Automated Detection of Mind Wandering: A Mobile Application

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Keywords: Biosignals, Mind Wandering, Mindfulness, Attention, Signal-Processing, Stress, Mobile Phone App.

Abstract: There is growing interest in mindfulness-based training of attention. A particular challenge for novices is learning to sustain focused attention while ensuring that the mind does not wander. This paper presents the development of a tool for the automated detection of episodes of *mind wandering (MW)*, on the basis of biosignals, while normal healthy participants engaged in *brief mindfulness-based training (BMT)* of attention. BMT required five 20-minute training sessions on consecutive days and entailed practice of breath-focused attention, a typical exercise in mindfulness-based techniques of stress-reduction. Heart rate, respiratory rate, electrodermal and electromyographic activity were measured, and participants pressed a button to indicate the subjective detection of MW during training. The data showed that BMT did not influence our measures of stress but BMT was effective in reducing the frequency of subjectively detected MW events. The algorithm for offline detection of MW achieved an accuracy of 85%. Based on this algorithm, a mobile application was developed for automated MW detection in real-time. The application requires the use of easily placeable sensors, provides a new approach to the real-time MW detection, and could be developed further for use in MW-related investigations and interventions (such as mindfulness-based training of focused attention).

1 INTRODUCTION

While Mindfulness has, like Zen, Tibetan Buddhism and Vipassan, a long history (Kabat-Zinn et al., 1985; Austin, 1999; Gunaratana, 2002), mindfulness-based training is flourishing in the USA and Europe as an intervention strategy for improving mental and physical health (e.g., Chiesa and Serretti, 2010; Bishop, 2004; Rubia, 2009; Lutz et al., 2006; Hofmann et al., 2010; Grossman et al., 2004). A key feature of mindfulness-based training is the self-regulatory control of attention (e.g., Goleman and Schwartz, 1976; Kabat-Zinn, 1982). Interest in using mindfulness-based training to enhance attentional performance is therefore growing (e.g., Lutz et al., 2008; Bishop, 2004).

A novice typically begins training by acquiring skill in the focusing of attention (Vago and Silbersweig, 2012; Kapleau, 1965), for various forms of attention see e.g., Jha et al., 2007. In mindfulness, this skill is most widely practiced in the form of *focused attention (FA)* meditation (Lutz et al., 2008). During FA the practioner learns to maintain an upright sitting posture, relax and direct full attention to a chosen object (typically the breath) while ensuring that the mind does not wander (Tops et al., 2014). In the event of *mind wandering (MW)*, the practioner is instructed to detect this as early as possible and voluntarily redirect the focus of attention back to the object where the focus should then remain. A particular challenge in learning to self-regulate the control of MW is that there is little meta-cognitive awareness that attention has actually become disengaged from the object of focus and entered a state of MW (Mooneyham and Schooler, 2013; Oken et al., 2006). Acquiring greater skill in detecting this state therefore requires cognitive effort and practice.

The aim of the present work was to develop a mobile tool that could be used for automated detection of MW in real-time during practice of eyes- closed FA meditation. This tool could also be integrated in other cognitive training strategies for improving fo-

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Cheetham, M., Cepeda, C. and Gamboa, H.
Automated Detection of Mind Wandering: A Mobile Application.
DOI: 10.5220/0005702401980205
In *Proceedings of the 9th International Joint Conference on Biomedical Engineering Systems and Technologies (BIOSTEC 2016) - Volume 4: BIOSIGNALS*, pages 198-205
ISBN: 978-989-758-170-0

cused attention in which attentional disengagement is indicated to the practioner or trainer as it occurs. Psychophysiological measures are ideally suited for use in eyes-closed meditation. But we are not aware of the development of a tool for automated detection of MW during cognitive training of attention, such as in FA meditation (but see work toward automated detection of MW during so-called *mindless reading*, Drummond and Litman, 2010; Franklin et al., 2011; Mills and Mello, 2015; DMello, 2013; Bixler and DMello, 2014; Blanchard et al., 2014).

