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Body maps of sound pitch and relevant individual differences in alexithymic trait and depressive state

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Abstract
Sound perception extends beyond the boundaries of auditory sensation, encompassing an engagement with the human body. In this study, we examined the relationship between our perception of sound pitch and our bodily sensations, while also exploring the role of emotions in shaping this intriguing cross-modal correspondence. We also compared the topography of pitch-triggered body sensations between depressive and non-depressive groups, and between alexithymic, and non-alexithymic groups. Further, we examined their associations with anxiety. Our findings reveal that individuals with alexithymic trait and depressive state experience a less localized body sensations in response to sound pitch, accompanied by heightened feelings of anxiety and negative emotions. These findings suggest that diffuse bodily sensations in response to sound may be associated with heightened feelings of anxiety. Monitoring pitch-triggered body sensations could therefore serve as a potential indicator of emotional tendencies linked to disorders such as depression and alexithymia. Our study sheds light on the importance of bodily sensation in response to sounds, a phenomenon that may be mediated by interoception. This research enhances our understanding of the intricate relationship between sound, emotions, and the human body, offering insights for potential interventions in emotional disorders.

Keywords Body map, Emotion, Embodiment, Interoception, Proprioception

Background

In the interaction of our multisensory experience, where various senses harmonize to shape our perception of reality, the relationship between audition and the other bodily sensations has long enthralled researchers [1, 2]. For example, even individuals without auditory-tactile synesthesia [3] have been shown to spontaneously associate higher-pitched sounds with sensations of upper, smaller, harder, colder, and drier objects compared to lower-pitched sounds [4–6]. Music is a powerful example of how sound can evoke strong bodily emotions, such as chills or tingling sensations, which are well-documented in the literature [7, 8]. Everyday sounds can also evoke bodily sensations, as seen in the phenomenon of ASMR (Autonomous Sensory Meridian Response), where specific sounds trigger tingling sensations in individuals [9, 10]. A neural study has provided evidence for anatomical connections between the neural substrates of the primary auditory cortex and those involved in bodily sensation, such as the primary and secondary somatosensory regions [11]. These findings highlight the well-established

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understanding that sound perception can elicit both auditory experiences and bodily sensations, supported by neural mechanisms underlying this crossmodal interaction.

Pitch perception can elicit not only body sensations but also various emotions, which in turn may induce localized body sensations [12–14]. For instance, a previous study reported that high-pitched sounds and ascending tones tend to be rated as conveying emotions such as happiness, brightness, and speed, in contrast to lower-pitched sounds and descending tones [12]. However, other research has suggested that high-pitched sounds are not always positive, as screeching and fear-inducing sounds are often high-pitched [13, 14].

Research has shown that emotions can be monitored by the topography of emotion-triggered body sensations [15]. Specifically, negative emotions such as fear, anger, sadness, and anxiety tend to elicit localized activation of the upper side of the body, while positive emotions such as happiness and love activate a broader range of the body. Such monitoring of emotion-triggered body sensation can be studied by not only verbal but also non-verbal emotions using music and sound stimuli [16–19]. This monitoring of emotion-triggered bodily sensations, based on both non-verbal body maps and verbal reports, offers a unique tool for understanding individual differences in emotional representation. For example, individuals with depression and those with alexithymia, which shows difficulty in identifying and labelling emotions [20] exhibit specific bodily sensations. That is, the emotion-triggered body sensations are weaker in individuals with depression, particularly in response to sadness and fear [21], and weaker and less localized in individuals with alexithymia [22].

Table 1 Demographic and clinical characteristics in alexithymic and depressive groups

Characteristic	Total Sample	Non-alexithymic (<45)	Alexithymic (>63)	*p* value
N	522	107	102	-
Age	38.8(±0.6)	42.4(±1.2)	36.1(±1.3)	<0.001
Min-Max age	20–78	21–60	21–68	
Sex (% female)	61.5	69.2	58.8	-
QIDS-J Score	4.7(±0.2)	2.4(±0.3)	9.1(±0.5)	<0.001
TAS-20 Total	54.5(±0.4)	40.3(±0.4)	68.4(±0.4)	<0.001
Characteristic	**Total Sample**	**Non-depressive (=0)**	**Depressive (>9)**	**p value**
N	522	107	103	-
Age	38.8(±0.6)	35.7(±1.3)	37.1(±1.3)	0.45
Min-Max age	20–78	20–59	21–70	
Sex (% female)	61.5	59.8	64.1	-
QIDS-J Score	4.7(±0.2)	12.7(±0.3)	0(±0)	<0.001
TAS-20 Total	54.5(±0.4)	50.5(0.9)	62.9(±1.0)	<0.001

* QIDS-J=Japanese version of Quick Inventory of Depressive Symptomatology, TAS-20=Test of Toronto Alexithymia Scale-20

According to previous studies, individuals with alexithymia and depression have been found to exhibit impaired auditory emotion recognition [23] and reduced ability to identify pitch, respectively [24]. Hence, it is possible that alterations in auditory processing and emotional representation in individuals with alexithymia and depression influence the mapping of sounds to the body through emotions. That is, pitch perception is "emotionally" mediated by body sensation, and monitoring of emotion-triggered body sensation may provide a biomarker for emotional disorders such as depression and alexithymia. However, to the best of our knowledge, few studies have investigated the direct relationships among pitch perception, emotion, and body sensation.

