations and to press a button on a device each time they felt a heartbeat. To calculate the accuracy during the Heartbeat Detection task (Acc-d), the recorded R-peaks and the corresponding tapping times were compared[75–77]. The Heartbeat Counting task (c) measures cardiac interoceptive accuracy by evaluating participants' performance in silently counting their felt heartbeats during specific time intervals[31]. Following each time interval, participants were required to verbally report the count or estimated number of heartbeats they perceived. Next, the accuracy score (Acc-c) was calculated by comparing the recorded heartbeats and the counted heartbeats[78]. See Supplementary Material for a detailed description of the task.

Interoceptive sensibility Interoceptive sensibility is the subjective account of experiencing internal bodily sensations[32]. This dimension can be assessed using subjective measures that index both the individual's confidence in their interoceptive ability and their interoceptive feelings[31]. We evaluated this dimension through the score of confidence in interoceptive accuracy during the performance of the Heartbeat Detection task (Con-d) and the Heartbeat Counting task (Con-c). This confidence rating was assessed using a scale ranging from 1 to 9, with 1 indicating low confidence (total guess/no heartbeat awareness) and 9 indicating high confidence (complete perception of heartbeat). We also used two self-report questionnaires: the Body Perception Questionnaire (BPQ)[79,80] and the Multidimensional Assessment of Interoceptive Awareness (MAIA)[81]. The BPQ generally evaluates body awareness and autonomic symptoms. From the BPQ we obtained a score for each subscale: the body awareness (BOA) that consists of items related to the upper parts of the body, the supradiaphragmatic (SUP) that is involved in regulating the functions of organs situated above the diaphragm and additionally, the subdiaphragmatic/body awareness factor (BOA/SUB), includes items related to subdiaphragmatic issues. The MAIA generally evaluates multiple dimensions of interoception. From the MAIA we obtained a score for each subscale: Noticing (1 M), Not-Distracting (2 M) Not-Worrying (3 M) Attention Regulation (4 M) Emotional Awareness (5 M) Self-Regulation (6 M) Body Listening (7 M) Trusting (8 M). See Supplementary Material for a detailed description of the task and questionnaires.

Interoceptive awareness Interoceptive awareness is the metacognitive awareness of interoceptive accuracy and refers to the correspondence between objective interoceptive accuracy and subjective confidence report[31,82]. We quantified the participant's awareness by comparing the accuracy and the sensibility in both the Heartbeat Detection task (Aw-d) and the Heartbeat Counting task (Aw-c).

Statistical analysis: machine learning approach

When attempting to predict an output based on input that may be correlated with each other, the high collinearity among features, combined with the high number of features compared to the number of samples (such as subjects or tests in our case), can potentially disrupt the results, leading to unstable predictions that are sensitive to noise and susceptible to overfitting and poor generalization. Various linear and nonlinear regression and classification algorithms have been created to avoid the issue of overfitting. These methods can employ different approaches, including penalizing the fitting parameter through techniques like regularization or reducing the dimensionality of the feature space to mitigate overfitting. In this study, a linear regression analysis was conducted using a technique that involves reducing the dimensionality of the feature space, namely the partial least square regression (PLSR). PLSR has been widely demonstrated to be successful in mitigating overfitting, especially when dealing with collinearity. PLSR is based on the fundamental assumption that the observed data is produced by a system or process influenced by a limited number of latent variables that are not directly observed or measured. PLSR enables the creation of regression equations by condensing the predictors into a more concise set of uncorrelated components, which are linear combinations of the initial predictors. This approach conducts regression on these components, identifying those that capture the most pertinent information within the independent variables. This aids in predicting the dependent variable while simultaneously reducing the complexity of the regression problem by employing a smaller number of components than the original count of independent variables. PLSR can be viewed as a supervised learning method, a sort of supervised Principal Component Analysis. In contrast to PCA, which reduces the dimensionality of the feature space by analysing the eigen solutions of the covariance matrix in an unsupervised manner, PLSR is a supervised learning algorithm. PLSR achieves this by determining feature space components that maximize the covariance between the independent and dependent variables, making it another form of supervised learning algorithm. The PLSR algorithm necessitates an a priori selection of one parameter, known as a hyperparameter, i.e., the number of uncorrelated components (K) to be used for regression. Generally, to conduct hyperparameter optimization, a training set, a validation set, and a test set are required. The training set is used to train the algorithm (e.g., estimate PLSR weights), the validation set is used to optimize the hyperparameter (e.g., estimate the optimal K), and the test set is used to assess the generalization performance of the learning process. This separation of data implies a reduced sample size as part of a trade-off choice among the sets.