The present study applied the well-established breath-focused meditation procedure (Levinson et al., 2014; Ramsburg and Youmans, 2012; Kabat-Zinn and Hanh, 1990; Lutz et al., 2008; Tang et al., 2007). This requires the practioner to attend fully to the subjective sensation of breathing where the air passes the nostrils. Psychophysiological change is linked to different states of attention (Andreassi, 2000).Specifically, MW has been reported to relate to a change in heart rate and skin conductance levels (Ottaviani et al., 2015; Smallwood et al., 2004; Smallwood and Schooler, 2009; Smallwood and Schooler, 2006). Our focus was placed therefore on measures of heart rate and skin conductance. Given our use of the breath-focused procedure and that respiration has been shown, at least on self-report basis, to indicate attention-related improvement during mindfulness training (Levinson et al., 2014), respiration was also measured. Finally, electromyographic activity was measured to assess whether postural change would occur during MW episodes. This was considered possible because inattention to perceptual information during MW could render the cognitive processing of posture more difficult (Kam et al., 2011; McVay et al., 2009; Rushworth et al., 2003).

Training in FA meditation was guided by a *brief mindfulness-based training (BMT)* protocol. BMT is known to have beneficial effects on alertness and attentional control (Elliott, 2014; Tang et al., 2007; Vinci et al., 2014; Srinivasan and Baijal, 2007). For the purpose of the present work, we adapted a training protocol (Zeidan et al., 2011; Zeidan et al., 2010) to create five 20-minute breath-focused training sessions. Our protocol placed the emphasis of training on the *attentional cycle* (Hasenkamp et al., 2012; Cahn and Polich, 2006). The attentional cycle comprises the main attentional states that are iteratively practiced during FA training: Directing of full attentional focus on an object, MW, subjective detection of MW, and the reinstatement of attentional focus on the object. Participants were required to press a button when they subjectively detected the occurrence of MW. This served both the purpose of ensuring that MW detection had been acknowledged (as part of the training protocol), as well as providing us with a participant-determined approach to the analysis of our psychophysiological data. Given that BMT is also known to have a beneficial effect on the self-regulation of stress (Cresswell and Gilmour, 2014), we explored the impact of BMT of FA meditation on levels of stress.

2 METHODS

2.1 Participants

Fifteen mindfulness-naive volunteers [8 female] participated (M = 22.67 years; SD = 2.29), This number was considered sufficient for data acquisition (Braboszcz and Delorme, 2011). All participants were normal healthy, native speakers of Portuguese, with normal or corrected-to-normal vision, and had no record of neurological or psychiatric illness, and no current use of medication or drugs. Written informed consent was obtained before participation in accordance with the guidelines of the Declaration of Helsinki. All procedures and con sent forms were approved by the Ethics Committee of the University of Lisbon. Each person received 15 Euro for participation.

2.2 Materials and Procedure

Five 20-minute training sessions (one on each of 5 consecutive days) were conducted, using the BMT protocol (adapted from Zeidan et al., 2011). The first and last sessions took place in the laboratory in order to acquire biological signals. All sessions were conducted in a quiet room, with comfortable temperature and dimmed light. At the beginning of the first session, the participant signed a consent form and provided demographic data. The participant also self-assessed the general quality of sleep on a 5-point scale (ranging from 1 ”poor sleep” to 5 ”good sleep”). The analysis of the self-assessment sleep data indicated no impact of sleep quality on MW. These data are therefore not reported any further. The sensors were then attached, and the participant read the BMT protocol. The experimenter verified the participant’s comprehension of the protocol and then left the room. After a duration of 20 minutes, the experimenter entered the room, asked the participant to stop training and the biosensors were removed.

2.3 Data Registration

Continuous acquisition of biosignals was performed with a biosignalsPLUX device (Plux - Wireless Biosignals S.A., Lisbon, Portugal). The acquired signals were *respiration (RESP)*, using 2 piezo-electric bands (chest and abdomen), *heart rate (HR), electrocardiogram (ECG)*, *electromyogram (EMG)*, using one electrode on the trapezius muscle of the right and left side of the neck, respectively, and *electrodermal activity (EDA)*. The recorded *button-press (BP)* indicated subjective detection of MW. The recorded signals were saved to text file using the signal processing software OpenSignals (Plux - Wireless Biosignals S.A., Lisbon, Portugal), with a sampling frequency of 100 Hz (12 bits ADC).

2.4 Data Pre-processing

The following Python Packages were used: Matplotlib (Tape, 2001), Seaborn (Haslwanter, 2015), NumPy (Bressert, 2013) and SciPy (Bressert, 2013).