The current study aims to examine the connections between pitch, emotion, and body sensation. We also compare the topography of pitch-triggered body sensations between depressive and non-depressive groups, and between alexithymic, and non-alexithymic groups based on questionnaires, and examine the relationships with anxiety, which is often co-occurred with depression and alexithymia [25, 26]. We hypothesized that, similar to emotion-triggered body sensations, individuals with alexithymic trait and depressive state will exhibit less-localized body sensations to pitch [21, 22]. Furthermore, it is possible that less-localized body sensations may be associated with negative emotions such as anxiety.

Methods

Participants

The Japanese participants took part in the study ($N = 522$, M_{age} = 38.8, female = 321, see Table 1 for Demographic characteristics). The data collection was conducted between15th July and 24th August, 2022. All participants who passed the pre-experiment screening completed the entire procedure, and no participants were excluded post hoc. Exclusion criteria (e.g., neurological or audiological disorders, absolute pitch) were applied prior to participation using self-report screening items, ensuring that only qualified individuals were included. Through explicit criterions of the inclusion with self-reports, all participants have no history of neurological or audiological disorders and no absolute pitch ability (i.e., perfect pitch, the ability to identify or re-create a given musical note without the benefit of a reference tone). In the previous study, an analysis of 527 participants indicated effect sizes (Cohen's d) ranging from 0.09 to 0.11 across different conditions (Daikoku et al., 2024). Based on these findings, we aimed to recruit more than 500 participants to ensure adequate statistical power in our study. We recruited participants widely through an online survey company (Cross Marketing Group) without compensation for their participation. The experiment was conducted in accordance with the guidelines of the Declaration of Helsinki and was approved by the Ethics Committee of The University of Tokyo (Screening number: 21–335). All participants gave their informed consent and conducted the experiments by PC. A participant flow diagram is provided in Figure S1 of Supplementary material to illustrate the recruitment process and data inclusion criteria.

Materials and methods

Stimulus

The experimental paradigm was created using Gorilla Experiment Builder (www.gorilla.sc; [27]), a cloud-based research platform for deploying behavioral experiments online. After the questionnaires of TAS-20 and QIDS-J, each participant was provided with the 16 pure tones (20 s, 44.1 kHz, 32bit, amplitude based on equal-loudness-level contours [28]), with different pitches (A1: 55 Hz, D2: 73.4 Hz, G2: 98 Hz, C3: 130.8 Hz, F3: 174.6 Hz, A#3: 233.1 Hz, D#4: 311.1 Hz, G#4: 415.3 Hz, C#5: 554.4 Hz, F#5: 740 Hz, B5: 987.8 Hz, E6: 1318.5 Hz, A6: 1760.0 Hz, D7: 2349.3 Hz, G7: 3136 Hz, and C8: 4186.0 Hz) with random order. That is, these tones were not produced using any acoustic instruments or human voice recordings. Thus, no timbral variation was present across the stimuli; all tones shared the same acoustic profile, free of harmonic overtones or instrument-specific characteristics. We aimed to isolate the perceptual and emotional effects of pitch alone, without introducing potential confounds from differences in timbre, which is known to independently influence emotional and bodily responses. By employing acoustically neutral stimuli, we ensured that any observed effects in body mapping and emotional ratings could be attributed specifically to differences in pitch, rather than tone color. Further, each pitch intervals were set to be equidistant, specifically a perfect fifth apart (i.e., five semi-tones). The lowest and highest tones of 16 tones were chosen to ensure they were audible when listened to through earphones. This arrangement maximizes the perceptual differences in pitch between each tone. Each 16-tone was preceded by 1 s of pure tone (A4: 440 Hz) and 500 ms of silence. By this, we aimed to assess the relationship between relative pitch perception and the body map, rather than absolute pitch. We implemented several procedures to ensure a consistent listening environment. All participants were instructed to use earphones (earbuds), rather than speakers, to reduce variability in sound delivery. Before starting the experiment, participants completed a brief sound test to confirm that the tones were clearly audible and not excessively loud. They were then asked to adjust their volume to a comfortable level where the sounds were easily heard but not unpleasant. These procedures helped ensure a relatively uniform auditory experience across participants. The full experiment design was available from: https://research.sc/participant/login/dynamic/46844BEE-692 C-4CD4-A714-BB44987E48C4. All original sound files are available freely from Open Science Repository (https://osf.io/rs4kh/?view_only=cbe06bcaac4d42dc809f1a54cb173596).

Questionnaire and group

All participants completed the Japanese version of Quick Inventory of Depressive Symptomatology (QIDS-J) [29] ([30] for Japanese version) and the Japanese version of Test of Toronto Alexithymia Scale-20 (TAS-20) [31] ([32] for Japanese version) (see the Supplementary material). In order to balance the number of participants across groups and to compare groups with scores at opposite ends of the spectrum in each test, we divided them into groups with extremely high scores (indicating strong alexithymic trait or severe depressive state) and those with extremely low scores on these tests. Cronbach's alpha coefficients were calculated to assess the internal consistency of the scales: $\alpha = 0.81$ for TAS-20 and $\alpha = 0.86$ for QIDS. Demographic and clinical characteristics in Alexithymic and Depressive groups are shown in Table 1.

