



Magnetic cortical oscillations associated with subjective auditory coolness during paired comparison of time-varying HVAC sounds

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Title: Magnetic cortical oscillations associated with subjective auditory coolness during paired comparison of time-varying HVAC sounds

Short title: Brain waves related to HVAC sound coolness

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22 **Abstract**

23 **Objective:** The impressions of heating, ventilation, and air conditioning (HVAC)
24 sounds are important for the comfort people experience in their living spaces. Revealing
25 neural substrates of the impressions induced by HVAC sounds can help to develop
26 neurophysiological indices of the comfort of HVAC sounds. There have been numerous
27 studies on the brain activities associated with the pleasantness of sounds, but few on the
28 brain activities associated with the thermal impressions of HVAC sounds.

29 **Methods:** Seven time-varying HVAC sounds were synthesized as stimuli using
30 amplitude-modulation. Six participants took part in subjective evaluation tests and
31 MEG measurements. Subjective coolness of the HVAC sounds was measured using the
32 paired comparison method. Magnetoencephalographic (MEG) measurements were
33 carried out while participants listened to and compared the time-varying HVAC sounds.
34 Time-frequency analysis and cluster-based analysis were performed on the MEG data.

35 **Results:** The subjective evaluation tests showed that the subjective coolness of the
36 amplitude-modulated HVAC sounds was affected by the modulation frequency, and that
37 there was individual difference in subjective coolness. A cluster-based analysis of the
38 MEG data revealed that the brain activities of two participants significantly differed
39 when they listened to cooler or less cool HVAC sounds. The frontal low-theta (4–5 Hz)
40 and the temporal alpha (8–13 Hz) activities were observed.

41 **Conclusion:** The frontal low-theta and the temporal alpha activities may be associated
42 with the coolness of HVAC sound. This result suggests that the comfort level of HVAC
43 sound can be evaluated and individually designed using neurophysiological
44 measurements.

45 **Keywords:** HVAC sound, air conditioning, auditory coolness, cortical oscillation,

46 paired comparison, magnetoencephalography

47

48 **Introduction**

49 Impressions of sounds are important factors in the degree of comfort people
50 experience in their living spaces. To provide a more comfortable auditory environment,
51 different impressions of various sounds have been investigated using psychoacoustic
52 measurements. For example, sounds generated by heating, ventilation, and air
53 conditioning (HVAC) systems affect the comfort of living spaces. While previous
54 studies on HVAC sound have mainly evaluated sound quality indices, such as
55 preference, annoyance, and loudness [1,2], a few studies have evaluated thermal
56 impressions, such as coolness and warmth [3,4]. These studies found individual
57 differences in impressions of HVAC sound, suggesting that a personalized approach to
58 finding the optimum HVAC sound is more effective than assuming that one way is fine
59 for everyone.

60 Revealing neural substrates of the impressions induced by HVAC sounds can
61 help to develop neurophysiological indices of the impressions even when psychological
62 responses differ individually. Whereas numerous functional brain imaging studies have
63 investigated the brain activities associated with pleasantness and preference induced by
64 several sounds, especially musical excerpts [5–7], few studies have investigated the
65 brain activities associated with the impressions of HVAC sounds. Moreover, brain
66 activities associated with the thermal impressions of sounds are poorly understood.

67 There are numerous studies on brain responses to thermal stimulation. Previous
68 PET and fMRI studies reported that innocuous thermal stimulation of the skin activates
69 the anterior/posterior insular and orbitofrontal cortices [8–10], and that activities in the
70 orbitofrontal and anterior/mid cingulate cortices were correlated with

pleasantness/unpleasantness of thermal stimuli [11,12]. Aizawa et al. identified brain regions involved in thermal sensation and dissociated the regions related to temperature sensation and thermal pleasantness: local thermal stimulation activated the anterior cingulate cortex, insula, and inferior parietal lobe and thermal pleasantness and unpleasantness were associated with the frontal region, and with the medial frontal and anterior cingulate cortices, respectively [13]. Previous MEG/EEG studies reported oscillatory activities induced by innocuous thermal stimulation: frontal theta [14]; 10 Hz oscillation in the posterior insula, secondary somatosensory cortex (S2), and premotor cortex [15]; delta (1–4 Hz) and gamma (55–90 Hz) in the operculo-insular cortex [16]. Thermal impressions of HVAC sounds may activate brain regions associated with thermal sensation, such as the insula, S2, and frontal region.

