Investigating Haptic Perception of and Physiological Responses to Air Vortex Rings on a User's Cheek

Yuka Sato
Graduate School of Design, Kyushu University
Fukuoka, Japan
sato.y.715@s.kyushu-u.ac.jp

Ryoko Ueoka
Faculty of Design, Kyushu University
Fukuoka, Japan
r-ueoka@design.kyushu-u.ac.jp

ABSTRACT
Haptic perception is one of the primary means of interaction with the world. Recent research on affective haptics suggests that it can affect emotional and behavioral responses. In this study, we evaluate user perceptions of haptic stimuli generated by air vortex rings on the cheek and investigate the effects on their physiological responses. To develop a cheek haptic display, we investigated and found that the cheek had enough resolution to perceive the differences in haptic stimuli in a two-point discrimination threshold test of the face. Additionally, the intensities of the haptic stimuli for experiments were determined by investigating the subjective impressions of different stimuli pairs. Finally, we conducted experiments to evaluate quantitatively the effects of four different combinations of haptic stimuli on the physiological responses in terms of stress modification, brainwave activities, task performance, and subjective assessment. The results suggest that different stimuli affect physiological responses and task performance.

Author Keywords
cheek haptic interface; haptic perception; air vortex rings; physiological responses; subjective impression.

ACM Classification Keywords
H.5.2 Information interfaces and presentation (e.g., HCI): User Interfaces – Haptic I/O;

INTRODUCTION
Haptic perception is one of the primary means of interaction with the world and is developed in the early stages of childhood [6]. People learn about the world by physical contact through haptic stimulation. They will have experienced, especially in childhood, carrying and touching a charm, stuffed toy, or blanket to provide ourselves relief from stress. A trustworthy object that gives a sense of security when they touch is known as a security blanket [29]. They agree that some kinds of haptic stimuli relieve their own tension. In contrast, some kinds of haptic stimuli, such as that caused by touching a sharp tip, increases their own tension. In this way, various haptic perceptions give a variety of emotional and behavioral experiences. In fact, the existence of connections between interpersonal haptic feedback and human emotional responses are supported by both physiological and behavioral data in various research studies detailed in [6].

In addition, recent human-computer interaction studies suggest that haptic stimuli affect emotional as well as behavioral responses [7] [22]. These studies suggest that specific patterns of haptic stimulus induce different emotional states or different response times. This research topic is called affective haptics, and it focuses on the design of devices and systems that can detect, process, or display the emotional state of a human by means of the sense of touch. Further, it studies how haptics affects the emotional reactions of humans [4]. Emotional reactions are often quantitatively observed through physiological responses such as heart rate and galvanic skin response (GSR) [7]. Many interface devices have been proposed for sending emotional information by sense of touch. However, systems that characterize the emotional status of a user by haptic stimuli are still an understudied topic [4].

In most conventional HCI studies, haptic stimuli are given to the fingers or hands to investigate their effect on physiological or behavioral responses. This procedure is consistent because these body parts have a high haptic resolution and they are always exposed. However, the face could be another candidate for the locus of the interaction of haptic stimuli because it is always exposed; hence, it is possible to present the tactile stimulus directly on the skin. Indeed, people usually perceive haptic sensation of the wind while driving a car by opening a window, or of the softness of a towel on their faces.

In particular, we noticed that the cheek is where people feel the haptic sensation on a larger area than the nose or the mouth, though the nose and mouth have a higher haptic resolution than the cheek. Other facial areas, such as the forehead that has a larger area among the different facial areas, are susceptible to changes in sensitivity depending on the presence or absence of hair. The cheek is indeed the locus of communication through haptic stimulation such as pecking on someone′s cheek for greeting them, which is similar to the form of haptic communication such as a handshake. Therefore, the cheek is an appropriate locus of interaction for a haptic display on the facial area.

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Since there are no investigations on haptic perception on a user′s cheek yet, we developed a prototype cheek haptic display to evaluate how people perceive haptic stimuli on their cheeks. In order to present haptic stimulus on the cheek, preferably contactless to prevent obtrusiveness, we chose air vortex rings as haptic stimuli for our prototype cheek haptic display. The vortex ring from an air cannon differs from the jet-type wind; it does not diffuse and it travels a long distance with unchanged strength, so it can present a tactile stimulus without contact. Additionally, it generates various haptic intensities by changing the air pressure; hence, it is possible to investigate the difference in impressions depending on the intensities being applied on the cheek.

To develop an interactive cheek haptic display, we first conducted a two-point discrimination (TPD) threshold test of the face to evaluate whether the cheek was sensitive enough to perceive the different haptic stimuli generated by air vortex rings, as a benchmark test for the sensitivity of the air vortex ring haptic stimuli. Second, we developed a prototype interactive cheek haptic display that generated strong and weak air vortex ring intensities by controlling the air pressure in either two or five-second intervals. The intensity of the haptic stimulus was determined by the subjective impression test of the haptic stimuli of different stimuli pairs. Finally, using our prototype system, we also conducted experiments to evaluate quantitatively whether the cheek haptic display, with four different combinations of haptic stimulus intensities and time intervals, affected physiological responses in terms of stress modification. This was accomplished by using changes in the low frequency/high frequency (LF/HF), brainwave activities measured with a portable brainwave sensor (EMOTIV EPOC+) as a pilot test, task performance by analyzing the task performance scores, and a subjective assessment of three feelings: fatigue, conscious drowsiness, and carelessness.

The results suggest that some combinations of haptic stimuli from the air vortex rings induce significantly different physiological responses, although subjective assessment is not affected. In addition, the specific responses or changes observed for the air vortex ring haptic stimuli were not seen for the simple vibration haptic stimulus.

RELATED WORK

Interfaces Using an Air Vortex Ring for Haptic Feedback

As a haptic interface for an unobtrusive interactive media system, air pressure has been suggested [24] [10].

Air vortex rings have also been applied as a non-contact haptic feedback system for gaming [23] [9] or three-dimensional (3D) theater [11]. An air vortex ring has the characteristic of travelling a long distance without decreasing its intensity or velocity. Therefore, it is considered to be a good stimulus for a non-contact haptic displays. These previous approaches mainly used air or vortex rings to add multi-modal sensations to audio-visual media for increasing the sense of immersion of conventional media. Hence, although they applied air vortex ring as a haptic feedback, the purpose of this research is different. Another noticeable difference from previous work except for [11] is that they presented haptic feedback at a single intensity. Because our research goal is to develop a haptic display with various haptic feedback types to control physiological responses of a user, our system has the ability to generate air vortex rings of various intensities. Furthermore, these haptic displays were hand-dominant, and there is not yet a device that presents haptic feedback to the cheek. In [11], the authors presented haptic feedback at two intensities on the face to increase the sense of immersion for 3D theater. The presenting area and function of the display are similar with our research, however the research purpose is different.

