Evaluation and Comparison of Four Mobile Breathing Training Visualizations

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***Abstract*—Breathing exercises are an accessible way to manage stress and many mental illness symptoms. Traditionally, learning breathing exercises involved in-person guidance or audio recordings. The shift to mobile devices has led to a new way of learning and engaging in breathing exercises as seen in the rise of multiple mobile applications with different breathing representations. However, limited work has been done to investigate the effectiveness of these visual representations. We utilized a within-subjects study to evaluate four common breathing visuals to understand which is most effective in providing breathing exercise guidance. Through controlled lab studies and interviews, we identified two representations with clear advantages over the others. In addition, we found that auditory guidance was not preferred by all users. We also identify potential usability issues with the representations and suggest design guidelines for future development of app-supported breathing training.**

***Index Terms*—breathing exercises, mental health, wellness, usability**

I. Introduction and Background

Mental health is an important public issue. In any given year, around 20% of the adult population in the United States suffer from mental illness [26]. The cost of mental illness is high, associated with an 8.2-year average decrease in lifespan [13] and accounting for $139.2 billion in lost income each year in the United States [20].

Breath training has been shown to reduce stress [5], improve athletic performance [18], and improve mental health symptoms [37, 5, 9]. Traditional breath training methods are presented in the context of stress reduction, symptom relief, or overall physical wellness and include a diverse set of schools including diaphragmatic breathing, deep breathing, Buteyko breathing, yogic breathing, tai-chi, and qigong. Each type of breathing practice is beneficial for solving specific types of problems although there are some overlaps in the benefits of each technique especially in the realm of stress reduction. Pursed-lips breathing [30] and diaphragmatic breathing, for instance, have been shown to improve breathing patterns in people with Chronic Obstructive Pulmonary Disease thus improving airflow [40]. Relaxation-breathing has also been shown to reduce anxiety in children [7] while the Buteyko breathing technique could improve symptoms of asthma [10]. Yogic breathing, or Pranayama, has been demonstrated to improve competitive swimmers' respiratory function and endurance [18]. Qigong breathing has been shown to have a beneficial effect on stress levels [21].

Traditionally, learning breathing techniques can be inaccessible. Having to learn from a professional limits the accessibility of such information for low-income populations (who also have greater rates of mental illness) [28] and using audio recordings is inaccessible for deaf and hard of hearing individuals. Recently, however, this gap has been bridged by using mobile applications, since mobile apps increase the affordability and accessibility of breathing exercises.

In this paper, we use the terms *representation* and *visualization* interchangeably to refer to methods of conveying the breathing exercises. While the underlying breathing technique may be the same, it can be presented in various ways according to the app designer. Visualizations can help facilitate breathing exercises by providing information on how long to breathe, when to inhale, exhale, or hold the breath, and often how deep the user should breathe. Such guidance is achieved using a combination of different visual encodings which show data such as breathing length or current phase as aspects of a visualization. For example, an area encoding can indicate the volume of air the user should inhale or exhale, and a color encoding (with different colors signifying different phases) can communicate the current phase of the breathing cycle.

Chittaro and Sioni [8], in their evaluation of two types of breathing representations, provided an overview of several different types of breathing visualizations. They have coined terms describing the four most common representations as described below.

The first visualization is *wave-based*, which shows a continuous straight or curved sine-based wave to guide the user's breathing cycle. An example of one such application is Paced Breathing [24], shown in Figure 1. The wave can be moving through a stationary line, or the wave itself can be stationary and the line is moving through it horizontally or vertically.

The second visualization is *sphere-based*. This is arguably the simplest representation which involves an animated circle (or sphere) expanding and shrinking according to the breathing phase. Figure 2 shows a simple sphere-based representation from The Breathing App [39]. Sphere-based representations can be more elaborate. The shape can be more complex such as in [38] but the underlying idea is the same.

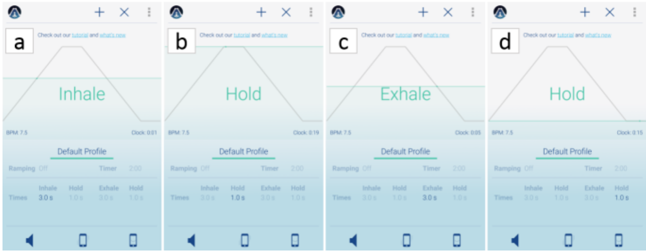


Fig. 1. Breathing exercise from Paced Breathing. The user can choose from a variety of audio options and customize the duration of each phase. (a) The horizontal line rises during the inhale phase until it reaches the peak. (b) Once it reaches the peak, it goes into the hold phase. There is a small circle at the overlap of the horizontal line and the breathing curve that indicates how far in the phase the user is currently in. (c) In the exhale phase, the horizontal line moves downwards. (d) The hold phase. Again, there is a small circle at the overlap of the two horizontal lines that indicates how far in this phase the user is currently in. Images used with permission from Mihai Bulic.

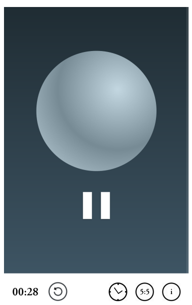


Fig. 2. Sphere representation from The Breathing App. The sphere expands as the user inhales until it reaches a maximum size. Then, it keeps its size while the user holds in the breath, and shrinks as the user exhales. Finally, it holds its smallest shape as the user holds their breath. Here, the sphere is rendered as a 3-D object but many other variations utilize a 2-D representation. This app allows users to customize the breathing rate. Images used with permission from Sergey Varichev.

The third visualization is *cylinder-based*. It shows a cylinder being filled to the top during the inhale phase and emptying in the exhale phase. Breathe2Relax [35] is an example of such an app. Figure 3 shows a mockup of such a representation.

The fourth visualization is a *donut chart*. It is typically segmented into three or four sections, with each section representing a breathing phase. The user can see their breathing progress through the cycle and phase, almost like a progress bar. Prana Breath [1] is an example as shown in Figure 4. Variations include a pie chart instead of a donut chart. There are also hybrid varieties, for an example, a sphere inside a donut chart such as in the Stop, Breathe, and Think app [34].