To examine trait alexithymia, participants were divided into two groups based on TAS-20 scores: an alexithymic group (score ≥ 56) and a non-alexithymic group (score ≤ 46), aiming for approximately 100 participants per group. The TAS-20 is a widely used and validated 20-item scale measuring difficulties in identifying and describing emotions [31]. In our survey, item #19 was displayed improperly, leading to increased non-response and neutral ratings. Following previous research practices [33], we excluded this item and adjusted cut-off scores accordingly. This adjustment also reflects prior concerns that the original cut-off score (≥ 61) may be overly conservative [34]. Similarly, depressive symptoms were assessed using the Japanese version of the Quick Inventory of Depressive Symptomatology (QIDS-J). Participants were grouped into a Depressive group (QIDS-J score ≥ 9) and a non-Depressive group (score = 0), again balancing the sample size. The QIDS-J measures the severity of depressive symptoms across nine DSM-based domains. Grouping criteria reflect mild to severe levels of depression severity (Table 1). In the end, out of all 522 participants, 54 individuals had both alexithymic and depressive state, 371 individuals had neither, 48 individuals had only alexithymic trait without depressive state, and 49 individuals had only depressive state without alexithymic trait.

Procedure

The present study consists of body-mapping tests and the following emotional judgements in every 16 sounds (Figure S2 of Supplementary material). After listening to each of the 16 sounds, the participants were asked to respond with clicks to the position in the body that they felt from the sound using the body image presented on the screen. The clicking was allowed any number of times up to a maximum of 100 clicks within 10 s, and participants were also free to skip clicking if they did not feel any bodily sensation (see Figure S2 in the Supplementary material for the details).

Two surveys were used to obtain emotional judgements. The first comprised multiple-choice categorical judgements; that is, in each sound, participants were required to select the best 5 emotional categories in ranking elicited by each sound from a list of 33 categories (see the Table S1 in the Supplementary material). However, they were not required to select all five and could choose fewer categories, or none at all, if they did not experience any specific emotion. The 33 emotion categories were derived from established emotion taxonomies, informed by the frameworks proposed by Keltner and Lerner [35] and empirically validated in previous studies by Cowen et al. [36–38]. They have revealed that semantically distinct categories—such as sadness, horror, joy, and amusement—were better captured by these 33 emotional experiences [37]. The second kind comprised nine-point dimensional judgments; that is, after hearing the sounds, participants were required to rate each sound along the valence and arousal. Each rating was obtained on a nine-point Likert scale with the number 5 anchored at neutral.

After all 16 tones were answered, participants performed 10 types of pitch discrimination tests. After one second of a pure tone at 440 Hz (A4, 44.1 kHz, 32bit) followed by 500 ms of silence, one second of pure tone with each 20-cent different pitch (44.1 kHz, 32bit) was presented with random order (+20cent: 445.1 Hz, +40cent: 450.3 Hz, +60cent: 455.5 Hz, +80cent: 460.8 Hz, +100cent: 466.2 Hz, -20cent: 434.9 Hz, -40cent: 430.0 Hz, -60cent: 425.0 Hz, -80cent: 420.1 Hz, -100cent: 415.3 Hz). The cent is a logarithmic unit used to measure musical intervals. It divides one octave into 1200 equal parts, so for example, the interval between two adjacent semitones is 100 cents. The participants were asked to answer whether the second tone was lower or higher than the first tone (i.e., 440 Hz) by forced choice. A training test in which a 440 Hz pitch and 500 ms of silence followed by 660 Hz was conducted before the 10 types of pitch discrimination tests. A Experimental Procedure Flow Diagram is provided in Figure S3 of Supplementary material.

Statistical analysis

Using the coordinate data of x and y in body mapping test, we extracted the number of different click positions and the total number of clicks in each participant. The raw data of x and y coordinates (see Figure S5 in the Supplementary material) were downsampled by a factor of 40. That is, to define a unique click, we downsampled the body map image, which has xy coordinates from the top of the head to the bottom of the body, into 40-pixel segments. The raw x and y coordinate data obtained from the body-mapping task were downsampled by a factor of 40 to define unique click positions. This downsampling factor was chosen based on our previous study [17–19, 39–41], which employed the same procedure. We found that this resolution provides an effective balance between spatial sensitivity and noise reduction, minimizing overcounting due to repeated clicks in a small area while preserving meaningful variations in body sensation patterns. Using the same downsampling factor also facilitates direct comparison between the current and previous findings. This means that multiple clicks within a 40-pixel area were all counted as the same unique click. On the other hand, when calculating the total number of clicks, we counted each click individually regardless of its position. The Figures of the body topographies of pitches (Figs. 1 and 2) were generated using Matlab (2022b) by interpolating the coordinates of x and y in a meshgrid format with a color map that represented the neighboring points. The results of the best 5 emotional categories in the ranking were used to score the intensity of 33 emotions. That is, the first, second, third, fourth, and fifth categories were each scored as a 5, 4, 3, 2, and 1 point. The scores of each 33 emotional categories were then averaged for all participants and each group (see the Supplementary material for all results). In this study, we particularly focus on the emotion of anxiety given this is important emotion for both alexithymia and depression [25, 26]. Because measuring both positive and negative affect can be a reliable method of obtaining responses [42], we utilized its opposite of Japanese-term, relief. To reverse the 1–5 scale to 5 – 1, we scored relief in the opposite direction. We then calculated the average of the anxiety score and the reversed relief score.