Furthermore, another approach that minimizes the loss of samples in the different sets while evaluating the algorithm's generalization capabilities is cross-validation (CV). In CV, the data is divided into folds, and the model is trained on all data except one-fold in an iterative manner. The out-of-sample performance (i.e., generalization) is assessed based on the remaining fold and averaged across iterations. If the number of folds equals the number of samples, which is often referred to as "leave-one-out" cross-validation, it provides a rigorous assessment of the model's generalization performance. If the hyperparameters of the model need to be optimized, the optimization process cannot be reliably determined based on a simple CV without sacrificing a generalizable estimate of model performance. CV can be adapted to simultaneously select the best set of hyperparameters and provide a generalizable error estimation through a procedure called nested CV. Starting with k folds, nested cross-validation (nCV) is performed with an outer loop of k folds and an inner loop of k – 1 folds. The outer loop estimates the generalization performance of the model (i.e., test), while the inner loop evaluates the optimal hyperparameters (i.e., validation).

In each iteration, a fold is selected as the outer set (for assessing generalization), and the remaining k – 1 sets are combined to form the corresponding outer training set. Then, each outer training set is further subdivided into j sets, and one set is iteratively chosen as the inner test set (for evaluating the optimal hyperparameters), with the j – 1 other sets forming the corresponding inner training set.

If the number of folds equals the number of samples for both loops, the procedure is referred to as leave-one-out nCV. In this study, a leave-one-out nCV was implemented to assess the PLSR generalization performance and the optimal number of components using the following variables as the dependent variables: SPQ-Cognitive-Perceptual (SPQ-CP), SPQ-Interpersonal (SPQ-I), SPQ-Disorganization (SPQ-D) and SPQ-Total (SPQ-TOT). For each of them, PLSR was used to test three models, each of which used exteroceptive, interoceptive, and intero-exteroceptive variables (BMI (R), A (actual), I (ideal), O (other), ΔAR, ΔIR, ΔOR, Pt. tot. A, Pt. tot. B, C-che, O-che, U-che, U-thi, O-thi, C-thi, HIT, AUC-av, AUC-at, AUC-vt, PSE-sj, JND-sj, PSE-pps, JND-toju, JND-tojc, SC-toj MRE-lh, MRE-rh, Acc-d, Acc-c, Con-d, Con-c, BOA, SUP, BOA/SUB, 1–8 M, Aw-d, Aw-c) as independent variables, described in Table 1, resulting in a total of 12 models. Each model was trained and tested separately.

The rationale for running the SPQ-TOT model in addition to the models examining the subscales of the SPQ is to identify common predictors shared across the subscales. While the subscale models provide more granular insights into the specific predictors for different aspects of schizotypy (e.g., cognitive/perceptual, interpersonal), the SPQ-TOT model allows us to examine broader, shared patterns that might not emerge when focusing on individual subscales. The lack of significant predictors in the SPQ-TOT model may reflect this more general nature of the measure, where the predictors that are significant in specific subscales do not consistently predict the total score.

The regression performances of the models were evaluated through correlation analyses between the predicted values and the actual values (which likely stand for some specific variable or outcome). The correlation coefficient, denoted as "r," is reported for each tested model. The degrees of freedom (DF) and the significance of the null hypothesis (p) are also reported in the analysis. These values help assess the strength and significance of the correlations between the predicted and actual values.

Furthermore, the statistical significance of the weights was assessed using a randomization procedure, which involved constructing a confidence interval for the null hypothesis of each weight being zero (iterating the same algorithm 10^6 times on random shuffled outcomes).

Results

Contribution of exteroceptive bodily dimension to schizotypal traits

To explore whether and to what extent different schizotypal personality traits are influenced to varying degrees by the exteroceptive dimensions of body representations, we ran three models, one for each of the three-factor construct of schizotypy: Cognitive-Perceptual (SPQ-CP), Interpersonal (SPQ-I) and Disorganization (SPQ-D). Furthermore, to explore the role of exteroceptive dimensions influencing the whole schizotypal construct, we also tested the total SPQ score.

The model testing the predictive impact of exteroceptive bodily dimensions on cognitive-perceptual traits of schizotypy (SPQ-CP) was significant after cross-validation. A significant positive correlation between the actual SPQ-CP and the predicted SPQ-CP was obtained ($r = 0.594$, $p < 0.001$). Dimensions that significantly contributed were: body image (BUT-A, BUT-B, ΔAR), spatial tactile acuity (C-che, C-thi, U-che, O-che, U-thi), body structural representation (HIT), multisensory temporal resolution (JND-sj) and sensorimotor functions (MRE-lh, JND-tojc, SC-toj) (see Fig. 1a).