There are other types of visualizations beyond those covered in Chittaro and Sioni's work [19, 15]. However, we focus on these four due to their popularity and availability.

Apps such as Paced Breathing [24] and Prana Breath [1] allow users to choose what type of audio feedback they would like to hear, if any, to signal the changes in the breathing phase. Most apps utilize only one method of visualization, and some will allow the user to customize speed settings and tactile and audio feedback.

While several methods of visualization exist, there is no indication as to which representation is the most effective in facilitating paced breathing exercises, thus we set out to investigate which methods are best for breath training. Our research questions are as follows:

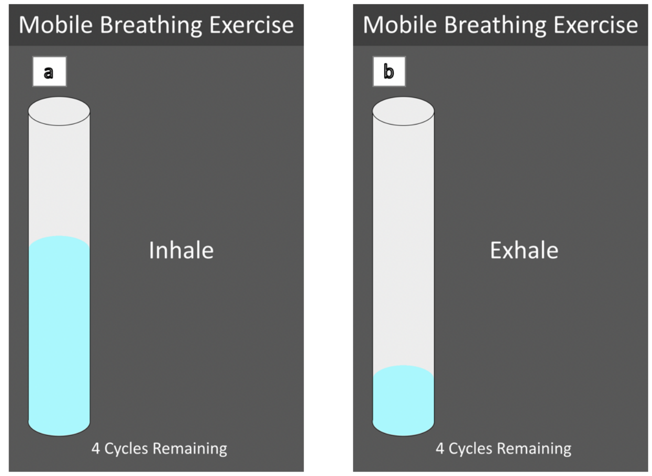


Fig. 3. A simplified mockup of a cylinder representation. (a) As the user inhales, the cylinder is filled up. (b) As the user exhales, the cylinder is emptied.

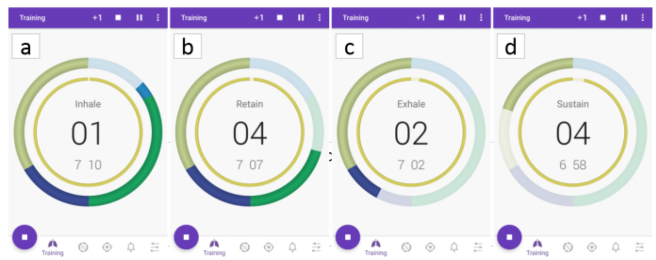


Fig. 4. Breathing exercise from Prana Breath. There are preconfigured exercises with more customization options available for a fee. The duration of the phases is not even, with more time allotted for the hold phases (here referred to as Retain for the hold phase after inhalation and Sustain for the hold phase after exhalation) than for the inhale and exhale phases. The large numbers in the middle of the circle indicate the length of time remaining in the current phase. (a) The greyed out portion of the arc increases as the user progresses through the inhale phase. The text changes to "Inhale" to indicate the current phase. (b) Once it reaches the end of the blue arc, it goes into the hold phase and continues into the green arc indicating the hold (or retain) phase. (c) The exhale phase is shorter than the retain phase but starts at the midway point of the current breathing cycle. (d) The hold phase. Note the golden circle inside the donut chart is indicating the progress of the entire exercise corresponding with the counter in the middle of the circle. Images used with permission from Daria Kurguzova.

Are some representations better than others in facilitating paced breathing exercises? We measure "better" using subjective user evaluation and breathing synchronization accuracy. We use synchronization accuracy since consistency of the breathing cycle provides health benefits [23]. Some representations perform better than others for facilitating deep breathing. However, a user can breathe in deeply but not consistently. Therefore, investigating synchronization allows us to examine the effectiveness of representations for guiding paced breathing exercises and not just deep breathing exercises.

How can visualization of breathing practices be optimized for greater effectiveness? In particular, we want to examine the strengths and weaknesses of each visualization and determine some design guidelines for future applications.

How does audio guidance impact the user experience in learning and performing the breathing exercise? A previous question was raised whether the visual element of breathing exercises would be helpful or distracting to people who wanted to perform breathing exercises. Chittaro and Sioni [8] concluded that this visual component was not distracting to users. We aim to extend this question further to the auditory realm and determine how audio feedback and guidance impacted users' experience in interacting with these apps.

II. Related Work

Previous attempts to render human breathing have been explored in the realm of computer graphics. Zordan et al. designed a model of an anatomically-accurate human torso and simulated the breathing using a model of a pair of human lungs [42] in order to model a human breathing pattern. Tsoli, Mahmood, and Black showed realistic human breathing but modeled it within 3-D models [36]. While both works do not directly reference breathing exercises, their models can be used to facilitate paced or deep breathing exercises.

While exact estimates of breaths per minute differ, slow breathing at an equal inhale/exhale rate is found to improve heart rate variability [23, 22] and improve physical and mental health [41]. Lin et al. utilized a form of wave-based breathing visualization to evaluate breathing rate [23]. However, they did not evaluate the visualization itself. Still, breathing exercises should be facilitated so that the duration of each phase of the breath cycle is equal.

Slow breathing is often integrated with biofeedback to regulate heart rate variability. This increasingly popular method is a promising one to decrease stress and anxiety [17] by monitoring the pace of breath, since a slower breathing frequency improves heart rate variability [22]. Furthermore, *cardiac coherence* measures the correspondence of respiratory rate and heart rate, which supports the health of the autonomic nervous system. Blum et al. found that slow breathing at a constant rate whether guided by an audio recording or by relaxing imagery using virtual reality improved cardiac coherence but had no significant differences between audio-only and virtual reality [4]. Thus, we are including breathing synchronization as a measure of performance of visual representations. Since measuring the user's synchronization to a breathing representation can give us insight to how consistently they are breathing, synchronization can tell us how well they are performing the paced breathing exercises. This is also motivated by the fact that we do not yet know which visual representation of these exercises facilitate this process.