We performed the Shapiro–Wilk test for normality on the number of different click positions, the total number of clicks in each participant, the anxiety score of the multiple-choice categorical judgements, and the valence and arousal scores of the nine-point dimensional judgments. Depending on the result of the test for normality, either the parametric or non-parametric (Kruskal-Wallis) One-Way analysis of variance (ANOVA) was applied to compare Alexithymic vs. non-alexithymic, and Depressive vs. non- Depressive groups in each pitch. We also performed the independent samples T-test for the average score of the 10 types of the pitch discrimination test. Statistical analyses were conducted using jamovi Version 1.2 (The jamovi project, 2021). We selected $p < .05$ as the threshold for statistical significance and used an FDR method for multiple comparison testing.

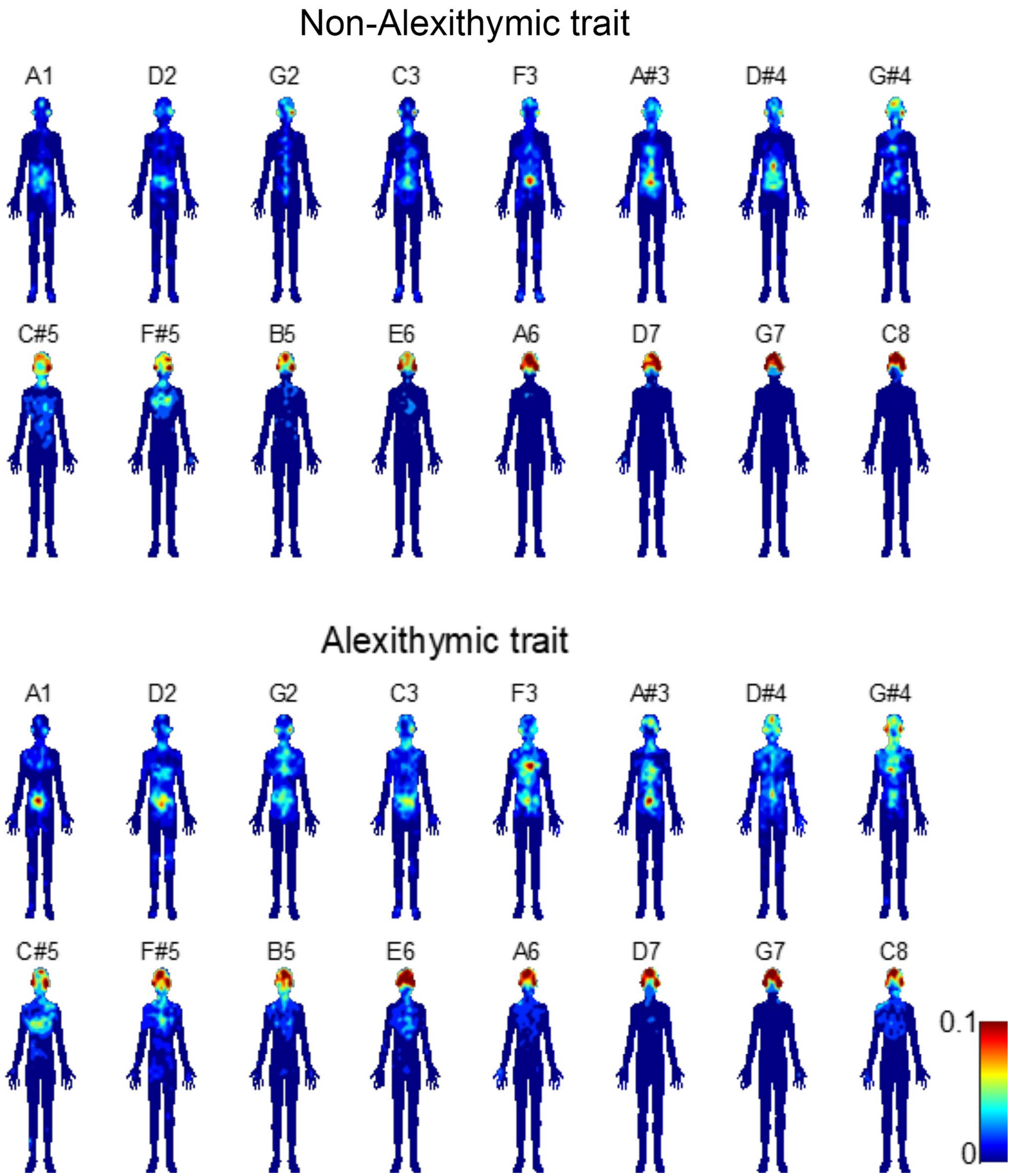

Fig. 1 Body topography of pitches in the Alexithymic group. The blue-to-red gradients represent the number of clicks. Individuals with alexithymic trait exhibit a less-localized or more diffused body map, compared to those without alexithymic trait