The first and last minute of data acquisition, during which the experimenter was present in the room, were removed. All signals were aligned at baseline, having removed the mean value. Raw data were rectified and filtered offline with a bandwidth 0-0.3 Hz for EMG, 0.2-0.5 Hz for EDA, 0.1-0.3 Hz for RESP, and 5-15 Hz for ECG. For movement artefacts, outliers of ECG and RESP were detected and replaced by the preceding correct value. For ECG, outliers were defined as a peak occurring between 0.4s before or 2s after the previous peak, and for RESP, as a peak occurring between 10s after or 1.5s before the previous peak. For EDA, peaks in skin conductance were recorded.

2.5 Detection of Mind Wandering

Based on previous studies (Ottaviani et al., 2015; Smallwood et al., 2004; Smallwood and Schooler, 2009; Smallwood and Schooler, 2006), we assumed that HR and EDA would increase during periods of MW. For the purpose of developing the algorithm and in the absence of any suitable literature known to us, we assumed - consistent with the increase expected in HR and EDA - that RESP would also increase. These changes reflect an increase in arousal (Noteboom et al., 2001). Analysis for MW was applied to 20s-long data epochs time-locked to the BP (Braboszcz and Delorme, 2011).

2.6 Assessment of Stress Level

The same biosignals were used to assess the impact of the BMT protocol on stress. Based on, for example, Everly and Lating (2013), Greenbaum (2012), Khazan (2013), Lenman (1975) we expected a general decrease in the respective value of these measures the between the first and final training sessions to indicate a reduction in stress levels. For ECG and RESP, we extracted the time and frequency domain parameters related to changes in stress (see Klabund, 2014), as presented in Tables 1 and 2.

Table 1: Stress level by ECG.

Time domain	**Frequency domain**
Time between peaks (s)	IHR (beats/min)
pNN20 (%)	LF (%)
pNN50 (%)	HF (%)
RMSSD (s)	$\frac{LF}{HF}$

Table 2: Stress level by RESP.

Time domain	**Frequency domain**
Mean (%)	Mean (breaths/min)
RMSSD (s)	
Inspiration time (s)	
Expiration time (s)	
Inspiration (%)	
Expiration (%)	
Pause of expiration (%)	
$\frac{Inspiration\,time}{Expiration\,time}$	
$\frac{Pause\,time}{Expiration\,time}$	

3 RESULTS

3.1 Mind Wandering Assessment

Receiver operator characteristic (ROC) curve analysis was conducted to determine the accuracy of our psychophysiological measures as classifiers of MW events in ROC space, that is, the plot of the true positive rate (sensibility) versus the false positive rate (1-specificity) (Raslick et al., 2007). Accuracy is measured by the area under the ROC curve (Hanley and McNeil, 1982). As a rough guide, a value between .80 and .90 is conventionally considered good. All data analyses were performed using SPSS version 21.0 (IBM Corp., Armonk, NY, USA).

ECG and EDA accomplished the best results and were classified as good in accuracy, with an *area under the curve (AUC)* for ECG and EDA of 0.809 and 0.808, respectively. RESP (0.709) and EMG (0.695) showed fair and poor accuracy, respectively. Combining ECG and EDA improved the AUC, with 0.854. This AUC is a good result, reflecting a high degree of accuracy compared to previous studies (though it should be noted that previous studies relate to mindless reading). Figure 1 represents an example of the algorithm used, in which the relation between the processed signals and estimated events can be seen. We then compared the BP data of each participant between the first and final sessions of training to determine whether BMT was effective in reducing the frequency of subjectively detected MW episodes. Paired t-tests were conducted (with $p < 0.05$ considered significant), showing a highly significant decrease (t_{14} = 2.045, p = 0.03) in MW between the first (M = 46.67, SE = 1.85) and last training sessions (M = 42.00, SE = 2.53).

3.2 Stress Level Assessment

Paired t-tests (significance level at $p < 0.05$), were conducted to compare the first and last sessions of training. The results showed one significant effect, namely, a decrease (t_{14} = 2.09, p = 0.03) in RESP (respiration time) between the first (M = 4.99, SE = 0.36) and fifth sessions (M = 4.64, SE = 0.34). No effects were found for ECG, EMG and EDA. The p-values of all parameters tested are presented in Table 3.