The aim of this study is to clarify the neurophysiological activity associated with subjective coolness induced by HVAC sounds. First, seven time-varying HVAC sounds were generated as stimuli using amplitude-modulation. It is expected that changes in amplitude over time will influence subjective coolness by reminding listeners of changes in the amount of airflow from the air conditioning vent to the listener. In subjective evaluation tests, subjective coolness of the stimuli was evaluated using a paired comparison method. By evaluating two stimuli at a time, participants were able to evaluate even slight differences in their coolness. Next, MEG measurements were taken while the participants listened to the stimuli; again, in the MEG measurements, participants compared the paired stimuli and reported which was cooler. Finally, time-frequency analysis and cluster-based analysis were performed on the MEG data to determine if there were differences in brain activity while each participant listened to HVAC sounds based on their comparative judgment.

Methods

Participants

Six participants (4 males and 2 females, 21–24 years old) took part in subjective evaluation tests and MEG measurements. All participants had normal hearing and no history of neurological disease. All necessary information regarding these experiments was given to the participants, and informed consent was obtained before these experiments were carried out. The study was approved by the Institutional Review Board on Ergonomic Research of National Institute of Advanced Industrial Science and Technology (AIST).

Auditory stimuli

Auditory stimuli were synthesized from a model HVAC sound using amplitude-modulation. The model HVAC sound was synthesized based on the recorded noise of an actual vehicle HVAC system [3]. The model HVAC sound was amplitude-modulated by a sinusoidal wave, as follows:

$$s_{\text{stimulus}}(t) = (1 + 0.15 \sin ft)s_{\text{model}}(t), \quad (1)$$

where f is the modulation frequency. Seven stimuli were synthesized by varying the modulation frequency: 0 (without modulation), 0.2, 0.4, 0.6, 0.8, 1.6, and 3.2 Hz. The duration of the stimuli was 5.0 s including 30-ms rise and fall times. A temporal waveform and the long-term power spectrum of the model HVAC sound are shown in Fig. S1, Auditory stimuli, Details of methods, Supplemental Digital Content 1.

Subjective evaluation tests

Subjective coolness of stimuli was measured using the paired comparison method under 3 room temperatures of approximately 20, 25, and 30°C. The participants were seated in a soundproof room. Two stimuli were paired and sequentially presented to both of the participant's ears with an inter-stimulus interval of 1.0 s. The stimuli were presented via insert earphones (ER-2; Etymotic Research, Inc., Elk Grove Village, IL, USA). Then, the participant rated which stimuli were cooler on a 7-point scale (± 3 , ± 2 , ± 1 , and 0). All permutations of the paired stimuli were randomly presented once in a session. For each room-temperature condition, two sessions were sequentially conducted with a break of approximately 5 minutes. Before the start of the sessions, each participant adjusted the sound-pressure level of the model HVAC sound to the level at which he/she was able to hear clearly and comfortably.

Scale values on coolness were calculated for all stimuli using a variation of Scheffé's method [17]. In this method, the measured comparative judgments were statistically analyzed based on the analysis of variance (ANOVA).

Details of the subjective evaluation tests are described in Subjective evaluation tests, Details of methods, Supplemental Digital Content 1.

MEG measurements

MEG activity during paired comparison of the stimuli was measured in a magnetically-shielded room using a 122-channel whole-head neuromagnetometer (Neuromag-122™; Neuromag Ltd., Helsinki, Finland). The measurements were conducted at a room temperature of approximately 21°C. Four stimuli were selected

from 7 stimuli for each participant, including the coolest and least cool stimuli in the subjective evaluation tests. The participant was seated in the shielded room. The paired stimuli were presented to the participant in the same way as the subjective evaluation test. After each presentation of paired stimuli, the participant was asked to report which stimuli were cooler using the buttons corresponding to the paired stimuli. The measurements for each participant consisted of 3 sessions with 2-minute breaks between sessions. All permutations of the paired stimuli were randomly presented 4 times per session. Each participant adjusted the sound-pressure level of the model HVAC sound to the level at which he/she was able to hear clearly and comfortably before the start of the series of the sessions. MEG signals were sampled at 400 Hz.