To evaluate whether our sample sizes were adequate for detecting expected effects, we conducted a post-hoc power analysis using both Cohen's d and epsilon squared (ε^2), which correspond to the statistical tests employed in the study. For both comparisons between the Depressive ($N = 103$) and Non-depressive ($N = 107$) groups, and between the Alexithymic ($N = 102$) and Non-alexithymic ($N = 107$) groups, the results indicated that the statistical

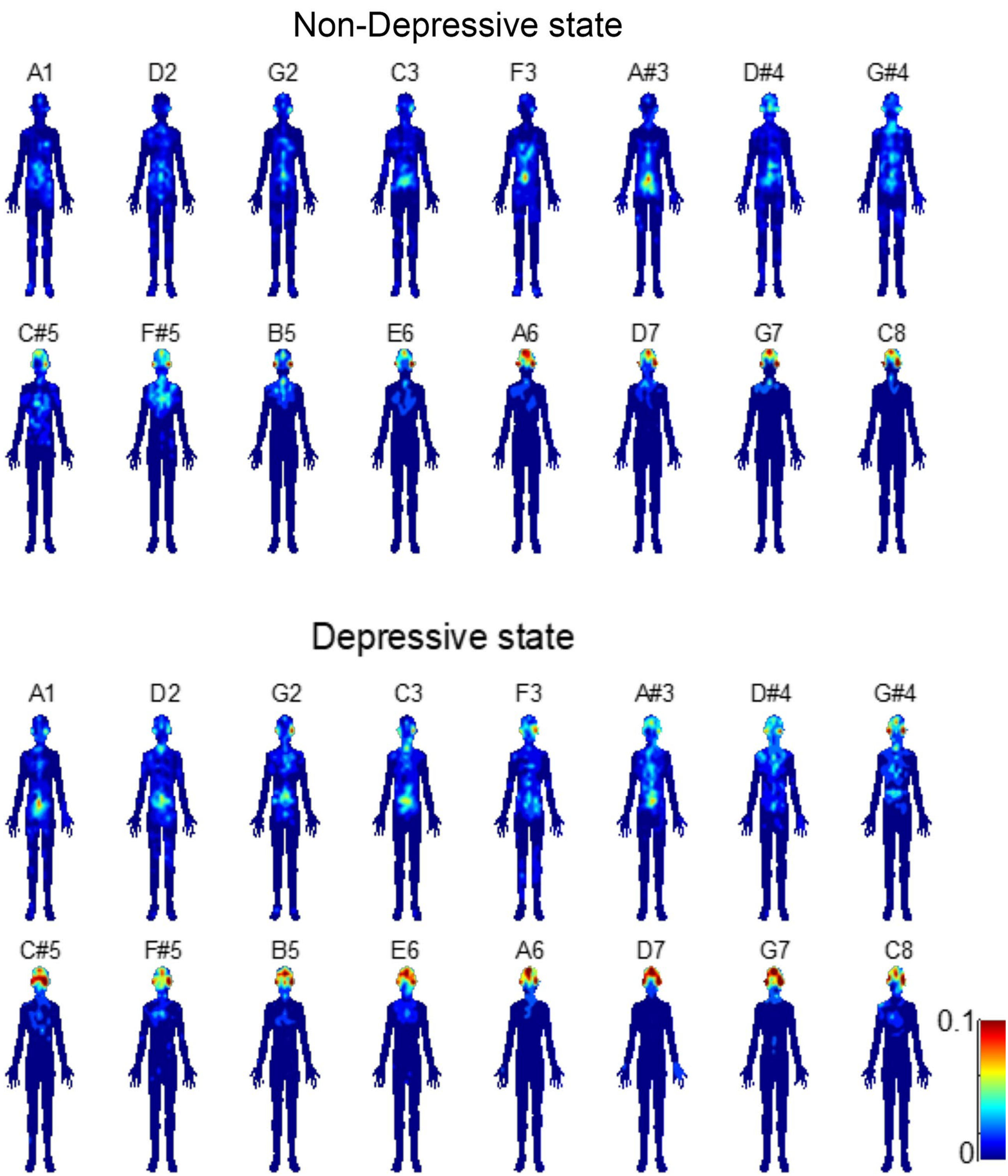

Fig. 2 Body topography of pitches in the Depressive group. The blue-to-red gradients represent the number of clicks. Individuals with depressive state exhibit a less-localized body map, compared to those without depressive state

power was approximately 0.30 when assuming a small effect size (Cohen's d = 0.2; $\varepsilon^2 \approx 0.0098$). When assuming a moderate effect size (Cohen's d = 0.3; $\varepsilon^2 \approx 0.0215$), the power increased to around 0.57–0.58. Notably, the observed effect sizes in our study, such as ε^2 values ranging from 0.03 to 0.09 reported in the Results section, exceed the conventional threshold for medium effects. These findings suggest that while the design may be underpowered for detecting very small effects, the sample sizes are sufficient to detect effects of medium magnitude or greater. This level of statistical power is appropriate given the exploratory nature of the study and is consistent with effect sizes reported in prior literature (Daikoku et al., 2024). A detailed summary of the power analysis is provided in the Supplementary Material.

