Using Real-time Biofeedback of Heart Rate Variability Measures to Track and Help Improve Levels of Attention and Relaxation

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ABSTRACT
The main purpose of the study was to investigate if it was possible for a person to use the real-time biofeedback of their heart rate variability (HRV), recorded from a heart rate monitor watch, to help improve their level of attention and relaxation. Attention and relaxation are important factors affecting creativity, so improvements in 'relaxed concentration' could help enhance creativity. New HRV analysis algorithms were developed and tested together with three different user interfaces to explore how the interaction design affects user performance. Initial results suggest that it is possible to estimate levels of attention and relaxation, at least at a crude level, and that people are able to use this information to help improve their level of attention and relaxation. In addition, the results suggest that the interaction design of the application has a very important role to play in supporting user engagement and to maintain motivation levels.

Author Keywords
Heart Rate Variability; Attention; Relaxation; Stress; Biofeedback; Creativity; Flow.

ACM Classification Keywords
G.4 Mathematical Software: Algorithm Design and Analysis; H.1.2 User / Machine Systems; H.5.2 User Interfaces; K.3.1 Computer Uses in Education.

INTRODUCTION

Our main research interests focus on the factors and processes that affect creativity [1][2][3][4]. Two factors of particular interest are attention and relaxation. Voluntary attention is described by Kahneman [5] as "an exertion of [mental] effort in activities which are selected by current plans and intentions". Csikszentmihalyi [6] suggested that people enter a state of 'flow' during creativity that he described as an "effortless, yet highly focused state of consciousness" where flow is characterised by high levels of concentration and positive affect. Others have also found a relationship between positive affect and creativity [7][8] and between creativity, motivation and mental effort [9][10]. Our own research findings support the suggestion that people have high levels of attention with positive valence when undertaking a creative activity [11][12].

Our main motivation for this study was to see if it was possible to develop a software application that could help people train and improve their own levels of attention and relaxation using the real-time biofeedback of their heart rate variability (HRV). The idea being that if people could improve their level of 'relaxed concentration' this could help enhance their own creativity.

HRV, Attention, Stress and Flow

Heart rate variability (HRV) can be measured from the variation in consecutive R-R intervals of the Electrocardiogram (ECG) or from the variation in consecutive pulse cycle intervals using techniques such as Photoplethysmography [13][14][15]. Previous research studies suggest that HRV data can provide valuable information on a person's level of attention, and that when there is an increase in mental effort there is also an increase in heart rate, and a reduction in HRV power [16][17][18]. Attention and mental effort have also been associated with a specific reduction in HRV power around 0.1 Hz [19][20]. HRV is commonly used as a psychophysiological measure of mental and physical health and past research has shown that stress and anxiety causes an increase in heart rate and a reduction in HRV power in the high frequency range (0.15 – 0.4 Hz) [21][22].

Several researchers, including Keller et al. [23], Peifer et al. [24] and Harmat et al. [25], have undertaken investigations into the physiological aspects of flow and found links between flow and psychophysiological measures including heart rate variability (HRV). Harmat et al. [25] studied the psychophysiology of flow during computer game playing and analysed the relationship between HRV (amongst other measures) and self reported states of flow, attention, valence and arousal. Their results showed a correlation between high levels of flow, attention and positive affect,

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and that higher levels of flow were associated with lower HRV power in the low frequency range (0.04 – 0.15 Hz).

Previously we found that it is possible to detect differences in HRV measures between states of high attention and relaxation from heart rate monitor watches such as the Mio Alpha 2 [12]. High attention was associated with reductions in HRV power in the low frequency range (0.07 – 0.15 Hz), while stress was associated with reductions in HRV power in the high frequency range (0.15 – 0.4 Hz) as well as an increase in heart rate [12].

AIMS AND OBJECTIVES

Our overall aim in this study was to investigate if it was possible to use the real-time biofeedback of a person's heart rate variability, recorded from a heart rate monitor watch such as the Mio Alpha 2 [26], to track and help improve their level of attention and relaxation. We believe this a novel approach. To try and achive this aim the following objectives were:

1. To evaluate the effectiveness of new HRV analysis algorithms for estimating levels of attention and relaxation in real-time.
2. To investigate how the interaction design of the software application affects user engagement and the ability of users to train and improve their levels of attention and relaxation.