Analyses of the MEG data

Low-frequency components (<2 Hz), the 60 Hz power-line noise, artifacts, and cardiac and ocular activities were removed from the MEG raw data by digital filtering and independent component analysis. The continuous wavelet transform (CWT) with the complex Morlet wavelet was performed on the preprocessed MEG signals to obtain time-frequency representations. The time and frequency ranges at which the signals were analyzed were from -700 to $5,000$ ms after the stimulus onset, and from 4 to 100 Hz, respectively. Then, the power change relative to the average over 700 ms before the stimulus onset was computed.

To find the brain activity related to subjective coolness of HVAC sound, the relative power change in the brain activity induced by the paired comparison was estimated. We assumed that the participant internally compared the second stimulus of the paired stimuli with the first stimulus during the second stimulation to report their

judgment later, and that MEG signals during the second stimulation reflect brain activities induced not only by the second stimulus but also by the internal comparison with the first stimulus. The relative power change induced by internal comparison, P_n^{comp} , was computed as follows, with $P_n^{(1)}$ and $P_n^{(2)}$ being the relative power change during the first and second stimulation in the n th trial:

$$P_n^{\text{comp}} = P_n^{(2)} - \bar{P}_{s_n^{(2)}}, \quad \bar{P}_s = \frac{1}{N_s} \sum_{n \in \{s_n^{(1)} = s\}} P_n^{(1)}. \quad (3)$$

Here, $\bar{P}_s$ is the average power change induced by stimulus s itself. $s_n^{(1)}$ and $s_n^{(2)}$ are the labels of the first and second stimuli in the n th trial. $\bar{P}_s$ was estimated from $P_n^{(1)}$, and was subtracted from $P_n^{(2)}$.

The relative power of the brain activity induced by the internal comparison was statistically compared between two conditions corresponding to comparative judgment. This statistical comparison was conducted for each participant in between-trials design. To correct multiple comparison at all the time-frequency-channel points, the cluster-based permutation test [18] was performed.

All the steps of the analysis were implemented on MATLAB (The Mathworks, Inc., MA, USA). Details of MEG data analyses are described in Analyses of the MEG data, Details of methods, Supplemental Digital Content 1.

Results

Subjective evaluation tests

The ANOVA of the comparative judgments on coolness revealed that scale values of coolness were significantly affected by the modulation frequency of the

stimuli ($F(6, 315) = 19.65, p < 0.001$, partial $\eta^2 = 0.27$). Individual differences of the scale value of coolness were also found ($F(30, 315) = 19.57, p < 0.001$, partial $\eta^2 = 0.65$). The comparative judgments on coolness were not affected by the combination of paired stimuli ($F(15, 315) = 0.77, p = 0.71$, partial $\eta^2 = 0.04$). The scale values of coolness were not affected by room temperature ($F(12, 315) = 0.86, p = 0.59$, partial $\eta^2 = 0.03$). The whole ANOVA table is shown in Table S1, Supplemental Digital Content 1. The scale values of coolness calculated for each thermal condition are shown in Fig. 1 and Table S2, Supplemental Digital Content 1. A larger scale value means the participant perceived the stimulus as cooler. Fig. 1 also shows that the scale value of coolness differed for each participant. In P1 and P2, the scale values had peaks between the modulation frequencies of 0.4–0.8 Hz. In P4, the scale value increased with the modulation frequency. In P5, variations of the scale values with the modulation frequency were small.

MEG data

The cluster-based permutation tests revealed that the brain activities of participants P2 and P4 changed significantly as they compared the coolness internally ($p < 0.025$). The three clusters of brain activity with the largest absolute cluster mass in the internal comparison of coolness are shown in Table 1 for each participant, and the p -values obtained by the cluster-based permutation test are also shown in Table 1. Fig. 2 shows the temporal-frequency range and spatial region of each cluster.