Results

Body map

Grand averages of pitch-triggered topography and the clicked positions were shown in supplementary materials (Supplementary). All of the anonymized raw data files and all of the results of statistical analyses including the descriptives have been deposited to an external source (https://osf.io/rs4kh/?view_only=cbe06bcaac4d42dc809f1a54cb173596).

The individuals with alexithymic trait (Fig. 1) and depressive state (Fig. 2) showed less-localised body sensations to pitch. Statistical analysis indicated that the number of different click positions and the total number of clicks is increased in individuals with Alexithymic and Depressive groups. The one-way analysis of variance (ANOVA) detected that the number of different clicks positions is significantly higher in individuals with alexithymic trait compared to the those without alexithymic trait, specifically in response to the sounds of D#4 (χ^2 = 3.89, $p = .049$, ε^2 = 0.02) and C#5 (χ^2 = 3.86, $p = .049$, ε^2 = 0.02). The number of different clicks positions is significantly higher in individuals with depressive state compared to those without depressive state, specifically in response to the lower-pitched sounds of A1 (χ^2 = 7.01, $p = .008$, ε^2 = 0.03), D2 (χ^2 = 7.14, $p = .008$, ε^2 = 0.03), G2 (χ^2 = 9.28, $p = .002$, ε^2 = 0.04), C3 (χ^2 = 7.18, $p = .007$, ε^2 = 0.03), F3 (χ^2 = 9.95, $p = .002$, ε^2 = 0.05), A#3 (χ^2 = 6.52, $p = .01$, ε^2 = 0.03), and D#4 (χ^2 = 6.60, $p = .01$, ε^2 = 0.03).

The total number of clicks is significantly higher in individuals with depressive state compared to those without depressive state, specifically in response to the lower-pitched sounds of A1 (χ^2 = 7.11, $p = .008$, ε^2 = 0.03), D2 (χ^2 = 7.39, $p = .007$, ε^2 = 0.04), G2 (χ^2 = 9.06, $p = .003$, ε^2 = 0.04), C3 (χ^2 = 7.19, $p = .007$, ε^2 = 0.03), F3 (χ^2 = 10.04, $p = .002$, ε^2 = 0.05), A#3 (χ^2 = 6.73, $p = .009$, ε^2 = 0.03), and D#4 (χ^2 = 6.61, $p = .01$, ε^2 = 0.03). No statistical difference in the total number of clicks was observed between individuals with alexithymic trait and those without alexithymic trait.

Emotion in response to pitches

All of the results of statistical analyses and the descriptives of the multiple-choice categorical judgements and nine-point Likert scale of valence and arousal have been deposited to an external source. The figures of the grand average data are shown in S3 and S4 Appendices (Figure a) in supplementary materials.

The multiple-choice categorical judgements test showed that the individuals with alexithymic trait and depressive state felt strong anxiety in response to several pitched sounds (see Figure S8 in the Supplementary material). The one-way ANOVA detected that the anxiety is significantly higher in individuals with alexithymic trait compared to those without alexithymic trait, specifically in response to the lower-pitched sounds of A1 (χ^2 = 6.86, $p = .009$, ε^2 = 0.03), D2 (χ^2 = 6.20, $p = .01$, ε^2 = 0.03), G2 (χ^2 = 4.52, $p = .03$, ε^2 = 0.02), A#3 (χ^2 = 5.50, $p = .02$, ε^2 = 0.03), and D#4 (χ^2 = 17.75, $p < .001$, ε^2 = 0.09). The anxiety is significantly higher in individuals with depressive state compared to those without depressive state, in response to the wide range of pitched sounds of A1 (χ^2 = 6.03, $p = .01$, ε^2 = 0.03), D2 (χ^2 = 4.99, $p = .03$, ε^2 = 0.02), C3 (χ^2 = 4.94, $p = .03$, ε^2 = 0.02), F3 (χ^2 = 13.02, $p < .001$, ε^2 = 0.06), D#4 (χ^2 = 7.36, $p = .007$, ε^2 = 0.04), F#5 (χ^2 = 4.02, $p = .045$, ε^2 = 0.02), B5 (χ^2 = 6.42, $p = .011$, ε^2 = 0.03), E6 (χ^2 = 5.48, $p = .019$, ε^2 = 0.03), A6 (χ^2 = 5.51, $p = .019$, ε^2 = 0.03), and G7 (χ^2 = 9.70, $p = .002$, ε^2 = 0.05).