Affective Change by Haptic Feedback Systems

Different patterns of brain activities that address the neural aspects of interpersonal touch [19] [20] were scientifically observed by Rolls et al. Different intensities of touch significantly affect brain activities, which is evidence that physiological responses are generated by haptic stimulus. Although in [4], EID described how physiological reactions such as heart rate, facial expressions, electrodermal activity, gesture expressions, or brain activities are possible methods for measuring the quality of experience to observe how a user emotionally reacts to haptic stimuli, there are few studies that use these methods to measure affective haptics quantitatively.

In [7], Gatti et al. measured physiological responses that are related to the responses to emotional stimuli. Although they did not find significant correlations between emotional state with and without friction-based haptic feedback rated by self-assessment and physiological responses, they noted that further investigation might find evidence for relations between haptic interactions and emotional states.

Nishimura et al. proposed a cushion-type tactile feedback device that simulates a false heartbeat for a user to influence his/her evaluation of the attractiveness of female/male images [14]. Although it was a pilot study, they reported that false heartbeats generated by vibrotactile feedback could alter physiological or emotional states.

Alonso et al. proposed Wigo, which is a tangible hand grabbing interface prototype that detects stress by using the trembling motion of a user′s hand and provides haptic feedback to support stress reduction [1]. Although a specific result was not obtained, in a small pilot study, the participants said that they appreciated the haptic feedback provided, which helped them relax.

Behavioral Change by Haptic Feedback Systems

Currently, few studies have investigated behavioral change using a haptic interface.

A previous study used a friction-based horizontally rotating fingertip haptic stimulator to investigate behavioral change in terms of response time by varying burst length, continuity, and direction [21]. Of 528 stimulus pairs, they concluded that stimuli with discontinuous forward rotation in a long bursts (100 ms) and continuous forward-backward rotation in short bursts (20 ms) caused the fastest and most accurate reactions. This outcome suggests that even for simple haptic feedback on a fingertip, participants distinguished the stimulus and unconsciously reacted with different behavioral patterns to specific stimulus pairs. This result encourages the hypothesis that different pairs of intensity and interval times generated by our cheek haptic display has the potential to change responses.

FatBelt is an interactive haptic feedback system for motivating dietary control. It gives physical feedback using an inflatable pack worn around the stomach [18]. The authors conducted a two-day experiment and found out that the haptic feedback impacted participants' physical self-concepts. When eating excessive calories, the participants felt like they had actually grown fat. This proof-of-concept work has the potential to actively change a user's dietary behavior by haptic feedback.

TWO-POINT DISCRIMINATION THRESHOLD OF FACE

In order to evaluate whether the cheek is an appropriate body area for tactile stimulation, we evaluated the tactile discrimination ability of 14 areas of the face using the TPD threshold test.

The TPD test measures basic touch acuity by evaluating how far apart two separate points need to be before they are perceived as two points rather than one. We agree that tactile stimulus response is related to the reactions of various mechanoreceptors, so it is not appropriate to conclude that there is a relationship between the accuracy of the tactile stimulus of the TPD test and that of the vortex ring. However, as there are no previous studies on tactile presentation on the cheek, we thought that quantifying the check tactile precision by TPD test could become a useful benchmark. The facial surface is known to be a very sensitive part of the body for perceiving tactile stimulation. According to the Weinstein's TPD test results, the two-point threshold is the second smallest on the face compared to all other body parts [25]. In Weinstein's TPD test, the detailed spatial acuity of the facial surface was not evaluated.

Thus, to verify this previous finding, we conducted a TPD test on 14 areas of left and right side of the face twice to observe the detailed spatial acuity of the facial surface. The minimum distance of the two-point stimulus was 1 mm and the maximum distance was 14 mm. We used an adjustable two-point caliper with a tip radius of 0.5 mm as the TPD stimuli. Applying the method of limits [17] with a gap size of 1 mm randomly tested on each participant, we investigated how far apart two separate points need to be in order to be perceived as two points by poking the cheek surface applying the caliper at right angle for making a hollow of skin about 2 to 4 mm. Examiners did sufficient practice for giving equal pressure of stimulus in each facial area before conducting the experiment. Ten participants (6 males, 4 females, mean age 21.3 years) participated the experiment.

Figure 1 shows the mean TPD results of the 14 facial surface areas. The bottom parts of the face have higher spatial acuity than the upper parts, and the lip areas (areas 10 and 11) have the highest spatial acuity. However, the cheek area (area 9) also has a high spatial acuity (5.8 mm), and is the fifth-highest spatial acuity of the 14 areas.
In conclusion, cheeks have a high spatial acuity, which is sufficient to be able to perceive the difference of various air vortex ring pressures. In addition, as we are able to induce tactile sensations directly on the skin over a comparatively wide and flat area, we concluded that the cheeks are the best area for presenting haptic stimuli.

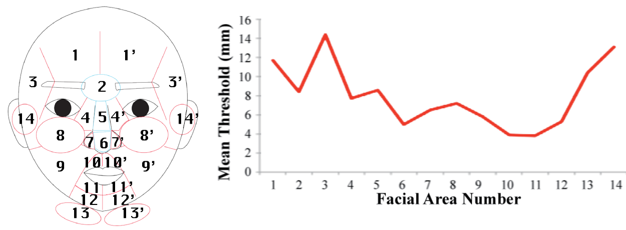

Figure 1. Areas of the face (left) and mean two-point discrimination threshold for each facial area (right)

DEVELOPMENT OF INTERACTIVE CHEEK HAPTIC DISPLAY SYSTEM

Principle of an Air Vortex Ring

We developed an interactive cheek haptic display using a diaphragm valve-type air cannon. When stress is detected, air vortex rings are presented on the cheek for one minute. When the valve is opened by an electrical switch, compressed air is pushed from the tank and it travels towards the surface of the air cannon, as in a microburst, poloidal spinning is generated by viscous friction between the layer of fast outward flow near the surface of the air cannon and the slower-moving fluid above it, and an air vortex ring is generated, as Figure 2 shows. The diameter of an air vortex ring D was set to about 100 mm, based on the average surface cheek area of Asian adults [16].

