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Research Letter

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Analysis of Heart Rate Variability Acquired During Deep Breathing Using a Breathing Visualization Lamp System

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Abstract Mindfulness (MF) is a type of meditation, the purpose of which is to free the mind from anxiety about the future and regrets about the past. Usually with MF, a person counts the number of deep breaths taken and focuses their attention on experiencing the "present moment." In practice, taking deep breaths is easy; however, it is difficult to achieve the effect; i.e., freeing the mind from wandering by reaching a mindful state, because it is very difficult to experience the present moment. What does it mean to experience the present moment? Phenomenologically, it is to be in a state in which "one feels to be here and now producing the reality, but also at the same time receiving the reality itself." This is not simply taking deep breaths according to some externally generated rhythm, but means that the external rhythm itself should be generated through feedback from the deep breath. To this end, we investigated the possibility of supporting MF using a lamp system that brightens and darkens in sync with deep breathing, rather than using a lamp that mechanically switches from light to dark. The idea of this study is to support mindfulness by visualizing one's own breathing. We evaluated whether the lamp system is beneficial for MF using the physiological index of heart rate variability and interview after the experiment.

Keywords: Mindfulness, Mind-wandering, Quality of life, Phenomenology.

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1. Introduction

Cancer survivors live with the aftereffects of their disease and the fear of recurrence, even after completing treatment [1, 2]. Such "mind-wandering" [3] reduces the quality of life (QOL) of cancer survivors. It is very important to improve QOL by focusing on the present moment, without the regret about having cancer or the fear of recurrence. Mindfulness (MF) is interpreted as "being aware that one is experiencing the present moment and to observe without making any evaluation"; therefore, it is necessary to observe the present moment. Several studies have examined the practical benefits of MF, including stress reduction [4] and dyspnea reduction [5], and MF is also important for cancer survivors. MF influences the heart rate variability (HRV), which is a measure of the autonomic nerve activity [6, 7]. In this study, we focused on mindful breathing, in which the individual observes deep breathing without making any evaluation.

The purpose of this study was to construct a support system for practicing MF. In MF, it is difficult to do something as simple as "just observe the present moment" correctly. From a phenomenological perspective, one experiences the "present moment" when one feels that "I am here and now producing this reality, but at the same time also receiving this reality itself" [8]. This implies that the deep breathing is not done according to an externally generated rhythm, but the external rhythm itself has to be generated through feedback from the deep breath. In other words, there should be a lamp system generating a light and dark cycle that synchronizes with the rhythm of deep breathing. Therefore, the user of the lamp system proactively generates a light and dark cycle

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according to deep breathing, and at the same time takes deep breaths by watching the cycle. The success of MF depends on the realization the above phenomenological perspective.

This lamp system can be considered to be a heart rate variability biofeedback (HRVB) system. In HRVB training, deep breathing is performed while monitoring one's own HRV [9]. The breathing rate that maximally increases HRV is approximately 0.1 Hz (6 breaths/minute). This lamp system is not designed to force the user to breathe at a specific breathing frequency, but is expected to induce the user to take slower deep breaths. Our aim is to verify whether such visualization of the breathing rhythm is useful for MF, i.e., whether it supports deep breathing in terms of HRV. As a preliminary study, we conducted an experiment in healthy young people.

2. Methods

2.1 Outline of breathing visualization system

The system configuration is shown in **Fig. 1**. The user watches the lamp in a darkroom. The system consists of a lampshade, a white light-emitting diode (LED; OS-WT3166B), a wooden base, an Arduino hardware, a pulse wave sensor (PulseSensor.com), and a personal computer for data recording. The lampshade is made of torn light green and white traditional Japanese paper (*Washi*), which is held together with a water-soluble bond. The wooden base is made of brown wooden plates arranged in a ring shape, with the lampshade placed on top (**Fig. 2a**) and an internal cavity inside where the Arduino is installed (**Fig. 2b**).

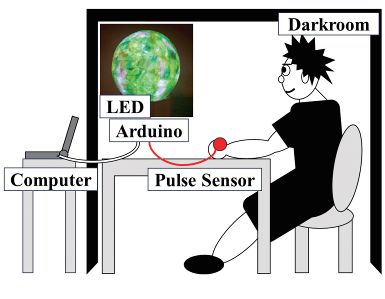

Fig. 1 System configuration.