Auditory guidance has been previously used to facilitate paced breathing. For instance, Gavish evaluated device-guided breathing with audio in the form of musical tones to help patients with hypertension, and found that the paced breathing exercises were effective in reducing physical symptoms. In this case, the musical tones helped the patients to emphasize the exhalation phase over the inhalation phase [16].

Dijk and Weffers developed an immersive system called Breath with the Ocean, which utilizes visual (light-based) stimuli, audio guidance, and haptic feedback with the goal of relaxation [11]. However, in both the fixed breathing guide and the fully-adaptive breathing guide, users had issues with synchronizing their breathing which led to increased stress rather than relaxation. Their users found the haptic feedback pleasing especially when used in conjunction with the audio feedback.

Paredes and Chan developed CalmMeNow, which is a stress-reduction system using haptic stimuli to guide users in deep breathing exercises via a wearable device. They suggest that haptic feedback in the form of pressure simulation may be better than utilizing vibrations [33].

Paredes et al. also compared a haptic system and a voice-only system in guiding users in guided slow breathing exercises in a simulated driving situation [32]. Their haptic system was integrated into the seat of a simulated car and utilizes directional vibrations to indicate the breathing phase, while the voice-only system utilizes a male voice that instructs the user to breathe in, hold, or breathe out. They found that users preferred the haptic system because it was more calm, integrated, and subtle than the voice commands which were often perceived as abrupt.

A. Evaluations of Visualizations

Within the frame of mobile-based breathing applications, there has only been one study conducted that evaluated the effectiveness of each representation. Chittaro and Sioni [8] compared audio-only guidance with the sphere-based representation and the wave-based representation to determine which one is more effective utilizing a within-subjects approach. They defined effectiveness using the change in physiological signs associated with relaxation as well as a subjective evaluation using a questionnaire. They found that the wave-based representation is significantly more effective both physiologically and subjectively than the audio-only instructions. However, they did not find that the sphere-based representation performed better than the audio-only instructions.

While Chittaro and Sioni's study investigated stress reduction and deep breathing to some degree, we are interested in better understanding why some representations outperformed others with respect to paced breathing and consistent breathing phase lengths. Thus, we are focusing on the users' ability to synchronize their breathing and their reactions to audio feedback. We also chose to evaluate synchronization since, as stated above, we can determine which visualization is the most effective in guiding users to breathe with the most equal phase length. Visualizations that are effective in guiding deep breathing may not perform as well when facilitating paced breathing. Furthermore, while Chittaro and Sioni investigate the consequences of the representations as defined by physiological signals and perceived relaxation, we are interested in examining the details of the interaction between the user and the representation, as seen in the ability of the users to synchronize their breathing and the consistency of their breathing. Thus, our approach is from a design perspective and we focus on design implications.

III. Study

To determine which method of representing breathing exercises is the most usable, we designed and implemented a user study with N=24 participants to measure their level of synchronization with the breathing app and to observe their responses to each design.

A. Survey of Mobile Applications

In order to determine which representations to focus on, we conducted a survey of the different versions of visual representations of breathing exercises found in the Apple App Store and the Google Play Store. Search keys included terms such as *deep breathing*, *breathing exercises*, *breathing techniques*, and *breath training*. We excluded virtual reality applications, voice-only applications, exact duplicates, sensor-only applications, and timer-only applications.

We found a total of 110 apps on both Google Play and the App Store that had breath training exercises. These included yogic breathing exercises as well as deep breathing exercises. Table I shows the most common breathing training visualizations available. The sphere had the greatest share of the market with 44% of the total representations. The miscellaneous visualizations were more elaborate such as dynamic ocean waves or the flutter of a butterfly's wings.

TABLE I
Most Common Visual Representations of Breathing Exercises

Category	Count	Percent of all applications
Sphere	48	44%
Donut	27	25%
Combination	7	6%
Cylinder	7	6%
Wave	6	5%
Other	15	14%
Total	110	100%

B. Study Design

We intended to assess the usability of each design by measuring the synchronization accuracy of each participant's breath with the visual cues provided by the application and by collecting participants' general responses to each visualization. To do so, we developed an application containing four of the most common breathing visualizations: the sphere, wave, donut chart, and cylinder. Because the apps available all vary widely in terms of customizability (of time and of appearance), visual aesthetics, auditory guidance, haptic feedback, and color design, we chose to create our own app. In doing so, we gained more control over potentially confounding variables such as haptic feedback and auditory guidance, and could ensure that the timings were the same for all four visualizations.

We chose to evaluate these four representations since they compose 80% of the currently available on the market as found by our survey. The remaining 20% of the apps consisted of either combinations of these 4 (6%) or miscellaneous representations (14%). Furthermore, Chittaro and Sioni only evaluated two representations, the sphere and the wave, which account for 49% of the total market. For consistency, we added text to indicate the current breathing phase (inhale, hold, exhale, and hold). Table II shows these representations used in our app in all four breathing phases.

Our implementation aims to capture the most broadly-used features of each design. Thus, the donut chart includes a progress-bar style animation with desaturated colors to show completed time. Both the cylinder and sphere use non-linear easing in their animations, as is seen in apps on the market. The sphere uses an animation to show the change in size of the circle, but no animation between color changes. Finally, in the wave representation, the black vertical line stays still, but the blue line moves horizontally. The current time is indicated by the vertical black line.

We also wanted to explore how participants reacted to audio feedback as this is the most common accompaniment to visual guidance provided in mobile apps. Thus, we included the above visualizations with additional auditory guidance in the form of a tone played during the inhale and exhale phases.

We utilized a within-subjects approach, randomizing the order of the applications presented to normalize the results. We presented each of the four visualizations first without sound, then the other four with sound so participants can compare the differences between them. We utilized a neutral computer-generated 261-Hz tone (the frequency of the middle C note) as the audio guidance as opposed to a human voice to eliminate bias towards male or female voices.