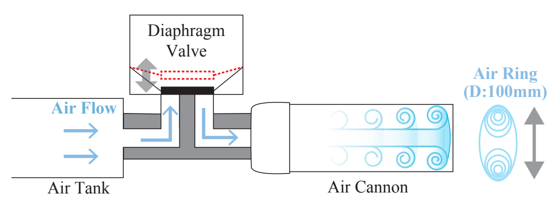

Figure 2. Generation of an air vortex ring

When the tank of the system is filled with air that is relatively higher in pressure than the atmospheric pressure (0.1013 MPa), it generates an air vortex ring with a faster speed, which gives the impression of a strong haptic sensation when it is presented. In contrast, relatively lower pressure air in the tank generates an air vortex ring with slower speed, which gives an impression of a weak and soft haptic sensation when it is presented.

Figure 3 shows a system diagram of the cheek haptic display. Given the radius of the vortex ring we wanted to generate, we chose the aperture D′ of the air cannon to be 50 mm. The principle of air vortex rings states that $D'/L \leq 4$, where L is the length of the cylindrical slug of air pushed out of the nozzle [28]. This ratio is the theoretical threshold value needed to generate the optimum air vortex ring; however, in practice, it usually differs for various vortex systems [23]. We empirically found the optimum ratio to be six in our experimental setup, meaning that the best value for L was 300 mm. Thus, the volume of the air tank is 392.5 cm^3. From this air tank, air at variable pressures is transferred to the air cannon, which creates a stable vortex ring that travels to the surface of the cheek. A silent air compressor and a 20-l air tank containing 0.3 MPa compressed air are connected to the air pressure regulator (SMC ITV2030-212S) that controls the pressure of the compressed air that flows to the air tank. A silent air compressor fills the tank with 0.3 MPa compressed air for about 1.5 min. Figure 4 shows the prototype system. It is portable, can be disassembled easily, and can be installed at any indoor location. The control signals of the diaphragm valves and the air pressure regulator are sent via an Arduino UNO from the device control PC.

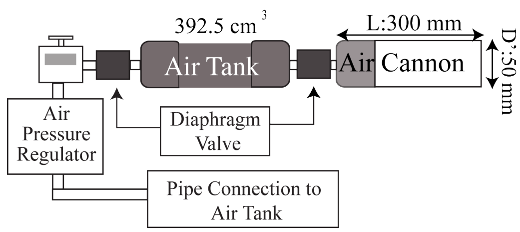

Figure 3. Vortex ring generation system

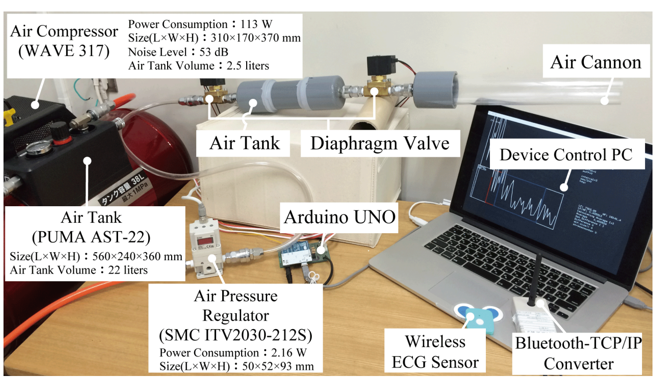

Figure 4. Prototype system

Determining Distance from an Air Cannon to Cheek

Experiment Procedure

Although vortex rings were generated immediately after they were expelled from the air cannon, a certain distance was required to form stable vortex rings. In order to determine the best distance from the nozzle of the air cannon to the cheek for displaying stable vortex rings, we conducted an experiment on all pneumatic pressures used in the experiments in this study and performed an experiment to determine the optimum distance for a vortex ring stabilization by measuring the point of generation and disappearance of a vortex ring. We then calculated the acceleration speed for every 5 cm interval. The minimum value of air pressure (0.06 MPa) was the weakest value of air pressure that would generate an air vortex ring. The maximum value of air pressure (0.20 MPa) was limited by the air pressure of the system′s regulator. We conducted 100 trial experiments on eight air pressure values (0.06 - 0.20 MPa in steps of 0.02 MPa) and recorded the generation process using a 240 fps high speed camera (iPad Pro). When setting the experimental environment, we used a black textile as a background to increase the visibility of the vortex ring and used a 100 cm stainless ruler as an objective index. Using the reference lines at every 5 cm interval overlaid on the video, we calculated the speed of a vortex ring in steps of 5 cm by referring to the video frame (4.16 ms/frame) and calculating the acceleration speed in each interval. We also measured the generation and disappearance point of the vortex ring from the video.

Result

Figure 5 shows the mean acceleration speed for each 5 cm interval. In every condition, acceleration speed instantly increases right after the generation of the vortex ring and then decelerates until the acceleration speed reaches zero. The mean distance of the zero acceleration point is 35.0 cm. The generation points of the vortex rings for all conditions range from 15.1 to 25.0 cm. Furthermore, the disappearance points range from 40.1 to 100.0 cm depending on the value of the air pressure. Within the range 30.1 to 40.0 cm, no vortex rings are generated or disappear. Using these results, we set the optimum distance from the tip of the cannon and the cheek to be from 35.0 to 40.0 cm. The acceleration speed is zero and the air vortex ring is stable. As it could cause a subtle difference during an experiment, we set the distance of the system to 40.0 cm so that it intrudes on the desk as little as possible.