The motivation for using a heart rate monitor watch, rather than an ECG chest strap, was because of its simplicity and convenience of use. However, it is important to note that the accuracy of HRV data collected from a heart rate monitor watch, compared to HRV data collected from an ECG chest sensor, is significantly reduced [27]. This is because of the need to take averages of pulse cycle interval estimates on the watch sensor to try and reduce recording errors. One of our own previous studies [12] showed that low and high frequency HRV power were reduced when using a watch sensor (compared to sensor clipped to the ear), with the high frequency range HRV power being the most affected.

APPROACH

The study was split into four stages:

1. The design and development of new HRV analysis algorithms to track levels of attention and relaxation in real-time.
2. Evaluation of the effectiveness of the new algorithms to track levels of attention and relaxation.
3. The design and development of three different user interfaces and interaction design modes for the software application to investigate how the user interface and interaction mode affects user engagement and the user's ability to train and improve their levels of attention and relaxation.
4. Evaluation of the three different user interfaces and interaction design modes.

The Cardiff School of Art and Design's Research Ethics Committee gave ethics approval for the study. All participants involved in the study gave their informed consent prior to their inclusion.

Stage 1

The software application was developed to run on an iPhone 5. The software communicated wirelessly in real-time with the Mio Alpha 2 Heart rate monitor watch [26] using the 'Bluetooth smart' protocol to receive the heart rate (HR) estimates together with time stamps. These heart rate estimates were then converted in real-time into equidistant samples using an interpolation method. Power spectrum density (PSD) estimates of HRV were calculated using Welch's Fast Fourier Transform (FFT) method (using a 64 second window), and PSD estimates were calculated for low frequency (0.07 - 0.15 Hz) and high frequency (0.15 – 0.4 Hz) ranges every 4 seconds using a moving window.

Attention and relaxation levels were calculated/estimated from estimates of the heart rate, the low frequency HRV power and the high frequency HRV power. The attention levels were calculated based on the power of the low frequency HRV (0.07 – 0.15 Hz), with an inverse linear relationship between the attention level and the low frequency HRV power. Attention levels were set on a scale from 1 to 6, where 1 represented low attention and 6 represented high attention. The relaxation levels were calculated based on a combination of changes in absolute heart rate (set from the initial 64 seconds of baseline data) and from the ratio between the peak power of the HRV signal (within the low frequency range) divided by the remaining HRV power. Relaxation levels increased with reducing heart rate, and also increased as the ratio value increased. Relaxation levels were also set on a scale from 1 to 6, where 1 represented low relaxation (high stress) and 6 represented high relaxation (low stress).

Stage 2

The accuracy and effectiveness of the new algorithms to track levels of attention and relaxation were initially evaluated by conducting a set of user tests with 22 design students and academic staff from the Cardiff School of Art and Design (11 females and 11 males), who were aged between 20 and 40 years (average age was 26.2 years old). Each of the 22 participants were asked (individually) to undertake three tasks.

The first task was a two minute Stroop test. The Stroop test has been used extensively to study attention [28] and is associated with high levels of mental effort, and often with increased levels of stress. The second task involved relaxing for two minutes. For the third task, participants were asked to draw something of their choice for two minutes. Our motivation for including the drawing task was because we regarded it as a creative activity. We therefore hypothesized that design students and academic staff would have high levels of concentration, but remain relatively relaxed, during such a creative task.

Every participant undertook the tasks individually in a quiet room while sitting (between 10am and 1pm). The Mio Alpha 2 watch [26] was used to record the heart rate (HR) estimates. The heart rate data being recorded was checked for accuracy before the start of each of the tasks. Before each of the three tasks, every participant was asked to sit quietly for three minutes to collect baseline data. After each task, participants were asked to reflect on their level of attention and relaxation during the task to see if their comments matched the results from the algorithms. All comments from the participants were audio recorded. Results from the evaluation are given in the results section.

Stage 3

Three different interaction modes were created for the software application to understand how the interaction mode affected user engagement and the corresponding attention and stress/relaxation levels.

The first interaction mode (the Zone game) gave feedback to the participant on their level of relaxation and attention separately by showing their state (via the location of a blue ball) on a focus/relaxation grid (shown in Figure 1 below). The focus/relaxation grid mapped directly to the attention and relaxation levels calculated from the heart rate data. The graphical user interface used colours (green, yellow and red) together with words ‘distracted/focused’ and ‘stressed/relaxed’ to give quick feedback to the participant on which zones represented high levels of attention and relaxation. The time spent in each zone by the participant was shown in seconds. The challenge for the participant in this interaction mode was to spend as much time as possible in the green zone representing high levels of attention and relaxation.