The model testing the predictive impact of exteroceptive bodily dimensions on interpersonal traits of schizotypy (SPQ-I) was significant after cross-validation. A significant positive correlation between the actual SPQ-I and the predicted SPQ-I was obtained ($r = 0.559$, $p < 0.001$). Dimensions that significantly contributed were body image (BUT-A), spatial tactile acuity (C-che, C-thi, O-che), body structural representation (HIT), multisensory integration (AUC-at) peripersonal space (PSE-sj) and sensorimotor functions (MRE-lh) (see Fig. 1b).

The model testing the predictive impact of exteroceptive bodily dimensions on disorganization traits of schizotypy (SPQ-D) was significant after cross-validation. A significant positive correlation between the actual SPQ-D and the predicted SPQ-D was obtained ($r = 0.501$, $p < 0.001$). Dimensions that significantly contributed were body image (BUT-A), spatial tactile acuity (C-che, O-che, U-thi), body structural representation (HIT), and sensorimotor functions (MRE-lh) (see Fig. 1c).

The model testing the predictive impact of exteroceptive bodily dimensions on total schizotypy (SPQ-TOT) was significant after cross-validation. A significant positive correlation between the actual SPQ-TOT and the predicted SPQ-TOT was obtained ($r = 0.699$, $p < 0.001$). Dimensions that significantly contributed were body image (BUT-A), spatial tactile acuity (C-che, O-che), body structural representation (HIT), and sensorimotor functions (MRE-rh, MRE-lh) (see Fig. 1d).