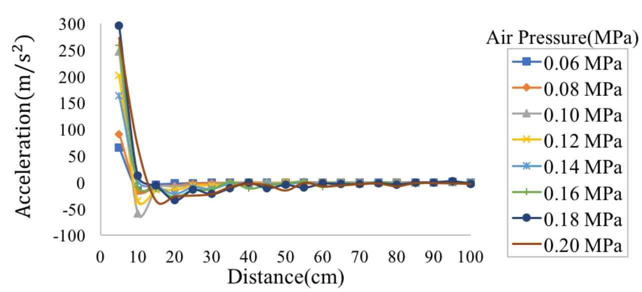

Figure 5. Acceleration speed of eight air pressure values

Subjective Impression Evaluation of Different Air Pressures of Air Vortex Rings

Experiment Procedure

In order to determine the value of air pressure needed to generate air vortex rings with different haptic perceptions on the cheek, we investigated whether the different intensities lead to different impressions of the haptic stimulus to determine the parameters for strong and weak haptic stimuli. Eight air pressure values (0.06 – 0.20 MPa in steps of 0.02 MPa) and two time intervals (2 and 5 s) were used for determining these parameters. In order to eliminate the order effect, we presented the sixteen conditions randomly to each participant. After each condition, participants answered questions using a seven-point bipolar semantic differential scale varying from +3 to -3 that had opposite adjectives at each end. As Table 1 and 2 show, ten types of adjectives pairs depicting intensity and six types of adjectives pairs depicting emotion were chosen from a previous experiment conducted by Hashiguchi et al. [12]. Ten participants (3 males, 7 females, mean age 21.3 years) participated in the experiment. The distance between a participant's cheek and the tip of the air cannon was fixed at 40.0 cm. In order to eliminate the effect of the sound generated when compressed air was expelled from the air cannon, a clamshell noise cancelling headset (SONY MDR-NC600D) playing a white noise sound was worn during the experiment. In addition, in order to avoid visual effects, we asked participant to close his/her eyes during the experiment. Air vortex rings for each condition were presented for 30 s.

	+3	0	-3
(1)	smooth	-	bouncing
(2)	tender	-	painful
(3)	protective	-	piercing
(4)	normal	-	shocking
(5)	patted	-	tapped
(6)	light	-	heavy
(7)	calm	-	furious
(8)	weak	-	strong
(9)	soft	-	solid
(10)	gentle	-	sharp

Table 1. Adjectives pairs for determining the impressions of intensity of the haptic stimuli generated by air flow (from Hashiguchi et al. [12])

	+3	0	-3
(a)	easy	-	uneasy
(b)	comfortable	-	uncomfortable
(c)	safe	-	scary
(d)	relaxed	-	tensed
(e)	calm	-	surprised
(f)	natural	-	artifical

Table 2. Adjectives pairs for determining the impressions of the haptic stimuli generated by air flow (from Hashiguchi et al. [12])

Results

Figure 6 shows the results of the mean impression of intensity of each of the ten types of adjective pairs for 16 conditions. We applied a two-way (2 interval times × 8 air pressures) ANOVA to all ten pairs, which showed a statistically significant difference between each air pressure ($p < .0001$). There was no significant difference between the interval time and no significant difference among the interactive effects between time and air pressure. The results showed that increasing the value of air pressure changed the impression from positive to negative gradually, independently of time interval. In order to determine the values for weak and strong haptic stimulus impressions for use in the experiments, Pearson's correlation coefficient for each adjective pair was applied and showed a statistically significant correlation between all pairs of two variables ($p < .001$). We then applied a two-way (2 interval times × 8 air pressures) ANOVA to the mean impression of the all ten types of pairs, which showed a statistically significant difference between the impression of each air pressure ($F(7, 8) = 129.9$, $p < .001$). There was no significant difference between the interval time and no significant difference among the interactive effects (interval time × air pressure). The results show that the air vortex ring generated by the air at 0.06 MPa generated the weakest impression and the air at 0.18 MPa generated the strongest impression on the cheek.

Figure 7 shows the results of the mean impression of all six types of adjective pairs for 16 conditions. A two-way ANOVA showed a statistically significant difference between the impression of each air pressure ($p < .0001$). There was no significant difference among the interactive effects.
The two adjective pairs (safe–scary, calm–surprised) showed a statistically significant difference between the impression for each time interval ($p < .01$). These results show that the difference of intensity or interval time of the haptic feedback generated by the air vortex ring could give the affective impression of a heartbeat experience. For the easy–uneasy and comfortable–uncomfortable pairs, there was not much difference among the 16 conditions. This indicates that the air vortex ring haptic stimulus is not good at expressing impressions along these axes, however, this could also imply the haptic stimulus was not very annoying under any condition.
Given the significant differences among the air vortex ring haptic stimuli for six impression adjective pairs, we reconfirmed that the air at 0.06 MPa and 0.18 MPa could deliver haptic feedback of different impression of intensities as well as emotions to the participants.

EXPERIMENT 1: PERCEPTION OF AIR VORTEX RINGS

We conducted an experiment to evaluate whether haptic stimuli generated by the air vortex rings could affect physiological responses. We also analyzed whether different stimulus parameters (intensity and time interval) led to different responses.

When the compressed air is pushed out of the nozzle and generates an air vortex ring, a discharge sound is also generated. Even though the participants used noise canceling earphones playing a white noise sound to eliminate surrounding noise, the discharge sound was not completely eliminated. Therefore as a control condition stimulus in this experiment, we used the prerecorded discharge sound of the 0.06 MPa/5 s condition. By comparing the effect of the control condition with the other conditions, we are able to evaluate whether any change of physiological responses are caused by the effect of pure haptic stimulus. When the control condition was executed, the speaker (Gateway Edison 2.0) was set at a distance of 40.0 cm from the cheek.

We intentionally created a stressful situation by asking the participants to perform 30-min SPI and TOEIC exercises on the PC. Five exercise sets of four 30-min tasks were created by combining SPI and TOEIC exercises chosen from textbooks. The time limit of an exercise was taken from the textbook. The exercises with longer time limits were more difficult and those with shorter time limits were easier. When

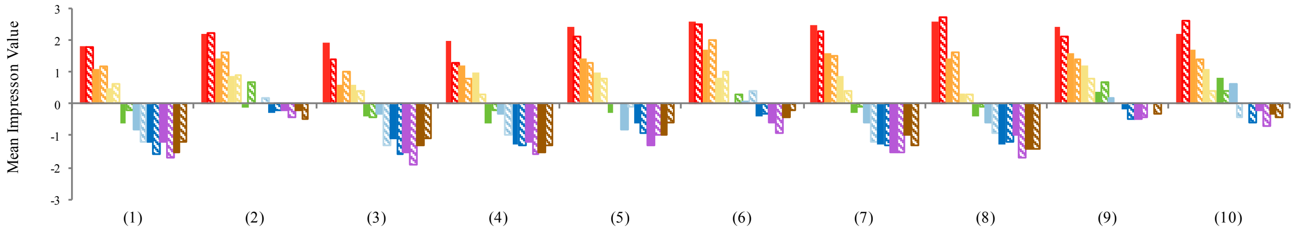

Figure 6. Impression of intensity of sixteen conditions. Solid (2-s interval) and strip (5-s interval) colors represent eight air pressure values (0.06 – 0.20 MPa in steps of 0.02 MPa) respectively. The numeric letters of x axis are equivalent to the numeric letters of Table 1.