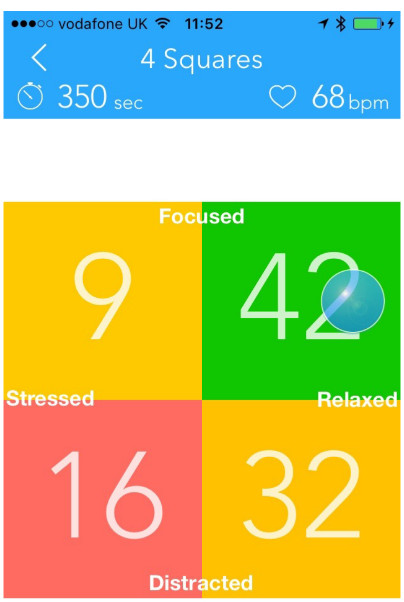

Figure 1. Screen shot of the Zone game.

The second interaction mode (the Bird game) followed a classic game format where the attention and relaxation levels were combined to create a ‘relaxed concentration’ score for a bird flying game (shown in Figure 2 below). This combined ‘relaxed concentration’ score was used to set the height the bird flies at, i.e. a high ‘relaxed concentration’ level mapped to a high height, and a low ‘relaxed concentration’ level mapped to a low height The user collects points as the bird flies through the clouds. The user must make sure that their ‘relaxed concentration’ level is high enough so that the bird does not crash into the oncoming mountains. If the bird crashes into a mountain the game ends. Note that the mountains get higher as the game progresses.

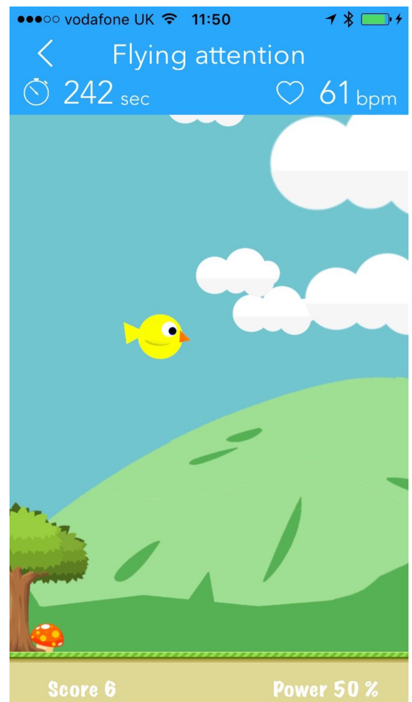

Figure 2. Screen shot of the Bird game.

One of the main differences between the Bird game compared to the Zone game is that the user might not know if they need to relax more or concentrate more (or both) to fly higher and avoid the mountains. This difference was introduced to see if users could deal with two factors, attention and relaxation, being combined. Another key motivation for introducing this new interaction mode was to see how participants reacted when they saw that the bird was not flying high enough to avoid an oncoming mountain. For example, would they be able to change their level of ‘relaxed concentraion’ quickly enough to avoid the oncoming mountain, or would the fact that they saw an oncoming mountain increase their level of stress and make their task of staying at a high level of ‘relaxed concentration’ harder? The design of the oncoming mountains in the Bird game also introduced distraction, with the potential to reduce concentration. A final motivation for introducing this interaction mode was to see if it was perceived as more enjoyable compared to the Zone game.

The third interaction mode (the Tree game) again used the combined 'relaxed concentration' score. However, in this mode the 'relaxed concentration' score was used as a measure to either enable flowers to appear on a tree (for high 'relaxed concentration' scores) or to fall off the tree (for low 'relaxed concentration' scores) (shown in Figure 3 below). The tree initially starts with no flowers on it. The challenge for the participant in this interaction mode was to generate as many flowers as possible on the tree.

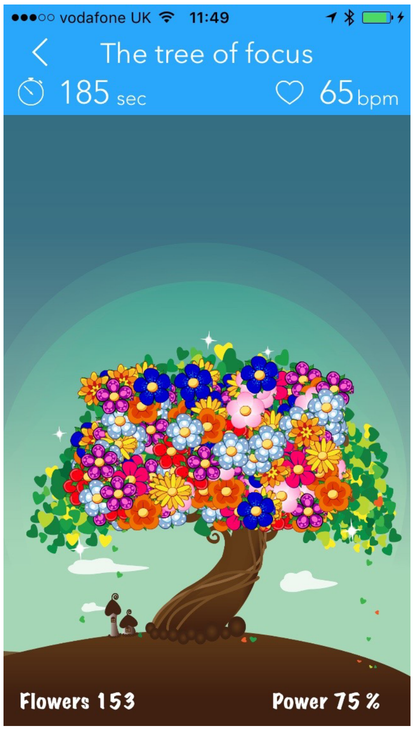

Figure 3. Screen shot of the Tree game.