4 MOBILE APPLICATION

Based on the offline algorithm for MW detection, a mobile application was developed for automated MW detection in real-time. The mobile phone application was programmed in Intel XDK, which comprises development tools for programming web applications on the basis of the language HTML5 (Intel, 2014). A plugin for Android devices was created to allow the device to vibrate (as a form of biofeedback) during the occurrence of a MW episode. The Android device is linked to the biosignalsPLUX device (Plux Wireless Biosignals S.A., Lisbon, Portugal) to acquire the biosignals (ECG and EDA). JavaScript (Simpson, 2012) was used to process the ECG and EDA signals in real-time according to the flowchart in Figure 2 (Kuo et al., 2006).

Table 3: P-values for stress (comparing first with last session).

Parameter		**Full sample**
ECG	RMSSD	0.30
	Time between beats	0.17
	NN20	0.34
	NN50	0.23
	IHR	0.27
	LF	0.28
	HF	0.28
	$\frac{LF}{HF}$	0.49
EDA	Stress level	0.37
	Number of peaks	0.35
RESP	RMSSD	0.34
	Respiration time	**0.03**
	Inspiration time	0.47
	Expiration time	0.08
	Inspiration	0.25
	Expiration	0.25
	Pause	0.20
	$\frac{Inspiration}{Expiration}$	0.45
	$\frac{Pause}{Expiration}$	0.33
	Respiratory rate	0.12
EMG Right	Stress level	0.48
	Mean amplitude	0.19
EMG Left	Stress level	0.39
	Mean amplitude	0.33

5 DISCUSSION

The aim of the present study was to initiate work toward development of a real-time algorithm for MW detection during eyes-closed meditation. The main finding was that our combined measures of EDA and ECG were good in detecting episodes of MW. The data show also that the BMT protocol was effective in improving the self-regulation of MW. Given the results of the ROC analyses, the specificity of the BMT protocol for training the attentional cycle, subjective reports at debriefing confirming that participants adhered to the protocol, and that there was an improvement in MW over training, we assume that the algorithm and the selected psychophysiological signals provide a sensitive means for classifying periods of attentional disengagement before subjective detection of MW.

We cannot determine with this method what the participant might be experiencing during attentional disengagement. MW has been associated with two specific changes in cognitive processing (Smallwood and Schooler, 2006). Considered in terms of our breath-focused meditation procedure, the first of these would relate to the drift of attention away from the sensation of breathing through the nostrils, resulting in attenuated processing of perceptual information. In other words, the attentional (or perceptual) disengagement from the breath results in failure to maintain FA. The second change is that this drift of attention is likely characterized by *stimulus independent thought* during which attention is directed to internal thoughts and feelings retrieved from memory (Smallwood and Schooler, 2006), though this not need always be the case (Stawarczyk et al., 2011). We did not collect self-report data to retrospectively ascertain the possible content of experience during MW or whether the content might have influenced psychophysiological state (Smallwood et al., 2004; Smallwood et al., 2004; Fahrenberg et al., 2001; Hinterberger et al., 2011). But at debriefing, subjective detection of MW episodes was most frequently cited as the most difficult part of the training (see Schooler et al., 2011).

This present study developed the algorithm primarily with a view to its potential application in mindful FA meditation. But this idea might be extended to other forms of cognitive training of attention. For training, this method could be used to cue the participant to reinstate attentional focus when the psychophysiological measures indicate occurrence of attentional disengagement. This form of intervention might be used to enhance the participant's metacognitive awareness of and skill in detecting MW episodes (Sayette et al., 2009). Further research is also required to consider when MW begins and when it stops (Smallwood and Schooler, 2015). Our method could be used also to examine inter-individual differences in the relationship between attentional disengagement and psychophysiological measures. Inter-individual differences might potentially relate, for example, to differences in the depth of MW during FA meditation, as considered in other contexts of MW research (see the *levels of inattention hypothesis*, Shad et al., 2011), change in day-today affective state (Snippe et al., 2015), in the perceptual and interoceptive awareness of body signals (Otten et al., 2015), or in trait mindfulness (Bishop, 2004; Brown and Ryan, 2004; Carmody and Baer, 2008; Thompson and Waltz, 2007).