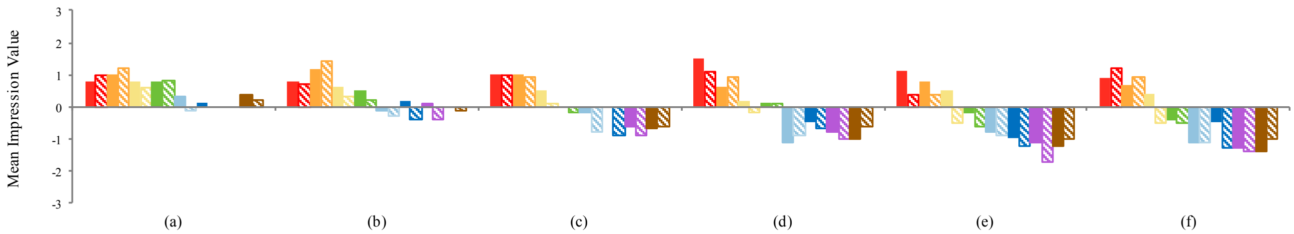

Figure 7. Impression of sixteen conditions. Solid (2-s interval) and strip (5-s interval) colors represent eight air pressure values (0.06 – 0.20 MPa in steps of 0.02 MPa) respectively. The alphabetical letters of x axis are equivalent to the alphabetical letters of Table 2.

the system detected that the participant was in a stressed state, haptic stimuli or audio stimuli were presented. Four set of tasks were conducted for each experiment. The flow of the experiment is illustrated in Figure 8.

Duration	5 min	30 min	30 min	30 min	30 min
Task	Pre-rest	Task 1	Task 2	Task 3	Task 4
Validation of VAS	Yes	Yes	Yes	Yes	Yes
ECG measurement	→	→	→	→	→
EEG measurement	→	→	→	→	→
Cheek haptic display		Baseline Stress level	When the stress level exceeded the baseline, 60 s of air vortex rings were applied to the cheek.		

Figure 8. Experiment flow for experiment 1

In order to detect a participant's stress state, we monitored the increase in the LF/HF of an ECG over its baseline. The ECG was measured by a wireless sensor at 204 Hz (RF-ECG2 GM3) and a customized Bluetooth-TCP/IP signal converter that received the signal and converted it to inter-beat (R-R) intervals to calculate the power spectrum using a fast Fourier transform. We extracted and accumulated both the LF (0.04 to 0.15 Hz) and HF (0.15 to 0.5 Hz) to calculate the LF/HF for the stress state analysis. The baseline of the stress state of each participant was determined by the mean LF/HF of the first task. An increased stress state was then identified when the LF/HF was higher than the baseline for more than 20 of the latest 30 samples. In this case, a haptic stimulus was applied to the cheek for 60 s. The ECG not only interactively monitored a participant's stress state, it also recorded this state during the experiment in a stress state log.

In order to monitor physiological response, we also used a commercial brainwave sensor (EMOTIV EPOC+), which is a wireless 14 channel EEG sensor [5]. Four emotional labels, short-term excitement, meditation, frustration, and engagement, were calculated by the sensor at 256 Hz, and we recorded the value of four affective parameters scaled from 0 to 100 for further analysis using a program we developed in the Xcode environment of OS X using the EMOTIV SDK.

Eleven participants (6 males, 5 females, mean age 21.8 years) participated in the experiment. We combined weak or strong air pressure (0.06 or 0.18 MPa) with short or long intervals (2 or 5 s) to form the haptic stimulus pairs. All participants performed each combination on different days. The experiment was conducted in a partitioned laboratory room with a black curtain to prevent the entry of surrounding visual noise. We set up the experiment in a room with closed windows and controlled temperature set to 25 °C without blowing the air conditioner on the participants. During the experiment, the participant wore an in-ear canal noise canceling headset (SONY MDR-NC300D) playing a white noise sound to standardize the noise environment among the participants. They were asked to have sufficient sleep on the eve of the experiment and finish their lunch at least one hour prior to its start. An example of a participant performing the experiment is shown in Figure 9.

RESULTS

We evaluated the stress state using the LF/HF change as well as observed the absent/focused state using brainwave activities. We also evaluated overall task performance and self-reported assessments of three feelings.

LF/HF Change

We evaluated the mean LF/HF ratio to analyze the effect of each condition on participant stress. The difference in LF/HF from tasks 2 to 4 on the basis of the mean LF/HF ratio of a

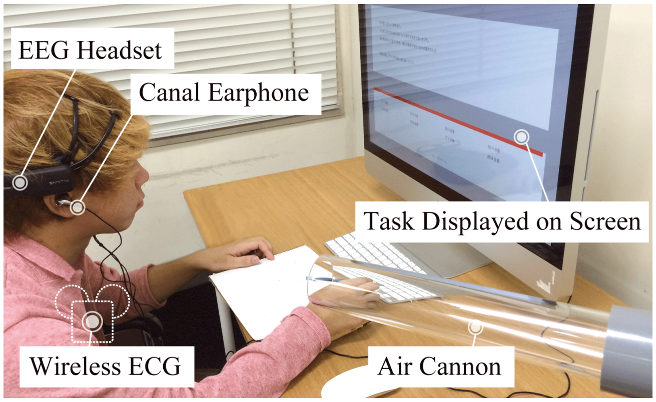

Figure 9. Experimental setup (experiment 1)

5-min pre-test was calculated. The results are shown in Figure 10. As we found no homogeneity of variance, we used a non-parametric one-way ANOVA (the Kruskal-Wallis test) to analyze the results. There was a significant difference ($X^2 = 82.329$, df = 4, $p < .0001$) among them. A non-parametric multiple comparison using the Steel-Dwass test was used for pairwise analysis. Three conditions of the cheek haptic stimuli (0.06 MPa/5 s: M = 1.025, SD = 0.312; 0.18 MPa/2 s: M = 0.984, SD = 0.364; 0.18 MPa/5 s: M = 1.026, SD = 0.362) were significantly different from the control condition (M = 1.144, SD = 0.362, $p < .01$). The 0.06 MPa/2 s condition was not significant compared to the control condition ($p = .053$). Among the four haptic stimuli conditions, the 0.18 MPa/2 s condition modified the increase in stress significantly with respect to the other three conditions (0.06 MPa/2 s, 0.06 MPa/5 s ($p < .01$), 0.18 MPa/5 s ($p < .05$)). On the other hand, the 0.06 MPa/2 s condition significantly increased the stress state (0.06 MPa/5 s, 0.18 MPa/5 s ($p < .05$), 0.18 MPa/2 s ($p < .01$)). The reason for this result is discussed in the discussion section.