The interaction design of the Tree game differed from the Bird game in terms of the time participants had to change their level of 'relaxed concentration'. In the Bird game participants might have to make quick changes to their level of 'relaxed concentration' to avoid crashing into the oncoming mountain. In the Tree game, participants could take their time more without any major consequences. The Tree game also differed from the Bird game in terms of having fewer distracting elements (such as the oncoming mountains in the Bird game). The motivation for introducing this third interaction mode was to see if participants could achieve a higher level of 'relaxed concentration' compared to the bird game format, and to understand how different game elements affect performance. In addition, we wanted to see how enjoyable this interaction mode was.

Tasks in each of the three interaction modes lasted two minutes. Before a participant started a task, 64 seconds of baseline HRV data was collected. This was presented to the participant as a warm-up period to get focused and relaxed.

Stage 4

15 design students and academic staff from the Cardiff School of Art and Design participated in testing the three interaction modes (7 females and 8 males), and were aged between 20 and 40 years (average age was 27.8 years old). Each of the 15 participants undertook two of the three interaction modes, and for each interaction mode, undertook the task three times to see if their attention and relaxation levels improved or not. Therefore 10 participants tested each of the three interaction modes. It was decided not to get the participants to undertake all three interaction modes as it was felt that the participants would get tired after performing several challenges. To further mitigate against fatigue affecting the results, the order with which the interaction modes were shown varied, so that 5 of the 10 participants played a particular interaction mode first (the other 5 playing it second). Within these criteria, participants were randomly assigned to two of the three interaction modes.

Similarly to the test protocol used in stage 2, every participant undertook the tasks individually in a quiet room while sitting (between 10am and 1pm). The Mio Alpha 2 watch [26] was used to record the heart rate (HR) estimates, and the heart rate data being recorded was checked for accuracy before the start of each of the tasks. Before each task, 64 seconds of baseline HRV data was collected.

All participants were asked to try and get as high a score as possible for each attempt, but no advice or guidance was given to the participants on how to increase their level of attention and relaxation. This was because we were interested to see whether participants were able to work out for themselves how to improve their attention and relaxation levels using the biofeedback information presented as the only guide.

After completing three attempts of one interaction mode, participants were asked how they found the experience and were also asked to complete a questionnaire to see how they estimated their levels of concentration and relaxation during the task; how easy it was to concentrate and relax; and whether they found the experience pleasant or unpleasant. Each scale was rated from a scale of 1 to 9, where 1 represented the lowest level and 9 the highest level.

RESULTS

Stage 2 Results

Table 1 below shows the averages of the estimated attention and relaxation levels (1 to 6) across the 22 participants for the three tasks: the Stroop task; the Relaxation task; and the Drawing task.

Verbal feedback from the participants matched these results, with participants generally finding the Stroop task the most stressful; the Relaxation task the most relaxing;

and the Drawing task quite relaxing. Attention was generally described as very high for the Stroop task; low for the Relaxation task; and high for the Drawing task.

Task	Attention level	Relaxation level
Stroop	5.17	2.87
Relaxation	3.48	4.48
Drawing	5.14	3.36

Table 1. Results of the estimated attention and relaxation levels for the three tasks: Stroop; Relaxation; and Drawing.

An analysis of variance (ANOVA) was conducted to study the difference in means between the attention and relaxation levels of the participants in the three tasks, using a repeated measures design. The alpha level was set at 0.05 for the classification of significant difference, and based on Cohen [29] we interpreted effect size as small when d = 0.2; medium when d = 0.5; and large when d = 0.8.

The attention levels for the Stroop task were not significantly different from the Drawing task, but the attention levels for the Stroop task were significantly higher than the Relaxation task, $F(1,21) = 15.31$, $p = 0.001$ with a large effect size, $d = 0.90$. The attention levels for the Drawing task were also significantly higher than the Relaxation task $F(1,21) = 22.01$, $p < 0.001$ with a large effect size, $d = 1.11$. The relaxation levels for the Relaxation task were significantly higher than the Stroop task, $F(1,21) = 29.17$, $p < 0.001$, with a large effect size, $d = 1.16$. There was also a significant difference in relaxation levels between the Relaxation task and the Drawing task, $F(1,21) = 10.61$, $p = 0.004$, with a medium effect size, $d = 0.69$. There was no significant difference in relaxation levels between the Drawing task and the Stroop task.