The characteristics of the three large clusters differed from participant to participant, but some clusters were common among several participants. Participants P1, P3, and P4 had positive clusters in the low-theta band (4–5 Hz) at the frontal-parietal

MEG channels, while participants P4, P5, and P6 had positive clusters in the alpha band (8–13 Hz) at the temporal MEG channels. Fig. 3 (b) shows time-frequency representations of the relative power change induced by internal comparison at frontal and temporal channels when P1 and P4, respectively, listened to the least cool/coolest stimulus after they listened to the coolest/least cool stimulus. A power decrease of 5 Hz activity around 3.5 s and a power decrease of 10 Hz activity around 3.0 s were observed when P1 and P4, respectively, listened to the coolest stimulus. These results are consistent with the large t -values shown in Fig. 3 (c), which were computed from all the possible comparisons of the stimuli.

To estimate rough source locations of the frontal low-theta activity and the temporal alpha activity found in the cluster-based analysis, coarse current vector maps of these activities were investigated. Since a planar gradiometer, which is equipped with the neuromagnetometer used in this study, is sensitive to the magnetic fields generated from a current vector parallel to the head surface and directly below the gradiometer, the coarse current estimates are obtained from the measured MEG signals [19]. The coarse current vector is defined as the gradient vector rotated by 90° in each gradiometer plane. To create the vector map, averaged MEG signals while the participant listened to the cooler/less cool stimulus were computed using a similar equation to (3). Fig. 4 (a, b, d) shows coarse current vector maps of the difference between the low-theta activity when P1 listened the less cool stimulus and the low-theta activity when P1 listened the cooler stimulus. Relatively large coarse currents are shown on the right frontal cortex. Fig. 4 (e) shows a coarse current vector map of the difference between the alpha activity when P4 listened the less cool stimulus and the alpha activity when P4 listened the cooler stimulus. Relatively large coarse currents are shown on the

temporal area in the right hemisphere. These locations of the large coarse current vectors are consistent with the location of the MEG channels with the maximum cluster mass shown in Fig. 3 (a).

Discussion

Auditory coolness of time-varying HVAC sound

The results of the subjective evaluation test showed that the modulation frequency of the HVAC sound affected the coolness of the HVAC sound for many participants. At the same time, it was confirmed that there were individual differences in coolness. For some participants, the coolness scale values peaked at modulation frequencies between 0.4 and 0.8 Hz. These results indicate that the optimal HVAC sound can be designed for each individual by modulating the amplitude of the sound.

The relative coolness between stimuli did not change significantly with different temperature conditions. A previous study [3] in which a paired comparison method was used also reported no change in the order relationship of coolness/warmth of HVAC sounds with varying spectral centers of gravity between temperature conditions (16–31°C). At least under room temperature conditions of 16–31°C, room temperature does not appear to have a significant effect on the relative coolness/warmth of the HVAC sound.

Cortical activities associated with auditory coolness

The cluster-based permutation tests revealed that brain activities changed significantly in several participants depending on the coolness of the HVAC sound. The

brain activities that differed significantly across conditions (i.e., those represented by the largest clusters) may be associated with coolness. However, the three largest clusters were not consistent across participants. It is possible that the individual differences in the evaluation criteria for coolness of the HVAC sound may also have an influence on the individual differences in brain activity.

Some clusters had common characteristics among the three largest clusters of several participants. The common clusters among several participants who showed significant brain activity by internal comparison may be brain activity related to the coolness of the HVAC sound.