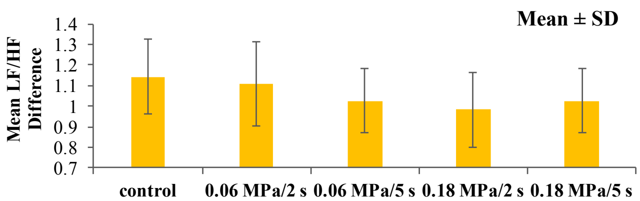

Figure 10. LF/HF change (experiment 1)

Brainwave Activities

In order to observe brainwave activities, we analyzed the ratio of meditation/short-term excitement as the "absent" index and engagement/frustration as the "focused" index using the scores of the four emotional labels that were provided by EMOTIV. Figure 11 shows the results for the absent and focused indices of each condition. For the absent index, as we found no homogeneity of variances, we used a non-parametric one-way ANOVA (Kruskal-Wallis test) for the analysis. There was a significant difference ($X^2 = 50.108$, df = 4, $p < .0001$) among the five conditions. A non-parametric multiple comparison using the Steel-Dwass test was used for pairwise analysis. Two conditions of the haptic stimuli (0.06 MPa/5 s: M = 0.765, SD = 0.819, $p < .01$; 0.18 MPa/2 s: M = 0.735, SD = 0.471, $p < .05$) were significant with respect to the control condition. Other two conditions of the haptic stimuli (0.06 MPa/2 s and 0.18 MPa/5 s) were not significant compared to the control condition.

As for the focused index, as we found no homogeneity of variances, we used a non-parametric one-way ANOVA (Kruskal-Wallis test) for the analysis. There was a significant difference ($X^2 = 110.06$, df = 4, $p < .0001$) among the five conditions. A non-parametric multiple comparison using the Steel-Dwass test was used for pairwise analysis. We found that the two 0.06 MPa conditions led to a significantly less focused state than the control condition (0.06 MPa/2 s: M = 1.205, SD = 0.864; 0.06 MPa/5 s: M = 1.436, SD = 0.765, $p < .0001$), whereas the 0.18 MPa/5 s condition led to a significantly highly focused state compared to the 0.06 MPa/5 s condition ($p < .01$).

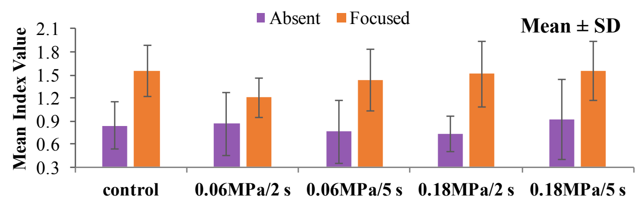

Figure 11. Absent/Focused index (experiment 1)

Task Performance

Because the difficulty of each task was different and the ability of each participant was variable, we did not count the correct/incorrect answers out of the total questions but instead calculated the score based on the difficulty of each task and normalized it. The score for each exercise was determined by its time limit. To normalize the scores, the difference of the mean scores of tasks 2 to 4 with respect to the mean score of the first task was calculated. Figure 12 shows the results.

After confirming the homogeneity of variances by Bartlett's test, a one-way ANOVA was used to compare the task performance under the five conditions. There was a significant difference ($F(4,160) = 3.519$, $p < .01$) among them. A multiple comparison using the Holm method was used for pairwise analysis. The result shows that there are significant differences between two pairs: the 0.18 MPa/2 s (M = 3.389, SD = 7.671) and control conditions (M = -3.654, SD = 10.290, $p < .05$) and the 0.18 MPa/2 s and 0.06 MPa/2 s conditions (M = -1.943, SD = 8.944, $p < .05$).

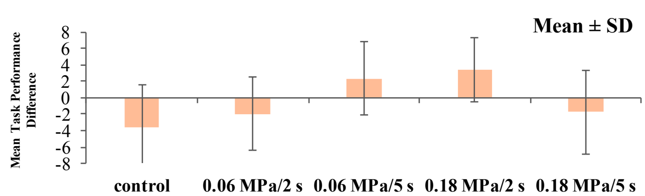

Figure 12. Task performance (experiment 1)

Subjective Assessment

We used a visual analog scale (VAS) of the self-reported ratings of three feelings: fatigue, conscious drowsiness, and carelessness. VAS is a measurement instrument that tries to measure a characteristic or attitude that is believed to range across a continuum of values and cannot easily be directly measured [8]. VAS is operationally a horizontal line and we set the scores of the line in this experiment to range from 0 to 100. A participant marks the line at the point that they feel represents his/her perception of his/her current state.
Figure 13 shows the difference of the mean VAS of tasks 2 to 4 with respect to the mean VAS of the first task. We found no significance among the differences of the five conditions for the three subjective feelings.

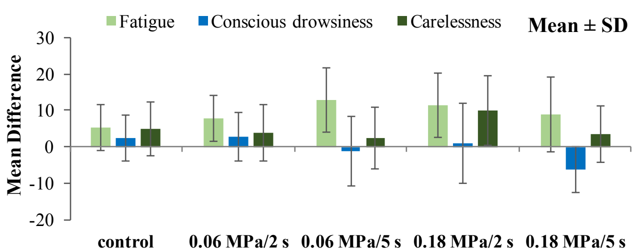

Figure 13. Subjective assessment (experiment 1)

DISCUSSION

All the haptic stimulus conditions, except the 0.06 MPa/2 s condition, successfully inhibited the increase in stress during the experiment. In particular, the 0.18 MPa/2 s condition inhibited the increase in stress significantly, as compared to all other conditions. The results of the absent/focused index analysis showed that the focused index increased while the absent index decreased. These results suggest that the strong haptic stimulus of an air vortex ring with short interval affects the stress state and modifies concentration. For the 0.06 MPa/2 s condition, we observed no modification in the stress. Further, the level of the stressed state was the highest for the cheek haptic stimuli conditions.