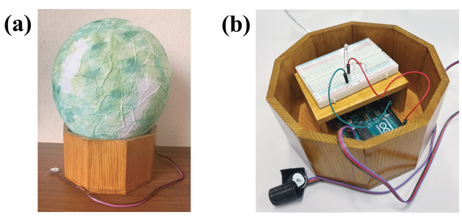

Fig. 2 (a) Lampshade made of traditional Japanese paper. (b) Wooden base composed of brown wooden plates arranged in a ring shape, with an internal cavity for installation of the Arduino.

To provide visual healing to the user, the system was designed with the theme of "trees (wooden base) and leaves (lampshade)." We used photoplethysmography for pulse wave sensing. The sensor and white LED are controlled by the Arduino system as follows. First, the intervals between the adjacent pulse peaks (inter-beat interval, or IBIs) are acquired from the pulse wave sensor. Next, the heart rate (HR) in beats per minute (bpm) is calculated from the inverse of the moving average of 10 IBIs (m_i), where the temporal sequences of IBI are represented as $x(n)$ at time n in milliseconds.

$$HR_i = 60000/m_i \quad (1)$$

$$m_i = \sum_{n=i}^{i+9} x(n)/10 \quad (2)$$

Finally, the intensity of the LED is changed in response to changes in HR. The HR increases when the participant inhales and decreases when the participant exhales. **Figure 3** shows an example of the change in HR when the participant actually takes a deep breath.

When $HR_{n+1} \geq HR_n$, it is regarded as inhalation and the light intensity becomes brighter. When $HR_{n+1} < HR_n$, it is regarded as exhalation and the light intensity becomes darker. The amount of change in intensity (Δ) of the light each time is determined as follows:

$$\Delta = k(HR_{n+1} - HR_n) \quad (3)$$

where k represents an arbitrary natural number that is adjusted for each participant before the experiment. The intensity of the light changes with each beat and varies between the minimum (0 lx) and maximum (1 lx) intensity during deep breathing.

2.2 Experiments

This study was approved by the Ethics Committee of Niigata University (No. 2021–0069), and was conducted in accordance with the ethical principles of the Declaration of Helsinki. Informed consent was obtained from all the participants prior to the experiments.

Ten healthy adults (six males and four females in their twenties) participated in the experiment. They were informed not to take caffeine, and were asked to maintain their daily routines from the day before the experiment. All the experiments were conducted between 1 pm and 3

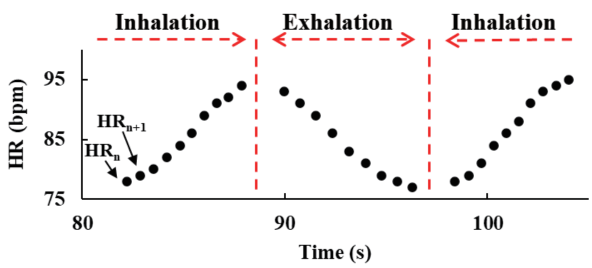

Fig. 3 Temporal changes of heart rate. The abscissa and ordinate represent time in seconds and heart rate in bpm, respectively.

pm (mean temperature: 23 degrees Celsius; mean humidity: 53%). All the participants were evaluated twice, once with the lamp and once without the lamp, and the two evaluations were performed on separate days. One-half of the participants were evaluated without the lamp system first and thereafter with the lamp system. The other participants were evaluated in the reverse order to eliminate any order effect.

First, every participant rested in a sitting position for 10 minutes. Next, they entered the darkroom and wore the sensor (**Fig. 1**). The measurement was divided into three portions; pre-experiment for 180 seconds (denoted as "Pre"), main experiment for 300 seconds (denoted as "Main"), and post-experiment for 180 seconds (denoted as "Post"), as shown in **Fig. 4**.

During the measurement, participants were instructed to wrap the sensor around their fingertips, place their fingers at the level of their heart, and maintain a posture that facilitated deep breathing (sitting position). During Main, the participants were instructed to take slow and deep breaths, and to be conscious of long exhalations. In this explanation, participants were not told about MF or meditation at all. For Pre and Post, the participants were instructed to "be natural" and not to control their breathing. After Post, the participants were asked some questions, and the experiment was terminated.