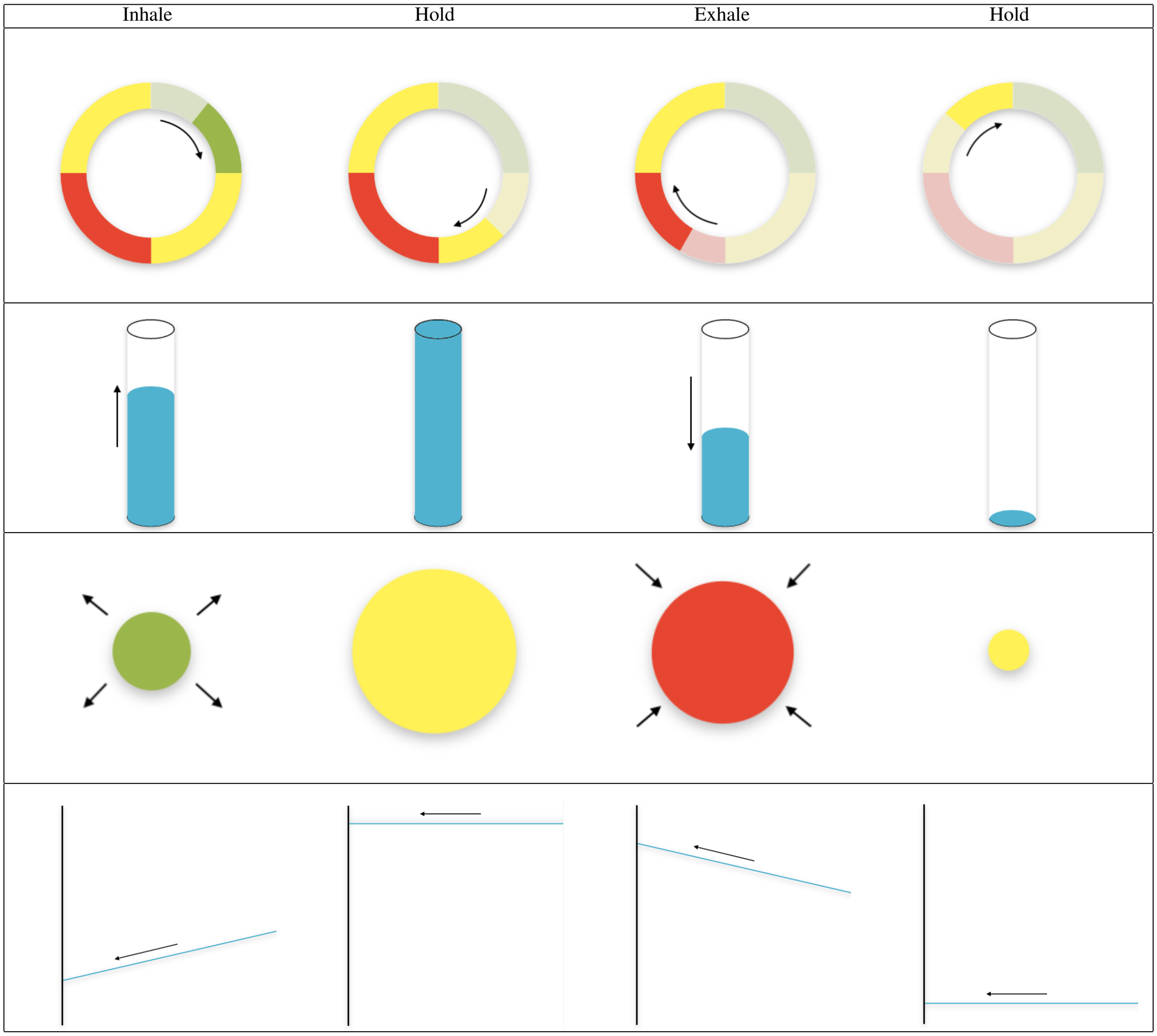
We used a two-camera set-up to record the current state of the visualization and the participants' breathing movement and to track the breathing phase changes. We utilized cameras as it has been shown that this relatively low-cost and unintrusive method performs comparably well to respiration belts [29]. One camera was set up to capture a similar range as that described by Nam et al. [29], recording the participants' chest and torso movements as shown in Figure 5. We also interviewed participants after the study to gain information about their experience in using the app.

C. Participants

We recruited 24 participants from the University of Notre Dame and the South Bend, Indiana community. Participants consisted of university students, staff, and community members. The participants' occupations ranged from student to data entry to retiree, and their ages ranged from 19 years old to 74 years old. The mean age of the participants was 35 years, the median age was 26 years, and the standard deviation was 15.4 years. There was an equal set of male participants (N=12) and female (N=12) participants, with one self-disclosed bigender female participant (who requested to be counted as female). We included a broader population set to

TABLE II

THE FOUR REPRESENTATIONS WE DEVELOPED FOR TESTING. WE EXTRACTED THE BASIC COMPONENTS OF THE FOUR MOST COMMON REPRESENTATIONS AND SIMPLIFIED THEM. HERE, EACH ROW CORRESPONDS TO A DIFFERENT KIND OF REPRESENTATION. FROM TOP ROW TO BOTTOM ROW: DONUT CHART, CYLINDER, SPHERE, AND WAVE. THE COLUMNS CONTAIN THE FOUR PHASES OF THE BREATHING CYCLE. FROM THE LEFTMOST TO THE RIGHTMOST COLUMN: INHALE, HOLD, EXHALE, AND HOLD. THE BLACK ARROWS WERE NOT INCLUDED IN OUR IMPLEMENTATION BUT ARE SHOWN HERE TO INDICATE THE DIRECTION OF THE ANIMATION. AN IMAGE WITHOUT AN ARROW MEANS THAT THE REPRESENTATION STAYED STATIC DURING THAT SPECIFIC PHASE.



gather a large variety of users and determine the usage needs of a larger population, rather than a specific population or one that is more comfortable with using mobile apps.