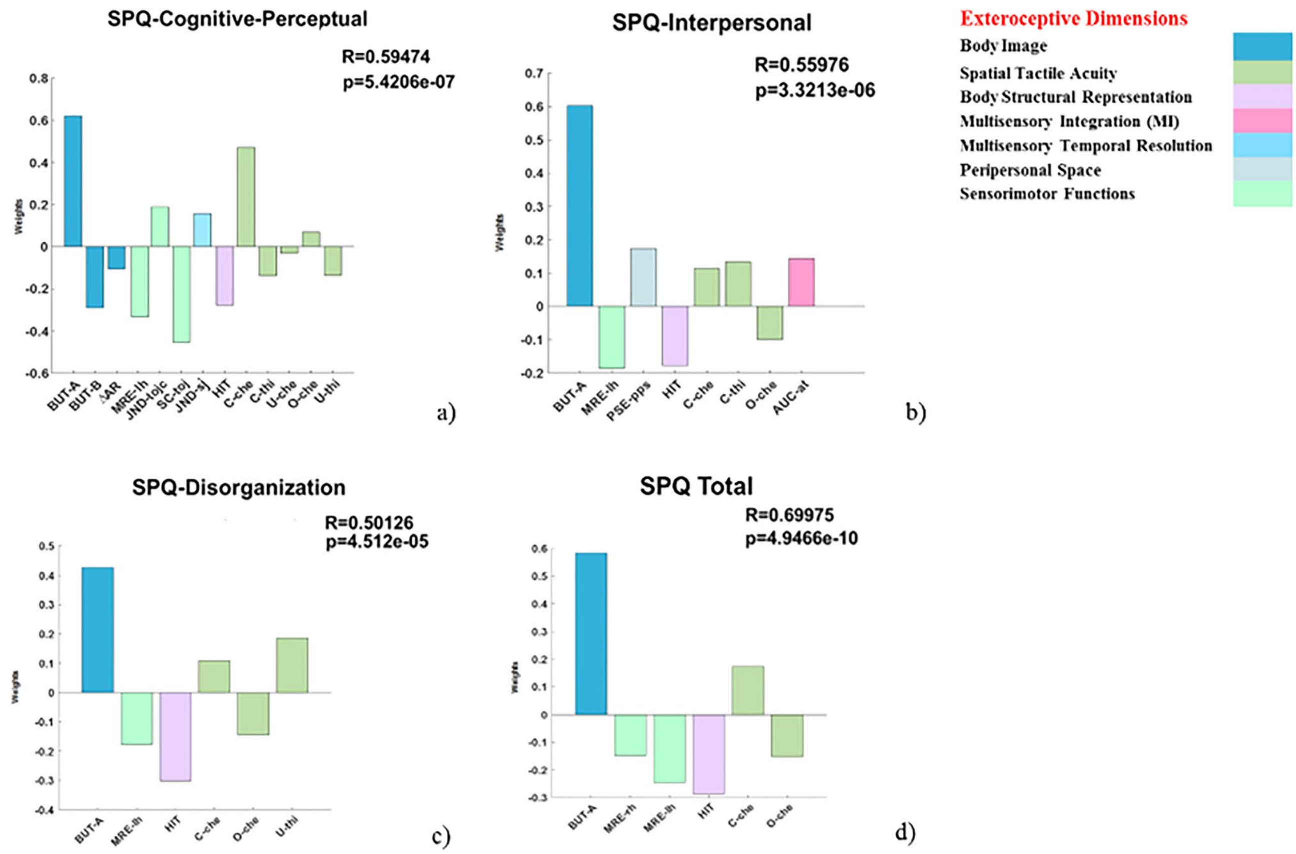

Fig. 1. Contribution of exteroceptive bodily dimensions to schizotypal traits. PLSR out-of-sample prediction of SPQ traits shows significant correlations between true and predicted values (R and p values reported). (**a**) SPQ-CP: Regression weights for exteroceptive variables (BUT A, BUT-B, MRE-lh, JND-sj, JND-tojc, SC-toj, ΔAR, HIT, C-che, C-thi, U-che, O-che, U-thi). (**b**) SPQ-I: Weights for variables (BUT A, MRE-lh, PSE-pps, HIT, C-che, C-thi, O-che, AUC-at). (**c**) SPQ-D: Weights for variables (BUT A, MRE-lh, HIT, C-che, O-che, U-thi). (**d**) SPQ TOT: Weights for variables (BUT A, MRE-rh, MRE-lh, HIT, C-che, O-che). Only weights exceeding the 95% confidence interval of the null hypothesis are reported. See Table 1 for full names of predictor variables.

Contribution of interoceptive bodily dimension to schizotypal traits

To explore whether and to what extent different schizotypal personality traits are influenced to varying degrees by the interoceptive dimensions of body representations, we ran three models one for each of the three-factor construct of schizotypy: Cognitive-Perceptual (SPQ-CP), Interpersonal (SPQ-I) and Disorganization (SPQ-D). Furthermore, to explore the role of interoceptive dimensions influencing the whole schizotypal construct, we also tested the total SPQ score.

The model testing the predictive impact of interoceptive bodily dimensions on cognitive-perceptual traits of schizotypy (SPQ-CP) was non-significant after cross-validation.

The model testing the predictive impact of interoceptive bodily dimensions on interpersonal traits of schizotypy (SPQ-I) was significant after cross-validation. A significant positive correlation between the actual SPQ-I and the predicted SPQ-I was obtained ($r = 0.388$, $p < 0.001$). Dimensions that significantly contributed were: interoceptive accuracy (Acc-c) and interoceptive sensibility (3 M, 4 M, 5 M, 8 M, BPQ-SUP, Con-d, Con-c) (see Fig. 2a).

The model testing the predictive impact of interoceptive bodily dimensions on disorganization traits of schizotypy (SPQ-D) was significant after cross-validation. A significant positive correlation between the actual SPQ-D and the predicted SPQ-D was obtained ($r = 0.488$, $p < 0.001$). The dimension that significantly contributed was interoceptive sensibility (8 M, BPQ-SUP) (see Fig. 2b).

The model testing the predictive impact of interoceptive bodily dimensions on total schizotypy (SPQ-TOT) was non-significant after cross-validation.

Contribution of both exteroceptive and interoceptive bodily dimensions to schizotypal traits

To explore whether and to what extent different schizotypal personality traits are influenced to varying degrees by both the exteroceptive and interoceptive dimensions of body representations, we ran three models one for each of the three-factor construct of schizotypy: Cognitive-Perceptual (SPQ-CP), Interpersonal (SPQ-I) and