2.3 Data analysis

We compared the effects of deep breathing with and without the lamp from the viewpoint of HRV response. It is known that time domain indices of HRV are used to assess the autonomic nerve activity [7]. Especially, we used SDNN and RMSSD, which are commonly used to evaluate MF [7]. These values decrease with stress. SDNN is the standard deviation of the IBI values and reflects joint sympathetic and parasympathetic coordination. RMSSD is the root mean square successive difference between the IBI values and reflects the vagal activity. Using $x(n)$ acquired from the pulse wave sensor, they are calculated as follows:

$$\mathrm{SDNN}=\sqrt{\textstyle\sum_{n=1}^{N}(x(n)-\bar{x})^2/N} \quad (4)$$

$$\mathrm{RMSSD}=\sqrt{\textstyle\sum_{n=1}^{N-1}(x(n+1)-x(n))^2/(N-1)} \quad (5)$$

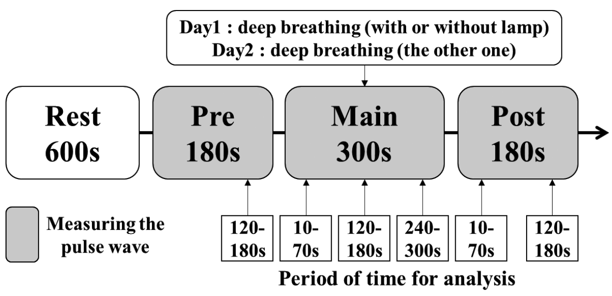

Fig. 4 Flow of experiment.

where $\bar{x}$ is the mean IBI of N samples (N represent the total number of data).

In order to evaluate detailed changes over time, we calculated the values of the pulse waves in 6 time segments: one segment in Pre (120–180 s); three segments in Main (10–70 s), (120–180 s), (240–300 s); and two segments in Post (10–70 s), (120–180 s). For all the time segments, paired t-tests were used to compare the heart rate variability between the evaluation with the lamp (experimental group) and that without the lamp (control group). Cohen's d, which is used to compare the difference between the means of two groups, was used to measure the effect size [10]. M_E and M_C in Eqs. (6) represent the mean values in the experimental and control groups, respectively. Similarly, SD_E and SD_C represent the standard deviations in the experimental and control groups, respectively. Effect sizes d of 0.2, 0.5 and 0.8 are estimated to be small, medium and large, respectively.

$$d=(M_E-M_C)/\sqrt{(SD_E^2+SD_C^2)/2} \quad (6)$$

3. Results

Figure 5 shows an example of a participant's temporal sequence of IBI, where the dots represent $x(n)$, used in Eqs. (4) and (5). **Figure 6** shows the mean SDNN of ten participants. The SDNN values were greater in the Main portion than in the Pre and Post portions, both with and without the lamp. The effect size was d = 0.18 for Main (10–70 s), d = 0.32 for Main (120–180 s), and d = 0.42 for Main (240–300s). **Figure 7** shows the mean RMSSD of ten participants. With the lamp, an increase in RMS-

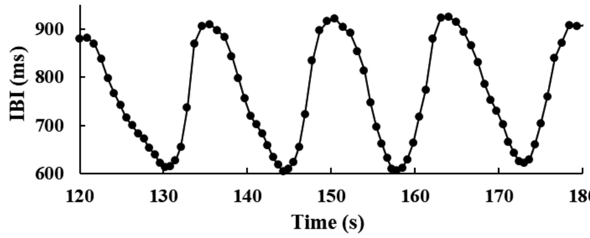

Fig. 5 An example of the inter-beat intervals (IBIs) of a participant for Main (120–180 s).

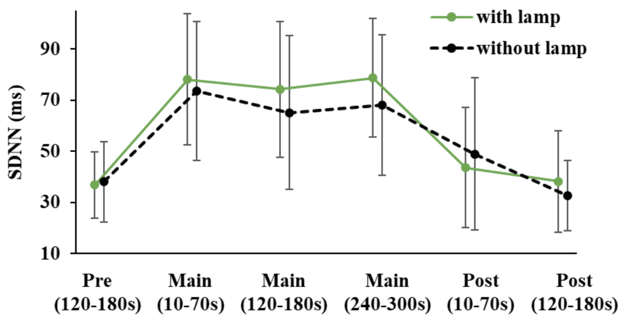

Fig. 6 Mean SDNN of the measurements with lamp (green solid line) and those without lamp (black dashed line).