Participants P4, P5, and P6 showed clusters in the alpha band at the temporal MEG channels. Previous studies have shown that the insula and its surrounding areas are involved in the processing of thermal sensation. For example, Mano et al. reported that the secondary somatosensory cortex (S2) is involved in the perception of cold and warmth differences [20]. Fardo et al. reported that cold, harmless stimulation of the left hand caused theta and gamma band activity in the anterior temporal MEG sensors, and that the source of these activities was in the operculo-insular region [16]. One EEG study also reported that cool stimulation of the right hand reduced the amplitude of the contralateral posterior insula, S2 at 10 Hz [15]. The clusters of the temporal alpha activity seen in participants P4, P5, and P6 have many similarities to the brain activity in response to thermal stimuli in these studies. A sensory stimulus including a content related to a different sensory modality sometimes activates brain regions associated with the different sensory modality. For example, a food image stimulus activates not only the visual processing region but also the gustatory processing region [21,22]. The

temporal alpha clusters may reflect activity in the S2 and insular cortex associated with coolness processing.

Participants P1, P3, and P4 showed positive clusters in the low-theta band at the frontal-parietal MEG channels. The activity represented by these clusters may be related to thermal comfort rather than thermal sensation. Several fMRI studies have shown that frontal cortex activity is involved in thermal comfort [12,13]. For example, Aizawa et al. reported that frontal regions are associated with thermal pleasantness, and medial frontal and anterior cingulate cortex with unpleasantness [13]. In a previous EEG study, Chang et al. reported that the frontal theta activity was decreased by cold thermal stimuli, and discussed the relationship between theta band activity and emotional response [14]. The frontal theta band has been shown to be related to emotion processing in many previous studies [23–25]. The cluster of the frontal-parietal, low-theta activity found in participants P1, P3, and P4 may be related to the emotional component of the coolness of the HVAC sound; i.e., thermal comfort.

Conclusion

To clarify brain activity associated with auditory coolness induced by HVAC sound, MEG measurements were carried out while participants listened to and compared time-varying HVAC sounds. Subjective evaluation tests revealed that subjective coolness of amplitude-modulated HVAC sounds was affected by the modulation frequency. Individual difference in subjective coolness was also found. A cluster-based analysis of the MEG data revealed that the brain activities of some participants differed significantly between when the participants listened to cooler and

less cool HVAC sounds. The frontal low-theta (4–5 Hz) and the temporal alpha (8–13 Hz) activities were observed. These activities may be associated with coolness of HVAC sound. The results of this study suggest that the comfort level of HVAC sound can be evaluated and individually designed using neurophysiological measurements.

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Legends for illustrations

Fig. 1

Scale values of subjective coolness for all the participants under the three thermal conditions: 20°C, 25°C, and 30°C. Dashed lines indicate the averaged scale values for all the participants for each thermal condition.

Fig. 2

Time-frequency and spatial regions of the three largest clusters for coolness. Upper rectangles of each participant show time-frequency maps of the sum of the t -values over all the MEG sensors. The lower circles for each participant show the topographic maps of the sum of the t -values over all the time-frequency points. The dots on the topographic maps indicate the MEG sensor locations.

Fig. 3

(a) A location of a frontal MEG channel with the maximum cluster mass in Cluster 1 of P1, and a location of a temporal MEG channel with the maximum cluster mass in Cluster 3 of P4. (b) Time-frequency representations of the relative power change induced by internal comparison at the frontal and temporal channels when P1 and P4 listened to the least cool/coolest stimulus after they listened to the coolest/least cool stimulus. (c) Time-frequency representations of t -values calculated in the cluster-based permutation test at the frontal and temporal channels. Regions surrounded by solid lines indicate the frontal and temporal clusters.