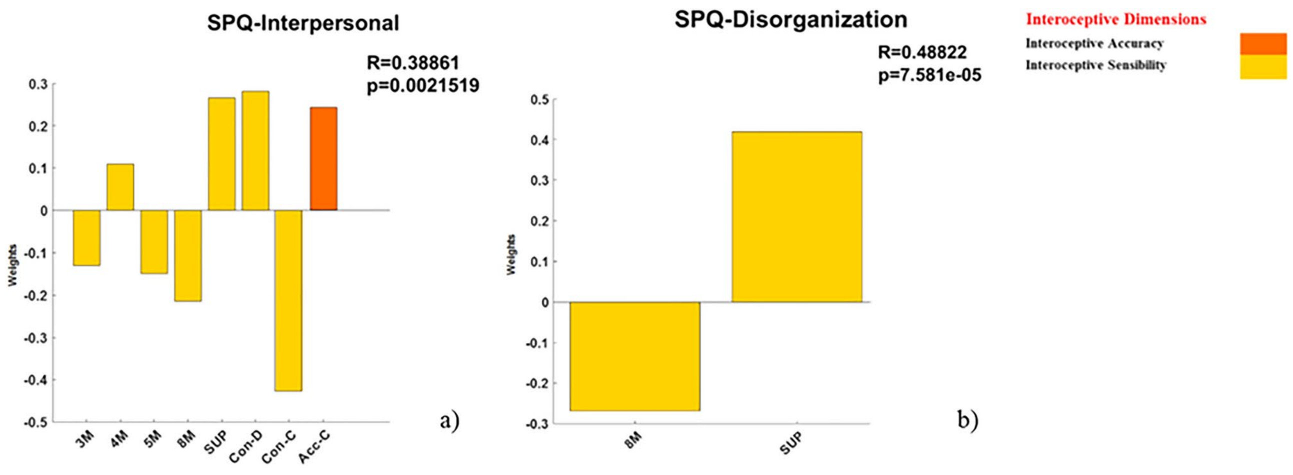

Fig. 2. Contribution of interoceptive bodily dimensions to schizotypal traits. PLSR out-of-sample prediction of SPQ traits shows significant correlations between true and predicted values (R and p values reported). (**a**) SPQ-I: Regression weights for interoceptive variables (3 M, 4 M, 5 M, 8 M, BPQ-SUP, Con-d, Acc-c, Con-c). (**b**) SPQ-D: Regression weights for interoceptive variables (8 M, BPQ-SUP). Only weights exceeding the 95% confidence interval of the null hypothesis are reported. See Table 1 for full names of predictor variables.

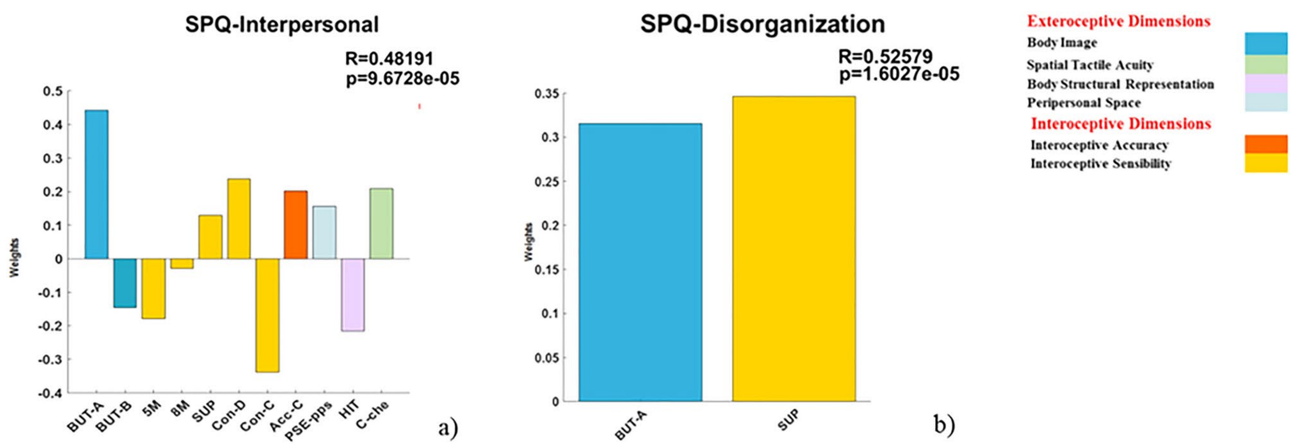

Fig. 3. Contribution of both exteroceptive and interoceptive bodily dimensions to schizotypal traits. PLSR out-of-sample prediction of SPQ traits shows significant correlations between true and predicted values (R and p values reported). (**a**) SPQ-I: Regression weights for exteroceptive and interoceptive variables (BUT A, BUT-B, 5 M, 8 M, BPQ-SUP, Con-d, Acc-d, Con-c, PSE-pps, HIT, C-che). (**b**) SPQ-D: Weights for variables (BUT A, BPQ-SUP). Only weights exceeding the 95% confidence interval of the null hypothesis are reported. See Table 1 for full names of predictor variables.

Disorganization (SPQ-D). Furthermore, to explore the role of both exteroceptive and interoceptive dimensions influencing the whole schizotypal construct, we also tested the total SPQ score.

The model testing the predictive impact of both the exteroceptive and interoceptive bodily dimensions on cognitive-perceptual traits of schizotypy (SPQ-CP) was non-significant after cross-validation.