We selected participants who were not familiar with or did not have much experience with using mobile apps for breathing, relaxation, or mindfulness training, since participants who are accustomed to a certain method of visualization employed by their application of choice could be biased towards the one that they use regularly. However, we did not control for whether participants had previous experience with guided breathing that was not supported by technology. Prior to the study, participants were not informed of the defined purpose of the representations beyond the fact that the representations were supposed to facilitate breathing exercises and thus they were not able to judge each representation based on its ability to meet its purpose of guiding breathing pace.

D. Procedure

Before the session, each participant filled out an informed consent form. At the beginning of the session, the experimenter described the study procedure. Then the experimenter applied two stickers on the participant's chest and torso (shown in Figure 5) to track the breathing movements. The experimenter showed the main screen of the application and gave the subject a randomized sequence of exercises to perform.

Fig. 5. Participant performing a breathing exercise. The two stickers can be seen here, one on the participant's chest and the other on their sternum.

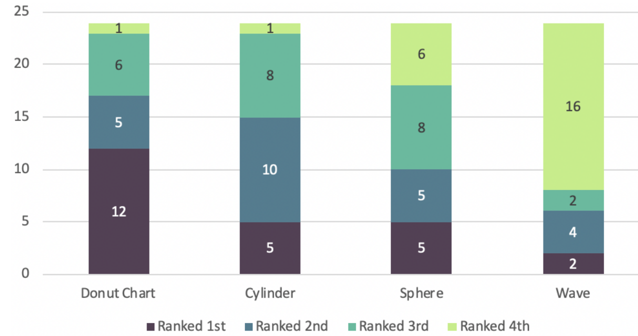


Fig. 6. Participant rankings of the exercises from most preferred to least preferred. The donut chart was ranked as the most preferred by the largest amount of participants, followed by the cylinder and sphere. The wave was the least preferred, with only two participants ranking it as their most preferred and sixteen ranking it as their least preferred.

Participants were asked to not interrupt the exercises but rather ask questions before or after each exercise.

Each of the four exercises had eight breathing phases over two cycles, with each phase lasting an equal amount of time. We chose two cycles as the base length of each exercise because our goal was to explore the usability of each design rather than its efficacy in reducing physical stress signals and having each participant complete an entire session of exercises for each representation was not necessary. The experimenter provided as little verbal information as needed to not influence the participant's impression of each representation. The sequence of exercises were different for each participant. Participants had to perform the exercises without any preconceptions as to how each representation worked.

After the exercises were completed, the experimenter interviewed the participant about their experience using the app, any difficulties they had, and their overall opinion of each visualization method. Participants were given a $5 gift card as compensation.

IV. Analysis

To obtain the breathing synchronization results, we measured the difference between the participants' breathing and what was displayed on the screen and used MANOVA, confidence intervals, and simple effect sizes to report our results. We also utilized open coding to qualitatively analyze the interview data.

A. Breathing Synchronization Quantification

We took the data from the two videos and compared the participants' breathing to the guidance provided in the visualizations. The two cameras recorded the video in 29.97-60 frames per second. We were able to synchronize the two recordings up to the frame. Our sampling was determined by frames per second used by each camera, and phase changes were marked down to the frame by noting the directional change in movement of the marker on both stickers. We used Lightworks, a video editing software, to synchronize and mark the breathing phase changes in both the visual representation and the participant's breathing.

In addition to using p-values, we utilize confidence intervals and simple effect sizes to report our results [12, 14] because of their robustness [2]. In this case, simple effect sizes refer to raw mean differences and have the same units (seconds) as the data. Although we interviewed 24 participants, due to complications when gathering the data, we were only able to collect 22 data points for the cylinder and sphere and 23 data points for the wave and donut chart.

B. Qualitative Analysis

After we completed the interviews, we transcribed them and used open coding to identify salient themes that emerged. By briefly going over the interview transcripts we identified areas of interest and generated a codebook. Two members of our team went through and coded four interviews independently. It was determined that a sufficient level of agreement was reached at 71%, and one team member coded the rest of the interviews independently.

V. Quantitative Findings

Based on an analysis of the data, the wave and the donut chart outperform the sphere and the cylinder in terms of breathing synchronization. However, the wave was the least favored while the donut chart was the most favored among users. Surprisingly, although users rated the wave-based visualization as their least favorite visualization and the hardest one to use, they breathed more in sync with it compared to the sphere and cylinder. Our finding that the wave performed better than the sphere in breathing synchronization aligns with Chittaro & Sioni's findings that wave-based visualizations perform better than sphere-based visualizations in stress reduction as measured by physiological signals [8]. While we used a different metric, our findings may help explain their results.

A. User Feedback

We asked participants to rank which representations they liked most to least and to identify the easiest and hardest representation(s) to use. We did not ask about their opinion of the auditory stimulus in this question. The rankings of the most to least preferred representations are shown in Figure 6. The donut chart was ranked the highest the most often, with twelve participants ranking it as their first choice and five ranking it as their second choice. Only one participant ranked it as their last choice. In contrast, the wave-based visualization was the least favored out of all four. Sixteen out of 24 participants ranked it as their least favorite, with only two ranking it as their favorite. The cylinder is the second most popular, with five ranking it as their favorite and another ten saying it was their second favorite. The donut chart and cylinder representations were ranked as the least favorite only once for each.

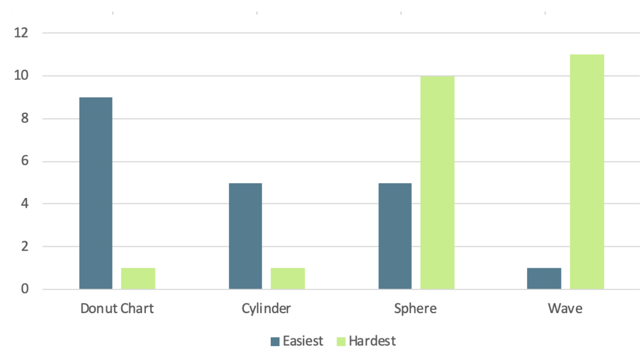


Fig. 7. Participant responses to which representation they found to be the easiest and hardest to use. The donut chart was viewed as the easiest representation by nine of the participants. The wave was chosen the least frequently, with only one person indicating that they thought it was the easiest representation to use. The wave was viewed as the hardest to use by eleven users, followed by the sphere with ten users. The donut chart and cylinder had one user each choose it to be the hardest representation to use.