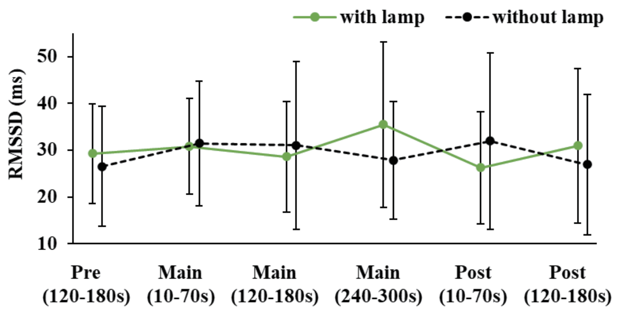

Fig. 7 Mean RMSSD of the measurments with lamp (green solid line) and those without lamp (black dashed line).

SD values was observed in Main (240–300 s), with an effect size of $d = 0.50$. Both with and without lamp, different changes in RMSSD were observed from Main (240–300 s) to Post (10–70 s). We observed, however, that the RMSSD values in Post (120–180 s) eventually returned to the same level as in Pre (120–180 s). Some participants commented that deep breathing without the lamp made it difficult for them to concentrate and made them sleepy.

In **Fig. 6** and **Fig. 7**, there were no statistically significant differences between the two experiments (with and without the lamp) in the present study. In **Section 4.1**, we discuss the qualitative difference that can be interpreted from these graphs. In **Section 4.2**, we discuss the effectiveness of the lamp system for MF from our interviews after the experiment.

4. Discussion

4.1 Interpretation of HRV

A sinusoidal change in IBI, as shown in **Fig. 5**, was observed in almost all the Main time segments. The IBI increased with exhalation and decreased with inhalation. It has been reported that the SDNN is greater during deep breathing than during normal breathing [11]. Similar results were also observed from Pre to Main in the present experiment, as shown in **Fig. 6**. We confirmed that the participants had deep breaths both with and without the lamp. In addition, a comparison of deep breathing at different respiratory rates suggested that deep breathing at a lower respiratory rate, i.e., more slowly, may result in a larger SDNN [11]. The SDNN was greater when breathing with the lamp than when breathing without the lamp, although there was no statistically significant difference between them. This suggests that the lamp may facilitate slower deep breathing.

On the other hand, RMSSD is said to be relatively free from the influence of respiration [12]. A temporary increase in RMSSD was found during the Main portion (240–300 s) with the lamp, as shown in **Fig. 7**, indicating that the value of RMSSD increased during deep breathing with the lamp, which is similar to the results found during 20–30 minutes of MF meditation [6]. Note that this feature was not observed without the lamp. Given that the participants were not told about MF before the experiment, these results suggest that deep breathing with the lamp may bring about the effects of MF meditation. In our next experiments, we need to consider the duration of using the lamp which is sufficient to achieve the same level of effectiveness as MF meditation. In the experiment with the lamp, a rapid decrease in RMSSD from Main (240–300 s) to Post (10–70 s) was observed. The cause of this decrease is not known, but we suspect it is due to the fact that the darkroom was opened once during this period to remove the lamp. Since a momentary glimpse of light outside could be a reason for physical stress, we assume that the participants were unable to maintain a high RMSSD.

As mentioned in **Section 3**, we confirmed that the values of RMSSD for Pre (120–180 s) and Post (120–180 s) were almost unchanged, i.e., the RMSSD remained almost the same when the participants were not conscious of their breathing. However, study has shown that continuous MF meditation interventions increase RMSSD during the time when participants are not conscious of their breathing [6]. According to Kirk and Axelsen [6], participants acquired the habit of mindfulness and became more tolerant of daily stress. We expect that continued use of the lamp will enhance the awareness of paying attention to the present moment, and that positive changes in HRV response will occur even during times when participants are not conscious of their breathing.