Stage 4 Results

Table 2 below shows the average scores for the different interaction modes across the three attempts.

Interaction Modes	First Attempt	Second Attempt	Third Attempt
Zone Game	60.0	68.0	69.2
Bird Game	42.6	37.7	22.4
Tree Game	86.3	119.0	74.0

Table 2. The scores relating to time spent in high 'relaxed concentration' during the task.

The score for the Zone game represented the average time spent in the green zone (in secs), representing high levels of attention and relaxation, over the two minute task. The score for the Bird game represented the average number of points gained by flying through clouds (equating to the time spent in a high level of 'relexed concentration'), before either crashing into the mountain, or completing the two minute task. The score for the Tree game represented the average number of flowers on the tree on completion of the two minute task, with the number of flowers again correlating with the time spent in 'relaxed concentration'. Note that you cannot directly compare the scores between interaction modes, but you can directly compare the changes in scores between attempts (for a particular interaction mode).

An analysis of variance (ANOVA) was conducted to study the difference between the means of the three attempts for each interaction mode, using a repeated measures design. Maulchy's test indicated that the assumption of sphericity was not violated. On average, the scores for the Zone game increased with each attempt, however the scores were not significantly affected by the attempt. For the Bird game the average scores decreased with each attempt, however, the scores were not significantly affected by the attempt. For the Tree game, the scores were significantly affected by the attempt, $F(2,28) = 3.65$, $p = 0.047$.

Comparing pairs of attempts for the Tree game, there was an increase in the average score from attempt 1 to 2, and this difference was significant, $F(1,19) = 7.46$, $p = 0.023$, with a large effect size, $d = 0.87$. From attempt 2 to 3 there was a decrease in the average score, and this difference was significant $F(1,19) = 6.46$, $p = 0.032$, with a large effect size, $d = 0.80$.

Table 3 below shows how the participants, on average, estimated their levels of concentration and relaxation across three attempts of a task; how easy it was to concentrate and relax; and whether they found the experience pleasant or unpleasant. Each scale was rated from a scale of 1 to 9, where 1 represented the lowest level and 9 the highest level.

Average Scores	Zone Game	Bird Game	Tree Game
Concentration level	6.8	6.0	7.2
Ease of concentration	5.3	3.9	5.0
Relaxation level	6.6	5.2	6.9
Ease of relaxation	5.7	4.5	6.0
Pleasantness level	6.0	6.0	7.4

Table 3. Summary (averages) of questionnaire results from participants after completing three attempts of a task.

Concentration and relaxation levels were reported as highest for the Tree game, slightly above the Zone game with the Bird game having the lowest reported levels of concentration and relaxation. Participants playing the Bird game also found it harder, on average, to relax and concentrate relative to the other two games. The Tree game was seen as the most pleasant to play.

DISCUSSION

The results from stage 2 suggest that it is possible to estimate levels of attention and relaxation, at least at a crude level, using heart rate estimates recorded from a heart rate monitor watch. However it might not be possible to distinguish between small variations in mental effort, as suggested by previous research [19][20], or even in small variations in stress levels.

We believe this is an important finding, even with these limitations, as heart rate monitor watches are simple and convenient to use, compared to other ECG recording methods, and provide an opportunity for easier adoption in the marketplace.

The results from stage 2 also suggest that participants undertaking a creative activity, such as drawing, have (on average) high levels of attention. This supports the suggestion by Csikszentmihalyi [6] that people have high levels of concentration during creativity.

The results from stage 4 provided some insights into how the interaction design of an interface affects the abilities of participants to use the real-time biofeedback of their own heart rate variability measures to help improve their levels of attention and relaxation.

During the Zone game, participants were able, on average, to improve their level of attention and relaxation (based on the HRV algorithm estimates) as they tried further attempts, spending more than half of the two minutes in the green zone, representing high levels of attention and relaxation. Participants reported that having separate feedback on concentration and relaxation levels helped, as they understood what aspects they needed to improve to increase their scores. Participants reported a range of techniques they used to improve their concentration and relaxation levels (note that they were given no advice on how to concentrate or relax).