The participants' rankings also corresponded to how easy or hard they found the exercises. Figure 7 shows which exercises participants indicated were the easiest and hardest to use. The sphere and wave visualizations were the hardest to use, according to users, with ten and eleven of the subjects saying that it was the hardest to use. One subject could not decide between them, and so included both. Only one subject said that the wave-based visualization was the easiest to use. When asked, participants said the sphere was hard to use because they could not determine when the breathing phase changes would occur.

B. Breathing Synchronization

Figure 8 shows the average time difference between each breathing phase change and the participant's breathing itself. The cylinder and sphere performed poorly compared with the other two representations, with 1.04 ± 0.22 seconds and 1.11 ± 0.26 seconds delay for visual only and 1.13 ± 0.17 seconds and 1.02 ± 0.38 seconds delay for audio guidance included. The wave-based and donut chart and wave representations had the lowest and best reaction times with 0.31 ± 0.24 seconds and 0.40 ± 0.38 seconds delay respectively for visual only and 0.30 ± 0.32 and 0.35 ± 0.23 seconds delay for audio guidance.

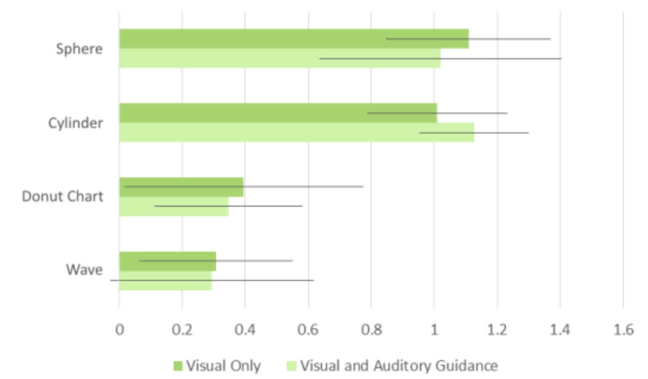


Fig. 8. Average difference (secs) between the representation's phase change and the user's change in breathing. Error bars show 95% confidence interval (n=22 for sphere and cylinder, n=23 for donut chart and wave.

These reaction times are average and the error bars in the figure indicate a 95% confidence interval. If the participants started the phase change earlier than the guidance indicated, the time delay will be negative.

While the wave breathing delay sample means indicate that users perform better than the donut chart, the error bars overlap so that we cannot confidently conclude that the donut chart outperforms the wave. Thus, given the intervals that the means can lie on in the 95% confidence interval, we cannot authoritatively state that the wave-based representation outperforms the donut chart. However, what we can say given the confidence intervals is that the wave and donut chart both perform better than the cylinder and sphere since their confidence intervals do not overlap.

The audio feedback did not result in a definite improvement in breathing synchronization. In the cylinder representation, users performed worse by an average of 0.09 seconds with the audio guidance compared to visual-only guidance. While it may seem that the wave representation performed slightly better with the audio than with the visual-only, it had a confidence interval that was too wide to yield any definite results. Thus, we cannot say that in all cases adding auditory guidance will improve breathing synchronization.

We performed Multivariate Analysis of Variance (MANOVA) with a Bonferroni correction of 0.00217. This analysis confirmed our previous results. We did not find a main effect of audio (F(1, 164 = 0.10, $p = 0.750$) or an interaction between the type of visualization used and the audio ($F(3, 164) = 0.58$, $p = 0.626$). We, however, did find a main effect of the type of visualization ($F(3, 164) = 76.30$, $p < 0.001$). Post-hoc pairwise tests reveal a difference between the donut chart and the sphere (t(168) 10.09, $p < 0.001$), the donut chart and the cylinder ($t(168) = 10.36$, $p < 0.001$), the sphere and the wave (t(168) 11.12, $p < 0.001$), and the cylinder and the wave ($t(168) = 11.39$, $p < 0.001$). However, no difference was seen in the donut chart compared

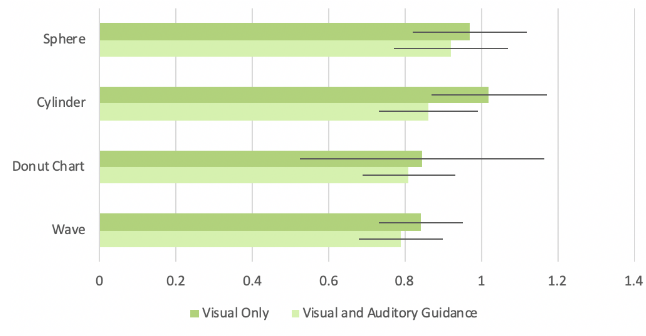


Fig. 9. Average intra-individual phase length variation (secs). The lower the variation, the more consistent the breathing phase lengths are. Error bars show 95% confidence interval (n=22 for sphere and cylinder, n=23 for donut chart and wave.

to the cylinder (t(168) = 1.045, p = 0.298) or the sphere compared to the cylinder (t(168) = 0.268, p = 0.789). Thus, these findings support our conclusions from above.

We suspected that it might be possible that a representation may have a larger time difference in phase changes between the guidance and the participants' breathing but still provide consistent phase lengths. For example, a user may consistently be off by 1.5 seconds from the representation, but still breathe at a steady pace of 6 breaths per minute. In this case, the representation could be effective. To test this hypothesis, we also computed the mean intra-individual phase variation as determined by the average standard deviation of each participant's breathing cycle length (Results shown in Figure 9). A lower value is more desirable, since this means that the phases are more equal in duration. While the donut chart and wave appear to perform slightly better than the sphere and cylinder, due to the wide confidence intervals we cannot say that any representation provided a clear advantage over the others.