These results suggest that the weak haptic stimulus of an air vortex ring with a short interval had little effect on the stress modification. A feedback from participants implied that the 0.18-MPa intensity felt strong and the 0.06-MPa intensity felt gentle or very weak as a haptic sensation, suggesting that they perceived two intensities as different stimuli. In addition, they commented that 2-s interval stimuli were more rhythmic than 5-s interval stimuli. We assumed that the 0.06 MPa/2 s condition–the rhythmic patting of weak intensity haptic stimuli on the cheek–induced an absentminded state, and the participants tried to stay awake during the experiment so that the level of the stressed state was kept high.

In addition, both the 0.06 and 0.18 MPa at 5 s intervals inhibited the increase in stress compared to the control and the 0.06 MPa at 2 s interval. However, the differences in effects between the two conditions were not significant, which suggests that these haptic stimuli affect the stress modification, but a longer time interval may reduce the effect of the difference in haptic intensities. The absent/focused index analysis indicated that both conditions showed a synchronous decrease or increase in both indices compared to the control condition. As the algorithm for the calculation of the emotional labels provided by EMOTIV is not openly available [3], we could not conclude whether the synchronous state of both indices suggested any meaningful result.

As for the task performance, the 0.18 MPa/2 s condition improved the score significantly compared to the control condition as well as the 0.06 MPa/2 s condition. This suggests that the 0.18 MPa/2 s condition caused an increase in the scores whereas the 0.06 MPa/2 s condition caused a decrease in the scores. Both the 0.06 and 0.18 MPa at 5 s intervals had no significance among any of the conditions, which suggests that these cheek haptic-stimuli conditions hardly affected the task performance.

With regard to the subjective assessment, we found no significant difference among all the conditions for the three subjective feelings. One of the reasons for this may be that the series of two-hour problem solving tasks would increase the feelings in these three questions under any condition, so the difference caused by each condition was unclear.
To summarize the results of this experiment, we found that the 0.18 and 0.06 MPa at 2 s intervals had significant differences in the LF/HF change, absent/focused index, and task performance.

EXPERIMENT 2: COMPARISON AGAINST VIBROTACTILE FEEDBACK

In the previous experiment, we found that certain haptic stimuli generated by air vortex rings affect physiological responses. As a comparative experiment, we evaluated whether a haptic stimulus generated by a vibration motor affects them. The procedure of the experiment was the same as that of experiment 1.

The vibration motor was chosen as a comparative stimulus because it is able to present haptic stimulus locally on the cheek area. An air fan was another candidate for the comparative stimulus. However, the air is diffused by the time it reaches the cheek. Hence, this stimulus does not present local stimulus on the cheek like an air vortex ring does. The results of this experiment are limited because we compared only one type of simple vibration stimulus, and a comparison with vibration stimulus does not generalize to all cases. For instance, Obrist et al. [15] presented the design potential of mid-air haptic stimuli for non-arbitrary emotion communication by modulating the frequency, intensity, and duration of ultrasonic haptic feedback.
We intend to evaluate the results in this experiment as a baseline test to compare the results of experiment 1.

As the vibration stimuli, a coin type vibration motor (TPC Motor FM34F: standard voltage 3.0 V, standard speed 13,000 rpm, standard current 100 mA, vibration quantity 17.6 m/s^2 (1.8 G)) was used. The intensity of the stimulus was determined by specifications of the motor, which vibrated at 216 Hz. It was wrapped in a soft cloth and placed on a cheek of the participant using surgical tape. The vibration pattern imitated the standard vibration pattern of a smart phone: a 0.5 Hz 50 % duty signal was presented for 60 s when the system detected that the participant experienced stress. The vibration was controlled by software using an Arduino UNO. Eleven participants (6 males, 5 females, mean age 21.3 years) participated the experiment.

RESULTS

We compared the results obtained under the two haptic stimulus conditions, 0.06 MPa/2 s and 0.18 MPa/2 s, which were found to affect the physiological responses significantly in experiment 1.

LF/HF Change

The result of LF/HF change is shown in Figure 14. As we found no homogeneity of variances, we used a non-parametric one-way ANOVA (Kruskal-Wallis test) for the analysis. There was a significant difference (X^2 = 30.661, df = 2, $p < .0001$) among the three conditions. A non-parametric multiple comparison using the Steel-Dwass test was used for pairwise analysis. The result showed that the change in LF/HF for the vibration condition (M = 1.062, SD = 0.44) was significantly low compared to that of the 0.06 MPa/2 s condition and significantly high compared to that of the 0.18 MPa/5 s condition ($p < .05$).

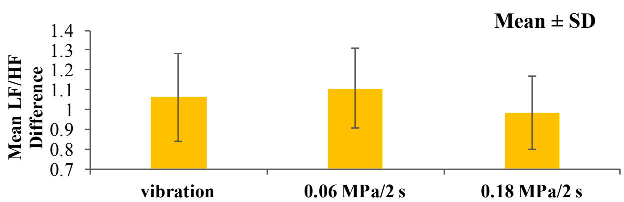

Figure 14. LF/HF change (vibration vs. air vortex ring)

Brainwave Activities

Figure 15 shows the results of the mean absent/focused state. For the absent state, as we found no homogeneity of variances, we used a non-parametric one-way ANOVA (Kruskal-Wallis test) for the analysis. There was a significant difference (X^2 = 29.194, df = 2, $p < .0001$) among three conditions. A non-parametric multiple comparison using the Steel-Dwass test was used for pairwise analysis. The results show that the vibration condition (M = 1.045, SD = 1.419) induced a significantly higher absent state than the 0.18 MPa/2 s condition ($p < .0001$). For the focused state, as we found no homogeneity of variances, we used a non-parametric one-way ANOVA (Kruskal-Wallis test) for the analysis. There was a significant difference (X^2 = 57.852, df = 2, $p < .0001$) among the three conditions. A non-parametric multiple comparison using the Steel-Dwass test was used for pairwise analysis. The results show that the vibration condition (M = 1.386, SD = 0.558) generated a significantly higher focused state than the 0.06 MPa/2 s condition ($p < .0001$).

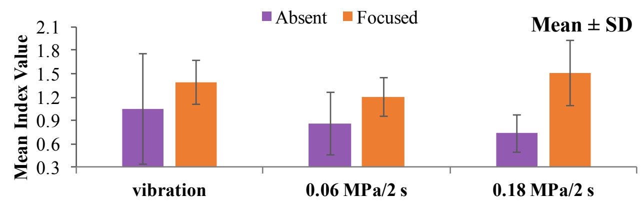

Figure 15. Absent/Focused index (vibration vs. air vortex ring)

Task Performance

The results of the task performance are shown in Figure 16. After confirming the homogeneity of variances by Bartlett′s test, a one-way ANOVA was used to compare the task performance obtained under the three conditions. There was a significant difference (F(2,96) = 3.686, $p < .05$) among them. However, a multiple comparison using the Tukey HSD test revealed that there was no significant difference between each of the two air vortex ring haptic stimulus conditions and the vibration condition (M = -0.00001, SD = 7.529).