The nine-point Likert scale of valence and arousal detected that the individuals with alexithymic trait and depressive state felt negative valence in response to several pitched sounds while no significant differences in arousal between the individuals with alexithymic trait and those without alexithymic trait and between the individuals with depressive state and those without depressive state were observed (see Figure S8 in the Supplementary material). The one-way ANOVA detected that the valence is significantly negative in individuals with alexithymic trait compared to those without alexithymic trait, in response to the lower-pitched sounds of D2 (χ^2 = 4.13, $p = .04$, ε^2 = 0.02), C3 (χ^2 = 4.59, $p = .03$, ε^2 = 0.02), F3 (χ^2 = 5.05, $p = .03$, ε^2 = 0.02), and A#3 (χ^2 = 7.04, $p = .008$, ε^2 = 0.03). The valence is significantly negative in individuals with depressive state compared those without depressive state, in response to the several pitched sounds of C3 (χ^2 = 4.89, $p = .03$, ε^2 = 0.02), F3 (χ^2 = 4.37, $p = .04$, ε^2 = 0.02), and A#3 (χ^2 = 5.40, $p = .02$, ε^2 = 0.03).

The participants also performed pitch discrimination tests after experiments of body sensation. The results showed no statistical significance between groups (Depressive vs. non-depressive: $p = .45$; Alexithymic vs. non-alexithymic: $p = .86$). This suggests that not pitch discrimination ability per se, but rather the bodily sensations evoked by pitch and the emotions that mediate them may be implicated in modulating pitch-triggered topography.

Discussion

The present study investigated individual differences in pitch-triggered body sensations between depressive and non-depressive groups, and between alexithymic, and non-alexithymic groups based on questionnaires (QIDS and TAS-20), and how these differences are associated with emotional responses such as anxiety and valence. The results indicated that alexithymic and Depressive groups exhibited less localized body sensations in response to pitch while there were no significant group differences in pitch discrimination ability. Furthermore, individuals with alexithymic trait and depressive state experienced strong feelings of anxiety and negative valence in response to several pitches. These results suggest that the diffuse bodily sensations are not inherently linked to pitch discrimination ability, but rather to the emotional responses triggered by sound pitches. This study suggests that the diffuse bodily sensations in response to pitch may induce negative emotions such as anxiety. On the other hand, our study did not revealed the causality between anxiety and body map directly and we detected that the effect for depressive group was found for almost all tones. Nevertheless, non-verbal measurements of body maps in response to sound, in addition to verbal responses to anxiety-related questions, may provide a novel method for using anxiety as an indicator.

Previous studies have suggested that emotion-triggered body sensations are modulated in individuals with depressive state [21] and alexithymia [22]. Specifically, individuals with alexithymic trait exhibit weaker and less localized emotion-triggered body sensations [22]. Our study extends these findings by demonstrating that pitch-triggered body sensations are also less localized in alexithymic trait and depressive state, and that this diffuse sensation is associated with feelings of anxiety. For instance, the pitch of D#4 induces diffuse body sensations and strong anxiety in individuals with alexithymic trait compared to those without alexithymic trait. It is possible that the diffuse body sensation is mediated by anxiety, which is frequently co-occurring with alexithymia and depression [25, 26]. Previous evidence has demonstrated that individuals with alexithymic trait have impaired auditory emotion recognition [23], suggesting that alterations in auditory processing and emotional representation in these individuals may affect the mapping of sounds to the body through emotions. Our findings suggest that while pitch discrimination ability is not inherently different between groups, the subjective experience of pitch is 'emotionally' mediated by body sensations. Individuals with depressive state and alexithymic trait exhibit diffuse body sensations in response to certain pitches, which are associated with heightened feelings of anxiety and negative valence. Monitoring these emotion-triggered body sensations in response to sounds may provide a biomarker for emotional disorders such as depression and alexithymia.

Previous studies have examined the relationship between pitch discrimination ability and mood disorders. They found that the pitch discrimination ability is enhanced in depression and that this can also be observed from the mismatch negativity (MMN) using electroencephalography (EEG) [43], whereas the pitch discrimination ability is decreased in schizophrenia [44]. While our study did not find a significant group difference in pitch discrimination ability, we did observe that individuals with depressive state perceive pitched sounds differently than those without depressive state, as evidenced by a significantly higher total number of clicks (see Figure S7 in the Supplementary material).

Our results also suggest a possible relationship with interoception for some reasons. The first is that the lowest part of clearly appeared bodily sensation felt in response to pitch was located at the abdomen, the lowest part of the visceral system. The second is that the body sensation evoked by emotions is suggested to entail interoceptive involvement [15]. It is possible that the diffuse body sensation of sounds could reflect a diminished "*bodily or interoceptive awareness*" in response to sound. That is, interoceptive awareness, which involves perceiving and interpreting bodily signals, may be altered in individuals with these emotional disorders. Understanding the role of interoceptive awareness in the perception of sounds and emotions has important implications for the development of interventions for individuals with sensory processing disorders, as well as for alexithymia and depression. Finally, our latest study suggests that auditory perception can evoke bodily sensations in specific interoceptive parts, such as the heart and stomach. In the future, it will be necessary to clarify the differences in body position experienced across various body parts.