We confirmed this with a MANOVA. We did not find a significant difference between type of visualization (F(3, 164) = 1.72, p = 0.165), presence of audio (F(1, 164) = 2.18, p = 0.142), or interaction between visualization type and audio (F(3, 164) = 0.28, p = 0.840).

C. Informal Study

After examining the results, we realized that the study raised more questions about the effectiveness of the cylinder and sphere representations. Our implementation of the sphere and cylinder were non-linear in their movement. The sphere expanded/contracted faster at the beginning of the inhale and exhale phases and slower as it reached the end of the phase. The cylinder also filled and emptied faster at the beginning of the inhale and exhale phases and slowed down as it approached the end of the phase. We implemented the representations in this way since it was representative of the apps available in the market. Thus, we wondered whether the non-linear movements of these representations reduce their breathing synchronization rates. These movements may have caused the participants to misjudge the length of each phase, and presenting these representations with a linear movement may increase the synchronization rate.

Thus, we recruited five participants for an informal study with these two representations presented linearly without auditory guidance and a donut chart presented without auditory guidance as well for reference. We analyzed the data in the same way as described previously. Our results did not indicate that removing the nonlinear aspect of the sphere and cylinder visualizations increased the users' breathing synchronization. The means for linear sphere and cylinders were 1.27 ± 0.31 seconds and 0.94 ± 0.27 seconds, respectively. The donut chart had a 0.19 ± 0.41 seconds delay.

VI. Qualitative Findings and Implications

In this section, we discuss the common themes that we found through qualitative analysis of user interviews. We also discuss design implications of these findings.

1) The wave-based representation was the most confusing: Eleven users said that they had issues with the wave-based representation. They were confused by the motion of the wave and some expressed that they felt there was a lack of guidance compared with the others. P8 elaborated, *"It was totally confusing especially when it came without sound...When it came without sound, I didn't know what to do. I thought the wave coming up is inhaling and the wave going down was exhaling but then after that I was no no no, not yet and it was confusing."* In contrast, six of the participants commented that they found the donut chart to be clear and intuitive.

Implication: While users performed well with the wave representation, they perceived it to be confusing. This mismatch between performance and perceptions suggests that designers may want to consider the use of the wave representation, but revisit the design to provide cues to reduce confusion especially with regard to the phase changes and direction of movement. In the meantime, application developers should consider using the donut chart representation.

2) Users are split over auditory guidance: Ten users liked the tone because it helped them focus on the exercise and bring their attention back to the current phase when their minds had wandered. Some also said that it made certain representations easier or more appealing. For example, P10 appreciated that *"It really helped with [the wave] to have the tone so I didn't have to be watching the line. I imagine if I were familiar with the app and I wanted to close my eyes and practice these exercises in a meditative state the tone would be very helpful."* Nine of the other fourteen preferred to perform the exercises in complete silence, while the other five said that they preferred a softer, "smoother" tone such as nature sounds or differently-pitched tones to indicate the current phase.

Implication: This split indicates that more work is necessary to understand the effects of sound on breathing synchronization. It may be that sound is useful when combined with some visual cues but not others. Until then, designers should allow for customization with respect to sound cues and the ability to select whether sound should be included at all.

3) Users prefer predictability in most cases: Seventeen of the 24 subjects commented on how predictable the exercises were. The most common complaints against the sphere and cylinder visualizations were the unpredictability of breathing phase changes. The donut chart was the most predictable of the four representations. Interestingly, although the wave-based visualization provides a level of predictability, many users such as P15 disliked it: *"I felt like it's one of those things you see moving back and forth and I kept going too early or too late or just not hitting the mark at all."* Only two of the seven users who remarked on the wave's predictability did so positively, saying that they liked that they could see what was happening next. Some users only liked a certain level of predictability. P7 wanted to see the entire cycle: *"I want to see the complete exercise. The whole cycle in the sense of like the whole interface."* However, when commenting on the donut chart, P18 said that she did not like it as much as the wave because the donut chart was *"thinking too far ahead."*

Implication: Predictability appears to be an important usability aspect of paced breathing representations and could explain the reason why the wave and donut chart performed better in breathing synchronization than the cylinder and the sphere did. Predictability can be enhanced by showing the entire breathing cycle such as in the donut chart or by making the transitions between phases more explicit. Again, while users performed well with the wave representation, the majority of those who did commented negatively about the predictability, thus, improving the predictability of the wave could likely increase its perceived effectiveness, for example, by adding colors that correspond to the current phase and markers that signify phase changes. Still, any representation should include cues to support predictability of phases.

4) The same representations mean different things to different users: Twelve of the fourteen users had twelve different interpretations of the representations, with the cylinder and wave being most commonly interpreted. For the cylinder representation, the various interpretations are container/glass of water (6), lungs (3), breathing machine (1), and progress bar (1). For the wave, the interpretations are string (1), sine function (1), and a *"flat line in a medical facility"* (1). The donut chart was interpreted as a progress bar (2) and a timer (1). The sphere was the least interpreted, with one user interpreting it as *"simulating machine breathing."* One user viewed the same visualization two different ways, seeing the cylinder as both a glass filling up and their lungs filling up.

Implication: Metaphors could potentially be very beneficial in improving usability. Designers should consider equating their representations to a concrete metaphor to help users construct a conceptual model of the interaction. They can use of visual cues or explicit instructions to equate the representation with a metaphor that supports the conceptual model [31].

5) Some users related the representations to their bodies: Seven users related eleven representations to their body movement or indicated that they disliked that they could not relate it to their bodies. The wave-based representation was found to be the least relatable. P9 said, *"That is just a line that goes up and down. It's not really relatable for me."* In contrast, the cylinder and sphere representations were the most related, with five and four instances respectively. Users said that the expansion of the sphere and the filling of the cylinder reflected their lungs expanding in their bodies.

Implication: Relatability increases the effectiveness of a representation when it is combined with predictability. In our study, the cylinder was the second most popular representation of the four. It was also the most interpretable and relatable to the body's movement since users related it to their lungs filling in and out. However, users did not synchronize to this visualization as well as the donut chart and wave representations because of its lack of predictability. While Metaphors related to a user's own body can be effective, they must be presented with an element of predictability.