The data indicated that the BMT protocol was not significantly effective in influencing our measures of stress. This finding contradicts the subjective reports of the participants at debriefing. One possible reason might relate to the RESP data. These showed many artefacts, suggesting that the piezoelectric bands were insufficiently reliable. Replacing the piezoelectric with an inductive band might be considered in order to improve the reliability of the signal. The present study was based on novices. A larger data set might include experienced practitioners of FA meditation to show how, for example, the psychophysiological signature of attention disengagement might evolve with practice. The mobile application developed in the present study needs to be subjected to further testing. This might be done with a view to its potential use as a tool for training of MW during practice of mindfulness-based breath-focused attention. This tool requires use of easily placeable sensors, provides a new approach to real-time MW detection, and could be developed further for use in MW-related investigations and interventions. Given that MW in normal healthy individuals is reminiscent of certain symptoms of *Attention-deficit/hyperactivity disorder (ADHD)* (Seli et al., 2015), one area of application might be in relation to ADHD.

ACKNOWLEDGEMENTS

The authors thank PLUX - Wireless Biosignals for providing the acquisition system, plug-ins and sensors.

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APPENDIX

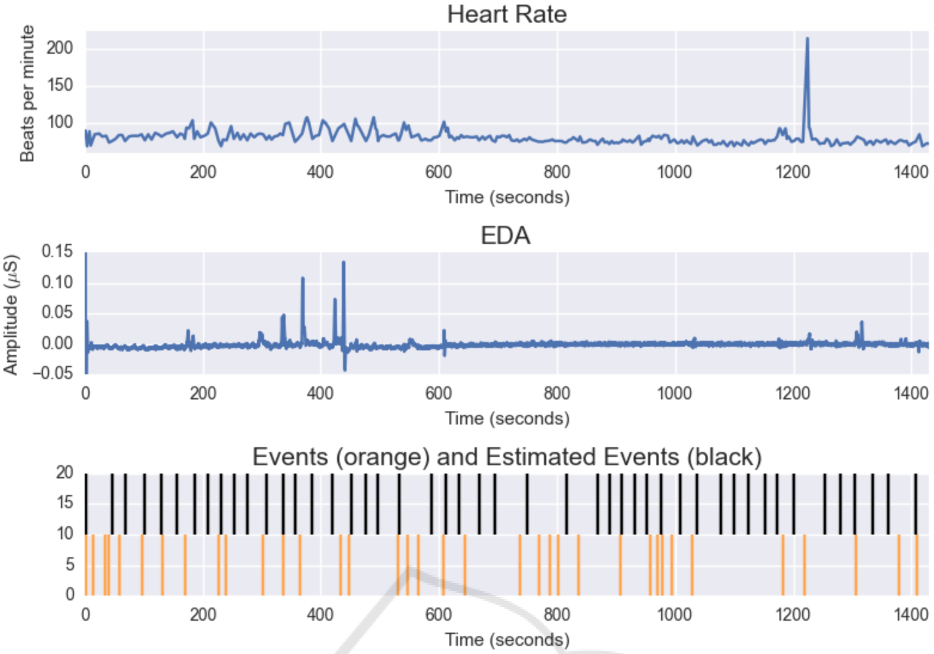

Figure 1: Mind wandering detection results.

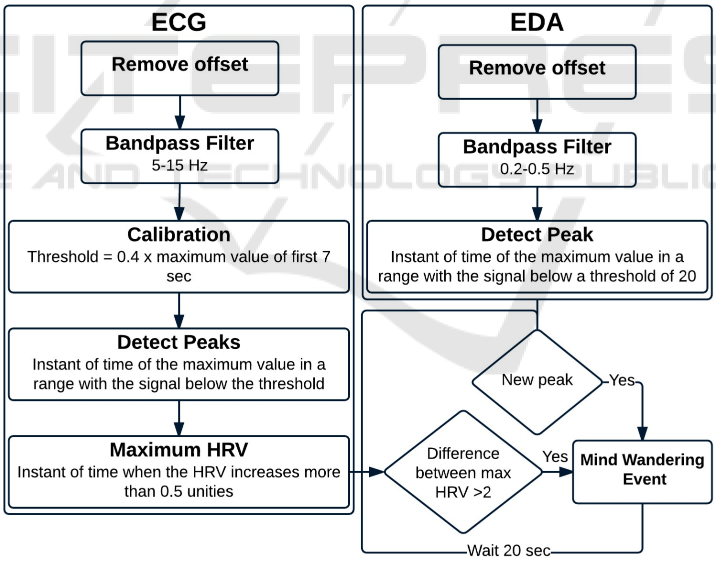

Figure 2: Real-time processing tools.