The model testing the predictive impact of both the exteroceptive and interoceptive bodily dimensions on interpersonal traits of schizotypy (SPQ-I) was significant after cross-validation. A significant positive correlation between the actual SPQ-I and the predicted SPQ-I was obtained ($r = 0.481$, $p < 0.001$). Dimensions that significantly contributed were: body image (BUT-A, BUT-B), spatial tactile acuity (C-che), body structural representation (HIT), peripersonal space (PSE-sj), interoceptive accuracy (Acc-c) and interoceptive sensibility (5 M, 8 M, BPQ-SUP, Con-d, Con-c) (see Fig. 3a).

The model testing the predictive impact of both the exteroceptive and interoceptive bodily dimensions on disorganization traits of schizotypy (SPQ-D) was significant after cross-validation. A significant positive correlation between the actual SPQ-D and the predicted SPQ-D was obtained ($r = 0.525$, $p < 0.001$). Dimensions that significantly contributed were body image (BUT-A) and interoceptive sensibility (BPQ-SUP) (see Fig. 3b).

The model testing the predictive impact of both the exteroceptive and interoceptive bodily dimensions on total schizotypy (SPQ-TOT) was non-significant after cross-validation.

	Cognitive-perceptual	Interpersonal	Disorganization	Total SPQ
Exteroception	Body image Spatial tactile acuity Body structural representation Multisensory temporal resolution Sensorimotor functions	Body image Spatial tactile acuity Body structural representation Multisensory integration Peripersonal space Sensorimotor functions	Body image Spatial tactile acuity Body structural representation Sensorimotor functions	Body image Spatial tactile acuity Body structural representation Sensorimotor functions
Interoception		Interoceptive accuracy Interoceptive sensibility	Interoceptive sensibility	
Exteroception and interoception		Body image Spatial tactile acuity Body structural representation Peripersonal space Interoceptive accuracy Interoceptive sensibility	Body image Interoceptive sensibility	

Table 2. Specific and non-specific contributions of exteroceptive and interoceptive dimensions to different schizotypal traits.

Discussion

In this study, we investigated the potential contribution of exteroceptive and interoceptive bodily dimensions to schizotypal personality traits, such as the cognitive-perceptual trait representing positive-like symptoms of schizophrenia, the interpersonal trait representing the negative-like symptoms, and the disorganization trait representing disorganized-like symptoms. For each schizotypal personality trait, we determined the contribution of exteroceptive and interoceptive bodily dimensions separately and in combination. To this aim, we employed Partial Least Squares Regression (PLSR). This method allowed us to integrate several bodily dimensions to understand their impact on schizotypy, revealing specific and non-specific contributions of exteroceptive and interoceptive dimensions to different traits, as shown in Table 2.

These results make a novel and significant contribution to the literature. By employing a predictive, multimodal approach that simultaneously tests multiple bodily dimensions, rather than analysing them individually, we were able to account for compensatory or synergistic interactions between bodily dimensions. For the first time, this methodology allowed us to predict the specific contribution of bodily experiences to schizotypy, revealing distinct patterns of influence for each trait that had not been previously explored. Furthermore, we were able to assess the specific roles of exteroceptive and interoceptive dimensions in schizotypal traits, enhancing our understanding of their respective contributions to the risk of developing psychosis along the schizophrenia continuum.

Contributions of bodily dimensions to cognitive-perceptual traits

Our findings suggest that altered temporal sensitivity to multisensory stimuli is a specific contribution to cognitive-perceptual traits[8]. This result is supported by previous literature indicating impairments in the temporal aspects of multisensory integration among individuals with schizophrenia across various sensory domains. Previous studies show that patients with schizophrenia exhibit deficits in integrating audiovisual stimuli, highlighting the importance of multisensory integration in perceptual and cognitive processes[83]. Furthermore, research indicates that these deficits are not limited to the integration of external inputs, such as auditory and visual information from the environment, but also extend to the processing of somatosensory stimuli and their synchronization with external stimuli, that is, audio tactile stimuli[8]. Additional reports show reduced temporal sensitivity of sensory processing and increased tolerance to asynchronies in both high schizotypy[23] and schizophrenia[84], reflecting abnormal temporal dynamics of neural activity. These findings suggest that abnormalities related to the temporal aspects of multisensory integration, including lengthened simultaneity ranges for auditory stimuli in schizophrenia[85], may contribute to positive symptoms such as auditory or visual hallucinations.