6) Breathing phase duration is subjective and dependent on user perception of the representation: Five participants felt that certain representations were longer or shorter than others despite the identical phase length duration. Their perceptions differed among all four representations. P13, for example, sensed that the wave took longer than the sphere while P18 remarked that the wave *"had the best timing."* P14 and P18 felt that the donut chart representation was too short. P10 commented that the cylinder took too long, *"beyond my comfort level of holding."* This perception of length also differs within representations as well, with P18 also feeling that the cylinder had a *"relatively long inhale and exhale and a relatively short hold period."* Some participants acknowledged that the phase duration was the same for all the visualizations but they still perceived some as longer than others.

Also related to length is the power or force of the air being breathed in and out. P6 liked the wave-based representation the best because he knew how powerful he should inhale or exhale. He did not like the cylinder because he could not get that information from it.

Implication: Designers can note and take advantage of the differences in perception of certain representations since some representations could be better for paced breathing while others may be better for deep breathing. Perhaps representations that are better for paced breathing are the ones that users feel are more even, while those that are better for deep breathing are the ones that allow users to gauge how powerful they should inhale or exhale. These subjective phase length variations could also be due to intra-individual physiological differences. Thus, designers can also provide customization options for cycle and even phase duration so that users do not feel like they are breathing for too long or short of a time.

VII. Discussion

Here we discuss themes that are related to both our quantitative and qualitative findings. We also discuss breathing guidance using methods other than visualization.

A. Use of Easing Functions

Using linear versus non-linear easing functions for animating the visualizations can help designers address the issue of differentiating between deep and paced breathing. Visualizations that are effective at guiding deep breathing may not perform well when translated to paced breathing and vice versa, since some participants commented that they felt like a certain representation helped them breathe in more deeply than others. This could be due to the movement speed in a phase or the linear versus non-linear progression within a phase.

In this study, we chose to utilize non-linear progression in the cylinder and sphere representations because it was the most commonly used method in the market. Also, since the human lung takes in air non-linearly [3], the sphere and cylinder's non-linear animations may be a more natural movement. However, it could make it harder for users to follow even if they feel it corresponds better with their body movement.

This was what motivated our informal study. Our results do not suggest, however, that making the representations linear will improve breathing synchronization. There are advantages and disadvantages to both approaches, choosing between the two depends on whether the main goal is to support deep or paced breathing. Making the movement in a phase non-linear speed could help users know how deeply they can breathe, while keeping this movement steady will help users know how quickly or slowly they are expected to breathe.

B. Visual Encodings and Effectiveness

Visual encodings are different ways in which data is shown inside a visualization and are clearly important to the effectiveness of a representation. For example, we know that position and size encodings are most effective for quantitative data [27]. In breathing synchronization, the primary variable to encode is the time remaining in a phase. By explicitly encoding time in the arc length, the donut chart proved successful especially in supporting predictability with time as well as the target for each phase change. The wave similarly has position and length encodings so it makes sense that users performed well with it (even though they did not perceive their performance as good). The sphere, on the other hand, did not encode position or length, but rather area and fails to communicate a positional target that helps anticipate phase changes, thus hindering predictability. Encoding the breathing phase, a nominal variable, is also important. For example, including color or spatial encodings for the phases made the current phase salient in both the donut chart and sphere, but proved difficult for the wave.

Perhaps there is a new, alternative representation that effectively uses visual encodings not present in the current evaluated visualizations. Moving forward, designers should pay careful attention to encodings, drawing from the visualization design literature [27, 25, 6] to choose effective encodings based on the type of data to be communicated.

C. Breathing Guidance Beyond Visualization

While users' views of the auditory guidance was mixed, there is still room to investigate further methods of teaching breathing exercises without relying on visualizations alone. For instance, it would be useful to evaluate user reactions to different auditory tones. Since study participants suggested using sounds from nature (such as ocean waves) or musical tones, it warrants an investigation on the roles that these sounds would play in the user experience overall.

Haptics is a broad field that has applications for teaching breathing exercises. As discussed in the related works section, previous works have analyzed the effectiveness of utilizing haptics alone or in conjunction with other feedback types for facilitating paced breathing. Paredes and Chan, for instance, found that haptics by itself is useful for guiding deep breathing exercises and that pressure-based haptic feedback could be better than vibration-based feedback [33]. However, Dijk and Weffers theorized that multiple forms of feedback can be overwhelming. Users who focused on visual, audio, and haptic feedback simultaneously spent much effort concentrating and could not relax as much as other users [11]. Therefore, haptic feedback should either be optional or unobtrusive if it were introduced. If both audio and haptic feedback are integrated into a mobile app, users should be able to choose what kind of feedback they desire and customize the combination or intensity of the feedback.

D. Limitations

Because the exercises were performed on a mobile device, like most touchscreen/portable devices it vibrates whenever it plays audio. While this is not caused by a vibration actuator, it is a source of haptic feedback and may affect the results of the audio portion of the experiment. Also, because we asked participants to place stickers on their chest and sternum, some participants may have been able to guess that we were measuring the pace of their breathing. In addition, while we ensured that participants did not have previous experience using breathing apps, we did not account for the differences in each participant's learning curve.

Our quantitative analysis was limited by our sample size resulting in a large confidence interval. Thus, we could not determine whether the wave or donut chart performed better, only that these two performed better than the cylinder and sphere representations.

VIII. Conclusion and Future Work

Our results align with previous study findings that wave-based visualizations outperform sphere-based visualizations. However, since users reacted the most negatively to the wave-based visualization, designers considering using it should improve it to increase user satisfaction while maintaining its effectiveness. Application developers who choose to utilize current visualizations should focus on the donut chart rather than the other three visualizations discussed. From our findings, the work remains to design and test a new representation combining the best features of the four that we tested. Future work could also include testing existing users of the four representations and then comparing their performance.

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