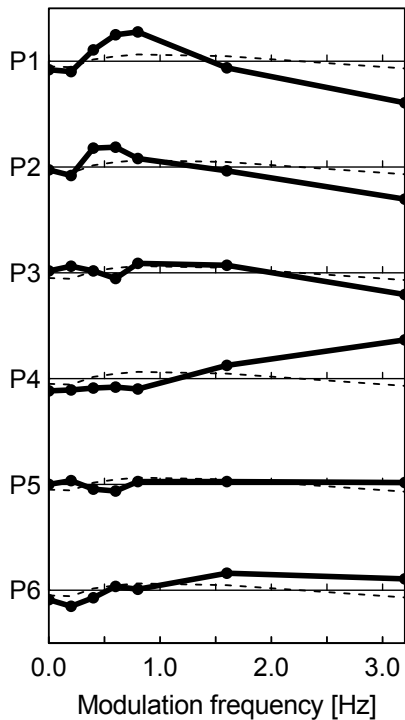
Fig. 4

Coarse current vector maps of the difference between the low-theta (4.0–5.2 Hz) activity when P1 listened the less cool stimulus and the low-theta activity when P1 listened the cooler stimulus at 3782.5 ms after the stimulus onset from the (a) top, (b) right-side, and (d) front views. Each square represents an MEG sensor, and a shaded one represents the sensor including the MEG channel with the maximum cluster mass in Cluster 1 of P1. The black and white circle indicate the left and right preauricular points, respectively. The black triangle indicates the nasion. (c) The low-theta oscillations at the MEG channel with the maximum cluster mass in Cluster 1 of P1. (e) A coarse current vector map of the difference between the alpha (6.7–11.3 Hz) activity when P4 listened the less cool stimulus and the alpha activity when P4 listened the cooler stimulus at 2895 ms after the stimulus onset from the left-side view. A shaded sensor represents the sensor including the MEG channel with the maximum cluster mass in Cluster 3 of P4. (f) The alpha oscillations at the MEG channel with the maximum cluster mass in Cluster 3 of P4.

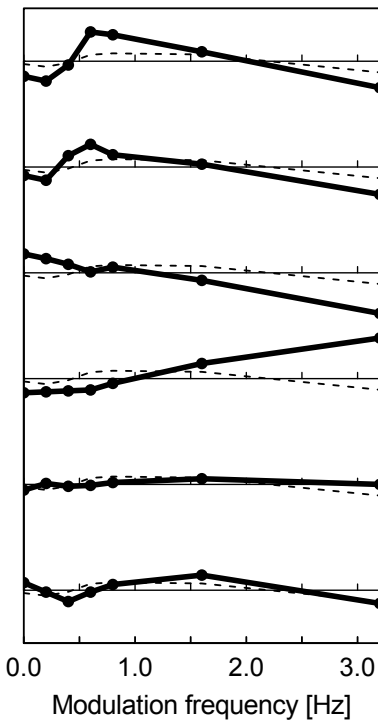
422 **List of Supplemental Digital Content**