Contributions of bodily dimensions to interpersonal traits

Our results show that peripersonal space is a specific predictor of interpersonal traits, representing the negative-like symptoms. These results are consistent with prior studies that provided evidence linking the extension of peripersonal space to negative symptoms but not to positive symptoms in patients with schizophrenia and in individuals with high schizotypy[86,87]. In these studies[9,86], peripersonal space was measured using a multisensory task[61] in which the peripersonal space mapping is allowed through the integration of visual or auditory and somatosensory information[88]. Consistent with this, another specific predictor of interpersonal traits is multisensory integration.

In agreement with the association between PPS extension and interoceptive accuracy shown in healthy individuals[89], we found that interoceptive dimensions that significantly predicted interpersonal traits were interoceptive accuracy and interoceptive sensibility. Few recent literatures focused on interoception in individuals with schizotypal personality traits[29] and schizophrenia[30,33] and the relationship between interoception and schizophrenia remains complex and not fully elucidated. While studies focusing on patients with schizophrenia consistently report lower interoceptive accuracy[29,30,33,90] and alterations in interoceptive sensibility[29,33] the nature of these differences and their relationship with clinical symptoms are still under debate. For instance, some studies mentioned before, suggested a potential association between interoceptive accuracy and symptom severity, with better interoceptive accuracy linked to more severe positive symptoms[30], while another, found associations with both positive and negative symptoms[33], and a third reported no significant relationship between symptoms and interoceptive measures[29]. Furthermore, a study that investigated the association between interoception and schizotypy found no significant associations[29]. However, for the first time, our results suggest a specific link between interoceptive dimensions and interpersonal traits or negative-like symptoms in schizotypy. These differences in results may regard various methodological and contextual factors, for example, the use of different SPQ questionnaire versions[29]. Additionally, the initial signs of schizophrenia typically manifest as negative symptoms[91], gradually intensifying until the onset of the first episode, followed by the emergence of positive symptoms[92]. Considering the link between interoception and the affective domains[93,94], and that negative symptoms mark the onset of the illness, it is conceivable that alterations in interoception may already be present within the subclinical population. However, this does not mean that interoceptive disruptions will not eventually affect cognitive symptoms as well. According to the somatic marker hypothesis[95,96] bodily signals, including interoceptive feedback, are crucial for both decision-making[97] and emotional regulation[98]. Disruptions in interoceptive processing may therefore contribute not only to the social and emotional difficulties observed in both schizotypy[99,100] and schizophrenia[97,101], but also to the impairments in emotion-based decision-making commonly seen in patients with schizophrenia[102].

Contributions of bodily dimensions to disorganization traits

Our results show no specific contribution for disorganization traits. According to the multidimensional model of schizophrenia, disorganization is considered a basic psychopathological dimension, together with positive and negative symptoms. While the DSM-V primarily captures disorganization in terms of language and behavior, disorganization is also linked to early onset of schizophrenia, a family history of psychosis, and low levels of insight and treatment compliance[103]. Moreover, recent studies demonstrate that in first-episode schizophrenia patients, disorganization is associated both with positive and negative symptoms[104]. However, disorganization has been less extensively studied with respect to the positive and negative dimensions, especially in the prodromal phases of schizophrenia, and thus warrants further investigation and the development of more specific tools to assess this dimension in schizotypy. The absence of specific exteroceptive and interoceptive contributions to disorganization traits in our study may reflect a limitation of the tests used, which may not fully address aspects of body representation linked to disorganization symptoms. Alternatively, disorganized symptoms may be more strongly related to other risk indices for schizophrenia, such as cognitive deficits, which can be assessed using cognitive batteries[105].

Previous studies have shown that cognitive deficits in areas like working memory, attention, and executive functioning are strongly associated with disorganized symptoms[106,107] and can predict long-term functional outcomes[106]. Our findings add to this by suggesting that exteroceptive alterations are specifically linked to cognitive-perceptual (positive-like) traits, while interoceptive alterations are associated with interpersonal (negative-like) traits in schizotypy.

This pattern indicates that bodily experiences may play a primary role in the positive and negative symptom domains, while disorganization is more closely related to cognitive functions. Consistent with this, network analyses have found that cognitive scores are distinct from positive and negative symptoms, although they are associated with disorganization[108,109]. This distinction supports the idea that, while bodily dimensions may contribute mainly to positive and negative traits, disorganized symptoms are likely to reflect underlying cognitive deficits, which could explain the lack of specific contributions to disorganization traits in our study.