Our findings contribute to understanding the interplay between emotion and auditory perception. For example, incorporating Polyvagal Theory [45] offers a deeper understanding of how the autonomic nervous system modulates emotional responses to auditory stimuli. According to Porges, the vagus nerve plays a crucial role in regulating heart rate and social engagement, which are directly influenced by auditory inputs. This perspective can help explain the variations in emotional responses observed in our study. Auditory research including music has emphasized the role of the limbic system, particularly the amygdala and hippocampus, in processing emotional aspects of auditory experiences [46]. our results align with these notions that auditory perception is deeply intertwined with emotional processing at a neural level. These theoretical frameworks highlight the complex relationship between auditory stimuli and emotional responses, underscoring the necessity of considering both physiological and psychological dimensions. Future research should continue to explore these interactions, potentially leveraging advanced neuroimaging techniques to further elucidate the neural mechanisms involved.

One notable limitation of this study is that no standardized diagnostic tool was used to screen participants for mental health disorders. Although participants self-reported no current psychiatric diagnoses or history of neurological or audiological disorders, the lack of formal screening may have introduced unmeasured variability in psychological status.

Further, there is the potential influence of participants' response strategies on the body map-clicking task. Although clicking was not mandatory, diffuse clicking may indicate uncertainty, particularly among those with poorer mental health. Future studies should include control conditions to address these concerns. Further, the present study was unable to strictly control the auditory environment due to the online experiment. For instance, it is probable that the negative valence is partially correlated with volume. However, in this study, all participants were instructed to use earphones (i.e., ear-bud), which ensured that the volume did not vary drastically among participants, in contrast to using speakers. Another limitation is that grouping was conducted only based on the questionnaire, which may have led to the less strict categorization of alexithymia and depression. However, given the large sample size of over 500 participants in this study, the noise in the responses is likely to have been offset. Given that even when targeting individuals assessed solely through questionnaires for alexithymia and depression, we detected groups difference in body map of sounds. That is, even when focusing on participants with extremely high or low alexithymia and de-pression scores, we could maintain over 100 participants per group. This could verify our hy-pothesis that the individuals with alexithymic trait and depressive state would exhibit less-localized body sensations in response to pitch, with enough sample size in each group. While we recognize the importance of including participants at the borderline of alexithymic trait and depressive state for understanding individual differences, including all participants could introduce arbitrari-ness in group assignments.

Additionally, the questionnaire used to assess depressive symptoms was based on DSM-IV-TR criteria, not the current DSM-5 because of the availability of Japanese version. DSM-5 introduced changes including the removal of the bereavement exclusion criterion, the inclusion of mixed features, and the addition of severity specifiers. These updates aim to improve diagnostic accuracy and treatment. Future studies should consider using DSM-5-based assessments for a more current understanding of depressive symptoms. It is important to note that Alexithymia and depression co-occur frequently. In this study, 54 participants belonged to both groups. In future research, it will be important to compare individuals who have only alexithymia with those who have only depression to investigate the specific differences between these two conditions. Finally, further research is needed to examine how musical education and culture influence the body sensation to sounds and to investigate whether the body sensation to sounds and the associated emotional responses are modulated depending on not only pitch but also differences in timbre or the semantic meaning of sound.

Although the current study did not collect detailed information about participants' musical experience, we included a pitch discrimination task to examine whether individual differences in pitch perception ability might account for the observed group differences in body sensation. The results showed no significant differences in pitch discrimination performance across groups, suggesting that the effects observed in body maps were unlikely to be driven by perceptual deficits. Nevertheless, we acknowledge that musical training could influence both auditory sensitivity and emotional responses to sound, and future research should consider explicitly measuring and controlling for musical background to further disentangle its potential impact.

In summary, the current findings support our main hypothesis that individuals with alexithymic trait and depressive state would exhibit less-localized or more diffuse body sensations in response to sound pitch. These sensations were associated with heightened anxiety and negative valence, as hypothesized. This supports the idea that pitch-triggered bodily sensations may be emotionally mediated, particularly in individuals with emotional difficulties. While causality cannot be established due to the cross-sectional nature of this study, such associations highlight the potential of non-verbal bodily sensation measures as early indicators of emotional tendencies—possibly before individuals are consciously aware of their anxiety. On the other hand, our secondary expectation—that pitch discrimination ability might differ between groups—was not supported. This may indicate that differences in bodily sensations are not due to perceptual deficits but rather to emotional processing. These results provide partial but strong support for our hypotheses, particularly in relation to body maps and emotional traits. Thus, the present study may suggest the importance of interoceptive awareness in the processing of pitch-triggered body sensations and its association with emotional responses. This study may also provide insight into potential interventions for alexithymia and depression by exploring methods to localize body sensations in response to pitch.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40359-025-02900-z.

Supplementary Material 1

Author contributions

T.D. and T.H. conceived the experimental paradigm and method of data analysis. T.D. collected the data, analysed the data, and wrote the draft of the manuscript and figure. T.D., T.H. and S.Y. edited and finalized the manuscript.

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Data availability

All of anonymized raw data files and stimuli used in this study have been deposited to an external source (https://osf.io/rs4kh/?view_only=cbe06bcaac4d42dc809f1a54cb173596). The other data and results of statistical analysis are shown in the file of supplementary material.

Declarations

Ethics approval and consent to participate

The experiment was conducted in accordance with the guidelines of the Declaration of Helsinki and was approved by the Ethics Committee of The University of Tokyo (Screening number: 21–335). All participants gave their informed consent and conducted the experiments.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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