423 Supplemental Digital Content 1. pdf

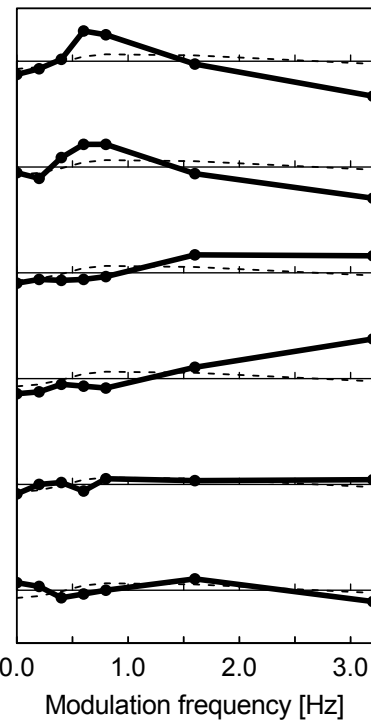
20°C

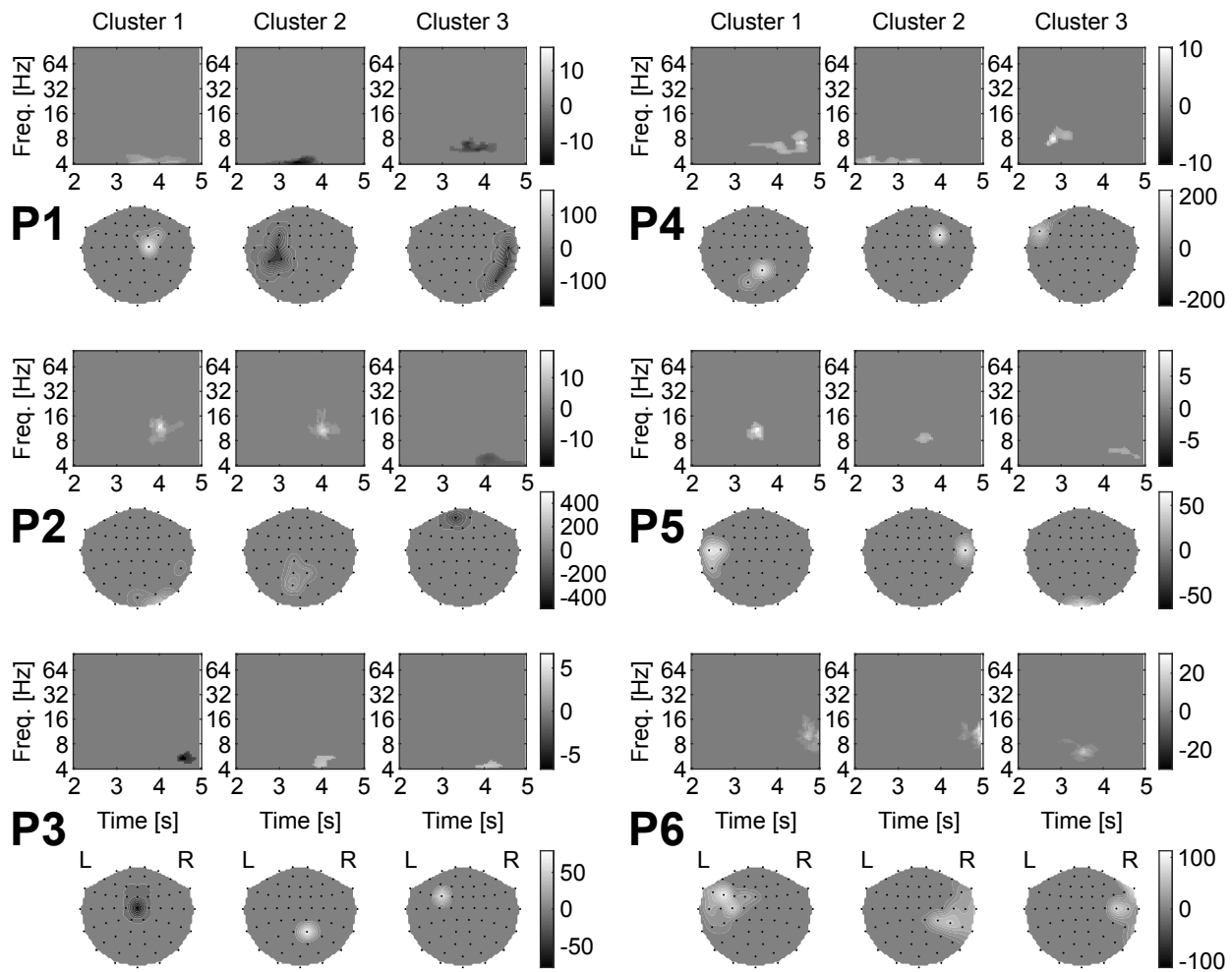


25°C

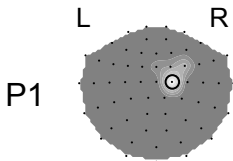


30°C

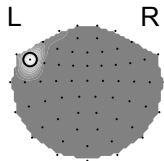




(a) Location



P4



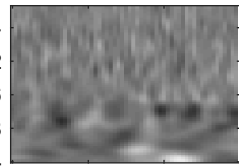
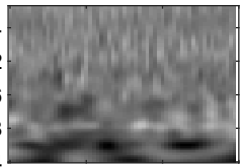
(b)

Relative power

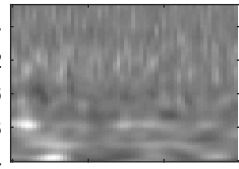
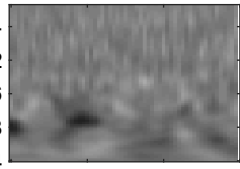
Least cool

Coolest

Frequency [Hz]