Non-specific contributions to schizotypal traits

Our results show that, among the interoceptive and exteroceptive bodily dimensions we tested, non-specific contributions to schizotypal traits, that is bodily dimensions that predicted all traits of schizotypy, came only from some exteroceptive dimensions, such as body image, spatial tactile acuity, body structural representation, and sensorimotor functions. The contributions of these exteroceptive dimensions suggest that these dimensions are common across schizotypal traits. Consistent with our results on spatial tactile acuity, previous studies have detected an association between two-point discrimination thresholds and schizotypal features[15]. Moreover, other studies have found that anomalies in body image[110] and abnormal sensorimotor representations[16] are common features of schizophrenia spectrum disorders and are observable also in schizotypy, significantly before the onset of the first schizophrenia symptoms occur[111]. Our findings are also in line with the observation from several studies indicating impairments in body structural representation[12] both in patients with schizophrenia[10] and individuals with high levels of schizotypy[11]. The identified exteroceptive dimensions seem to characterize the schizotypal construct, suggesting their basic role across all schizotypal personality traits. These same dimensions are also significant predictors of the total SPQ score, further confirming their essential contribution to the overall schizotypy.

Regarding interoceptive dimensions, interoceptive sensibility was found to contribute to both interpersonal and disorganized traits, further supporting the somatic marker hypothesis by highlighting the potential role of interoceptive deficits in impairments of emotional regulation and emotion-based decision-making[40,41], which are commonly observed in patients with schizophrenia. Overall, our results support the phenomenological psychopathology and embodied neuroscience perspectives, which suggest that a core feature of the schizophrenia spectrum is abnormalities in fundamental selfhood, or 'ipseity'[112,113]. This pre-reflective sense of self is likely grounded in the body, which subtly influences cognition without explicit conceptualization[114]. The body thus provides a tacit, background sense of first-person presence, grounding the relationship between self and environment[115–117].

Limitations and future directions

Our study provides valuable insights into the relationship between interoception and schizotypy, though some limitations should be noted. To thoroughly assess interoception, we employed two distinct cardiac tasks: the heartbeat detection task and the heartbeat counting task. Although the heartbeat counting task has raised concerns regarding its validity as a measure of interoceptive accuracy (e.g.[118,119]), it remains one of the most widely used tools in interoception research, particularly in studies on schizophrenia and schizotypy (e.g.[29,30,33,90]). To enhance the robustness of our assessment, we also included the heartbeat detection task as a complementary measure, providing a more comprehensive evaluation of cardiac interoception. Nonetheless, interoception research is still in its infancy, and our reliance on these tasks reflects this developmental phase in the field.

Additionally, while our study primarily focused on cardiac interoception, we recognize that interoception encompasses a broad array of physiological signals, including those related to the gastrointestinal, respiratory, and proprioceptive systems[120]. These other domains may play an important role in understanding the full scope of interoceptive processing in schizophrenia.

Looking forward, there is significant potential for improving our understanding of interoception in both schizotypy and schizophrenia. Future research should refine cardiac interoceptive tasks and consider expanding beyond cardiac signals to include other interoceptive domains, such as respiratory signals. A more comprehensive approach to interoception could lead to a more nuanced understanding of interoceptive processing, with important implications for both clinical and non-clinical populations.

Overall, our study brings to light two key observations. Firstly, while exteroceptive dimensions contribute to all aspects of schizotypy, interoceptive dimensions only show a contribution to interpersonal and disorganized traits, commonly occurring during the prodromal phase of schizophrenia and preceding the onset of positive symptoms[120]. This association may stem from the putative role of interoception in fostering the stability of the bodily minimal self, contrasting with the ever-changing nature of exteroceptive information[27]. Consequently, early interoceptive deficits may let exteroceptive information, including those related to the body, undermine the minimal self. Secondly, our work highlights the importance of exploring the role of bodily dimensions to identifying both specific and non-specific therapeutic intervention targets. Particularly, interoception emerges as a potential prodromal marker, suggesting that early intervention aimed at enhancing interoceptive processing could be crucial for developing tailored treatments. By identifying specific deficits in interoception and exteroception, our work not only enhances our understanding of the bodily dimensions underlying schizotypal traits, but also has significant clinical implications. It opens the door to symptom-specific therapeutic approaches, such as tool-based[121] or multisensory-based[122] training to improve peripersonal space, as well as virtual reality technologies[123] designed to enhance bodily self-awareness. Additionally, specialized interoceptive training programs—such as heartbeat perception training[124,125]—could help improve interoceptive accuracy. However, further research is needed to evaluate the effectiveness of these interventions in individuals with high schizotypy and in patients with schizophrenia.

Data availability

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

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MRP: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft; MGP: Data curation, Resources, Software, Validation; PC: Formal analysis, Methodology; AK: Writing – review

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