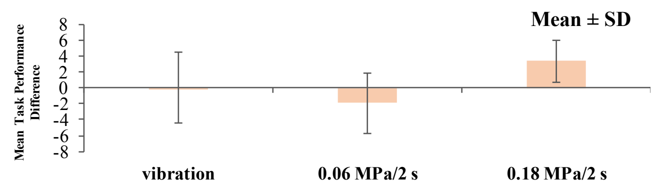

Figure 16. Task performance (vibration vs. air vortex ring)

Subjective Assessment

Figure 17 shows the results of the mean ratings of the three subjective feelings. There were no significant difference in fatigue and conscious drowsiness. However, for carelessness, after confirming the homogeneity of variances by Bartlett′s test, a one-way ANOVA was used to compare the task performance obtained under the three conditions. There was a significant difference (F(2,96) = 8.086, $p < .0001$) among them. A multiple comparison using the Tukey HSD test confirmed that the vibration condition (M = 23.120, SD = 24.086) induced significantly higher carelessness ratings than both the 0.06 MPa/2 s condition ($p < .0001$) and 0.18 MPa/2 s condition ($p < .05$).

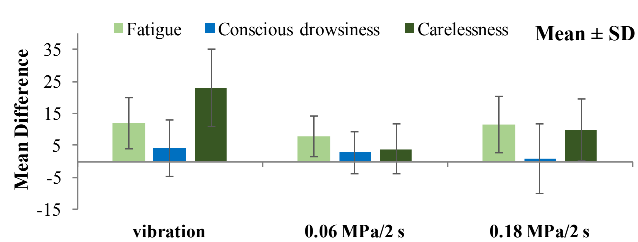

Figure 17. Subjective assessment (vibration vs. air vortex ring)

DISCUSSION

As a comparative experiment, we evaluated whether the haptic stimulus generated by a vibration motor affects physiological responses in a user similarly to the haptic stimulus generated by air vortex rings. With respect to the LF/HF change, we found that the increase in stress was less inhibited by the vibration stimulus compared to the 0.18 MPa/2 s condition. In addition, a decrease in stress was observed compared to the 0.06 MPa/2 s condition, which increased the stress the most. This implies the vibration stimulus neither decreases nor increases stress. With respect to the brainwave activities, we observed a synchronous increase in both absent and focused indices. However, we note that the results of experiment 1 do not suggest any meaningful results with respect to the synchronous state of both indices. With respect to the task performance, we found no significant difference between the results of the vibration and air vortex ring stimuli. This implies that the vibration stimulus neither increase nor decrease the task performance. With respect to the subjective feelings, we found that significantly high ratings of carelessness were observed in the vibration condition. Comments from the participant clarified that the haptic feedback of the vibration prevented concentration during the experiment and the stimuli were annoying.

LIMITATIONS

It is important to mention the limitations that arose in this experiment. To be precise, we do not know the details of the algorithm used to measure the four emotional labels determined by the EMOTIV′s proprietary algorithm. Although EMOTIV is widely used in HCI research to measure emotional state objectively in an non-invasive way [2] [13] [27] [26], the raw data of spectral bands recorded as the alpha, beta, and theta states should be computed to get valid results. Although the emotional labels are not fully trustworthy, we observed different tendencies among different conditions in the experiments. Therefore, although we do not know the exact formulae used to derive the labels, we discuss the results of the EEG as an example of the observed tendencies. However, we do not generalize the conclusion in this study.

We also admit the limitation of the number of participants in this experiment being small, and because it was a short-term experiment, we cannot reach definite conclusions yet. However, as an initial experiment, it is meaningful in that we could observe a few physiological responses induced by the air vortex ring haptic stimuli.

In the subjective assessment in experiment 1, we could not find any difference among all stimuli conditions. One of the reasons is that the question topics (fatigue, conscious drowsiness, and carelessness) were inadequate for observing the difference in subjective feelings for this experiment because the series of two-hour problem solving tasks would increase the feelings in the questions in any situation. In addition, because subjective feelings are considered explicit responses, whereas physiological responses or cognitive responses indicated by task performance are implicit, haptic stimuli using air vortex rings may not be effective in affecting explicit feelings yet. We need to conduct the experiments with a greater number of participants, with long-term tasks to evaluate these questions. One function that we have to implement for lengthy experiments is a tracking system that deals with a participant′s movements. In this study, because there was only one task in the experiment, which was a short-time computer operation in a sitting position for 30 min, we could present the tactile stimulation on the cheek without having the participant′ move much.

CONCLUSION

To develop a haptic display that would present haptic stimulation directly on anyone′s skin, we adopted the cheek as a display area after investigating quantitatively that it had enough resolution to perceive the difference in air vortex ring stimuli generated by the system. In addition, we developed an interactive cheek haptic display that presented either a strong or weak intensity stimulus at two- or five-second intervals when a participant experienced stress. The intensities of the display were determined by the experiment, where the subjective impression of sixteen different stimuli pairs were investigated (8 different intensities $\times$ 2 time intervals). In this study, we used the strong (0.18 MPa) and weak (0.06 MPa) intensities that the participants felt the most from among the stimuli pairs. These intensities also presented different impressions for six adjective pairs depicting emotion.

Further we conducted an experiment to evaluate how participants perceive haptic stimuli generated by air vortex rings and observed the effect of the air vortex rings on the physiological responses. We found that the 0.06 MPa/2 s condition did not inhibit the increase in stress and led to a low task performance. We also observed a relative increase in the absent state of the brainwave activities. In contrast, the 0.18 MPa/2 s condition effectively inhibited the increase in stress. Furthermore, it led to a high task performance and we observed a relative increase in the focused state of the brainwave activities. In the additional experiment, we compared the effect of stimuli generated by the air vortex rings with that generated by a vibration motor. The simple vibrotactile feedback on the cheek had no effect, but created a subjective feeling that concentration was lost.

Given these results, we will revise the interactive air-vortex-ring haptic display for long-term experiments. By conducting a long-term experiment, we want to find out the varieties of haptic stimuli combinations that induce attention or relaxation depending on the user′s situation.

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