Participants in the Bird game generally found it difficult to have a consistently high level of 'relaxed concentration', and reported that this was partly because of confusion on whether to relax more or to concentrate more, but also because of the stress and distraction created by seeing that the bird was about to crash into the mountain unless they increased their 'relaxed concentration' level (mapped to bird height) quickly. The reduction in the scores, on average, from attempt 1 (42.6) to attempt 3 (22.4), was also reported as being caused by increasing frustration at not being able to maintain a high level of 'relaxed concentration' when noticing oncoming mountains. This is further supported by participants' own ratings of how easy it was for them to concentrate and relax (on average, 3.9 and 4.5 respectively).

In the Tree game, participants, on average, significantly increased their 'relaxed concentration' score from attempt 1 to attempt 2, $F(1,19) = 7.46$, $p = 0.023$. Participants spent, on average, more than half of the two minutes in a high level of 'relaxed concentration' during attempt 2. However, there was also a significant decrease in their score from attempts 2 to 3, $F(1,19) = 6.46$, $p = 0.032$. This reduction in score from attempt 2 to 3 seemed mainly due to tiredness and a lack of motivation on the third attempt. Some participants reported that after achieving a high score in attempt 2, they did not have the motivation to repeat the high score in attempt 3.

Compared to the Bird game, participants in the Tree game did not seem to have a problem having feedback on their attention and relaxation levels combined into a 'relaxed concentration' score. This seemed to be because they felt they had more time to try different techniques to improve their levels of concentration and relaxation compared to participants in the Bird game. It could also be due to fewer distractions in the interface.

The Tree game had the highest rating in terms of the pleasantness level (7.4) compared to the other two interaction modes (both at 6.0) and most participants who played the Tree game reported that they enjoyed it. A small minority of the participants who played the Bird game said that they enjoyed the experience, and mentioned that they liked the challenge, however this was balanced against the majority of participants who stated that they found it frustrating, and this is reflected in the overall pleasantness rating. Feedback on the Zone game was more neutral.

Other comments from participants after the tests suggested that the software application could be useful in two modes: firstly, a 'training mode', as tested in this study; and secondly, a 'background mode' that gives a daily log of attention and relaxation levels throughout the day giving summaries and a detailed breakdown in terms of time and possibly location, so that users can reflect on when and where their attention levels dropped, or their stress levels increased. Note that further research is required to see if it is possible to use a heart rate monitor watch in such a 'background mode' as this could be problematic. This is because a range of factors can affect HRV, including physical exercise and respiration rates/depths. In addition, there is an increased likelihood of recording errors when a person is moving. Many other factors can also affect HRV [30].

LIMITATIONS

A significant amount of HRV data was lost by using a heart rate monitor watch, compared to an ECG chest strap. It is likely that this lost data could have improved the tracking of attention and relaxation levels further. However, one of our main motivations was to see if a heart rate monitor watch could at least provide some indication of attention and relaxation levels due to their ease of use. Further work is required to accurately measure the effectiveness of the heart rate monitor watches in tracking attention and relaxation, including the comparison of different algorithms.

Only 22 participants were involved in stage 2 of the study, and only 15 participants involved in stage 4. These are small sample sizes, so it is not possible to assume that the results presented in this study would apply to a general population.

Further larger scale studies are required to valid these results.

CONCLUSIONS

The results from stages 2 and 4 of the study tentatively suggest that it is possible to use the real-time biofeedback of heart rate variability measures to track and help improve levels of attention and relaxation using a heart rate monitor watch, at least at a crude level. In addition, the interaction design of the application has a very important role to play. Results strongly suggest that the interaction design of the application significantly affects user engagement and the ability of users to train and improve their levels of attention and relaxation. The results also suggest that the interaction design of the application must make sure that motivation levels are maintained, where the challenge and skill level match well, otherwise, users could get frustrated or bored. Lessons need to be learned from game design principles in terms of freedom to fail; providing rapid feedback; offering progression; and embedding a storyline to maintain engagement/motivation with the application over a period of time.

FUTURE IMPLICATIONS

A software application that can help improve attention and relaxation levels has possible benefits in terms of helping people enhance their levels of creativity, as attention and relaxation are key factors associated with creativity. Such a software application could also have potential in helping children improve their levels of concentration at school. Another possibility is to integrate the technology into 'mindfulness' applications targeted at both children and adults to help improve attention, reduce stress and promote well-being. In addition, the technology could possibly be used for niche markets such as sports applications requiring improved levels of relaxed concentration, such as golf.

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