64
32
16
8
464
32
16
8
42
0
-2

Frequency [Hz]

64
32
16
8
464
32
16
8
45
0
-5

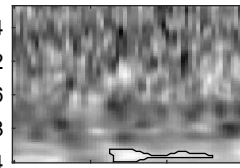
Time [s]

Time [s]

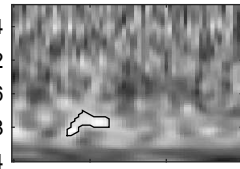
(c)

 T -values

Frequency [Hz]

64
32
16
8
44
2
0
-2
-4

Frequency [Hz]

64
32
16
8
44
2
0
-2
-4

Time [s]

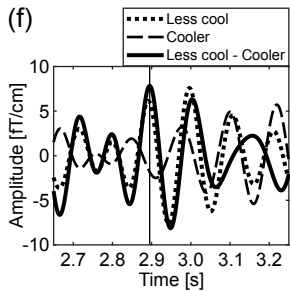
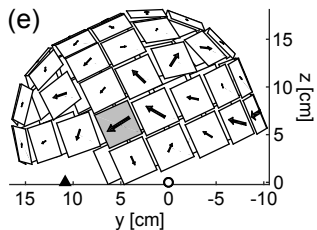
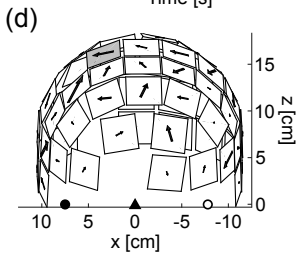
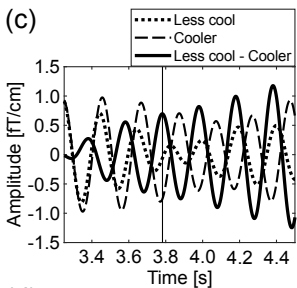
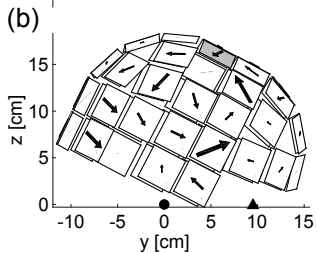
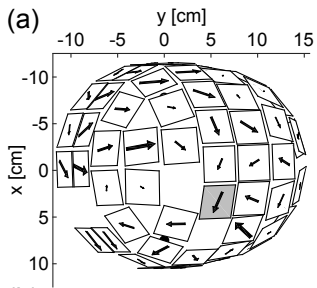


Table 1

The three largest clusters in the cluster-based permutation tests on comparison of coolness.

Partici pant	<i>P</i> -value		Cluster 1	Cluster 2	Cluster 3
P1	0.0340	Time range [ms]	3250–4600	2700–3900	3200–4250
		Frequency range [Hz]	4.0–5.2	4.0–5.0	5.7–8.4
		Cluster mass	658.9	– 649.0	– 591.4
P2	0.0100*	Time range [ms]	3750–4550	3700–4400	3800–4900
		Frequency range [Hz]	7.3–16.0	8.4–19.9	4.0–5.7
		Cluster mass	776.4	646.4	– 537.7
P3	0.3013	Time range [ms]	4450–4850	3800–4300	3800–4400
		Frequency range [Hz]	4.8–6.4	4.2–5.7	4.0–5.0
		Cluster mass	– 175.8	158.9	124.7
P4	0.0240*	Time range [ms]	3350–4700	2000–3550	2650–3250
		Frequency range [Hz]	5.4–9.9	4.0–5.0	6.7–11.3
		Cluster mass	580.8	469.7	339.9
P5	0.0410	Time range [ms]	3300–3650	3400–3800	4150–4850
		Frequency range [Hz]	8.4–13.5	7.7–9.9	5.0–6.7
		Cluster mass	302.6	129.7	124.5
P6	0.1154	Time range [ms]	4450–4950	4400–4950	2950–3850
		Frequency range [Hz]	6.4–18.2	6.7–14.7	5.0–9.1

Cluster mass	993.4	894.4	584.0
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Asterisks * indicate $p < 0.025$.