4.2 Interpretation of the lamp system as a support for MF

After the experiment, one participant commented, “The lamp helped me confirm whether I was doing good deep breathing.” while another said, “Without the lamp, I didn’t know what to follow to take a deep breath.” The lamp system made the users think that their breathing controlled the brightness of the lamp. The former comment was a correct impression that the participant’s breathing controlled the lamp. For the latter comment, however, the participant eventually began to feel as if he/she was breathing coinciding with the brightness of the lamp, and, as such, had a reversed impression that the lamp controlled breathing. This is evidence of the phenomenological viewpoint, i.e., “I am here and now producing this reality, but at the same time also receiving this reality itself [8].” Therefore, the lamp system presented in this study functioned as a support system for MF.

5. Conclusion

In this study we designed and constructed a lamp system that repeatedly brightens and darkens in sync with the user's breathing. Ten participants performed deep breathing using the lamp system. The results suggest the possibility that the lamp supports deep breathing and leads to mindfulness meditation. We are now starting to study cancer survivors using the lamp system. Future work will focus on increasing the number of experimental participants and statistically verifying the effect of the lamp system. There are already several MF interventions for cancer patients with sleep disturbances [13]. If use of this lamp before sleep has a positive effect on HRV during sleep, this system may be applied to improving the daily lives of different people, not only cancer patients, but also people with general wakefulness disorders such as jet lag and shift workers.

Conflict of Interest Discloser

We have no conflict of interest with any company or commercial organization.

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References

1. Mehnert A, Brahler E, Faller H, Harter M, Keller M, Schulz H, Wegscheider K, Weis J, Boehncke A, Hund B, Reuter K, Richard M, Sehner S, Sommerfeldt S, Szalai C, Wittchen HU, Koch U: Four-week prevalence of mental disorders in patients with cancer across major tumor entities. J Clin Oncol. **32**, 3540–3546, 2014.
2. Sakai S: Cancer recurrence and progression from evidence into practice (Evidence kara Jissen ni Otoshikomu Gan no Saihatsu·Shinkou). Cancer-Nursing with you (YORi-SOU Gan Nursing). **14**(5), 2024 in press (in Japanese)
3. Killingsworth MA, Gilbert DT: A wandering mind is an unhappy mind. Science. **330**, 932, 2010.
4. Mulla ZR, Govindaraj K, Polisetti SR, George E, More NRS: MF-based stress reduction for executives: Results from a field experiment. Business Perspect Res. **5**(2), 113–123, 2017.
5. Tan SB, Liam CK, Pang YK, Ng DLC, Wong TS, Khoo KWS, Ooi CY, Chai CS: The effect of 20-minute mindful breathing on the rapid reduction of dyspnea at rest in patients with lung diseases: A randomized controlled trial. J Pain Symptom Manage. **57**(4), 802–808, 2019.
6. Kirk U, Axelsen JL: Heart rate variability is enhanced during MF practice: a randomized controlled trial involving a 10-day online-based MF intervention. PLoS One. **15**(12), e0243488, 2020.
7. Tung YH, Hsieh JC: The impacts of mindfulness on heart rate variability: A brief review. Int J Pharm Med Biol Sci. **8**(4), 132–137, 2019.
8. Taguchi S: Phenomenology as a way of thinking (Genshougaku toiu Shikou). Chikuma Shobou. 205–210, 2014 (in Japanese)
9. Lehrer P, Vaschillo B, Zucker T, Graves J, Katsamanis M, Aviles M, Wamboldt F: Protocol for heart rate variability biofeedback training. Biofeedback. **41**(3), 98–109, 2013.
10. Mizumoto A, Takeuchi O: Basics and considerations for reporting effect sizes in research papers. Stud Engl Lang Teach. **38**, 57–66, 2008 (in Japanese)
11. Lin IM, Tai LY, Fan SY: Breathing at a rate of 5.5 breaths per minute with equal inhalation-to-exhalation ratio increases heart rate variability. Int J Psychophysiol. **91**(3), 206–211, 2014.
12. Hill LK, Siebenbrock A: Are all measures created equal? Heart rate variability and respiration. Biomed Sci Instrum. **45**, 71–76, 2009.
13. Han J, Cheng HL, Bi LN, Molasiotis A: Mind-body therapies for sleep disturbance among patients with cancer: A systematic review and meta-analysis. Complement Ther Med. **75**, 102954, 2023.

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