Available online at www.sciencedirect.com

SCIENCE DIRECT®

International Journal of Psychophysiology 55 (2005) 291–298

INTERNATIONAL JOURNAL OF PSYCHOPHYSIOLOGY

www.elsevier.com/locate/ijpsycho

Preliminary investigation of the effect of peppermint oil on an objective measure of daytime sleepiness

Mark Ian Keith Norrish*, Katie Louise Dwyer

Psychology, Coventry University, Priory Street, Coventry, CVI 5FB, United Kingdom

Received 8 June 2004; received in revised form 15 August 2004; accepted 31 August 2004
Available online 6 October 2004

Abstract

The assertion, often quoted in the popular literature, that peppermint has invigorating properties has been investigated through objective assessment of daytime sleepiness. Pupillary fatigue oscillations have been used to give an index of pupillary unrest that can be used as a reliable measure of daytime sleepiness. When compared with a no-odour condition, the presence of peppermint oil limited the increase in sleepiness during 11 min spent in a darkened room. This significant difference in sleepiness between the peppermint oil and the no-odour conditions was shown not to be related to differences in subjective ratings of initial sleepiness, from the Stanford Sleepiness Scale (SSS). Neither was it related to differences in initial pupillary unrest or mean pupil size. It seems that in conditions that favour an increase in daytime sleepiness, peppermint oil can indeed reduce sleepiness. However, the mechanisms by which peppermint oil has its effect and the applicability of these findings to situations in everyday life will require further empirical investigation.

Keywords: Sleepiness; Peppermint; Essential oil; Pupillary; *Mentha x piperita*

1. Introduction

There seems to be, within popular literature at least, some consensus as to the benefits and effects of various essential oils. In particular, peppermint oil is thought to be both stimulating (Hopkins, 1991) and invigorating (Devereux, 1993). More recently, peppermint has been shown to be an aid to athletic performance (Raudenbush et al., 2001). Others make even more specific claims as to its effectiveness in reducing sleepiness. These include the inhalation of peppermint oil to revive and stimulate junior doctors while on a night shift (Buckle, 1997) or to counteract after lunch sleepiness in the workplace (unsourced quote appearing on multiple websites). These commonly held assertions about the invigorating effects of peppermint have been confirmed, at a subjective level, by a sensory profiling assessment of 16 essential oils in a variety of experimental settings (Sugawara et al., 1999).

In contrast to these widely held beliefs about the effects of peppermint oil, there are comparatively few

* Corresponding author. Tel.: +44 24 76888209; fax: +44 24 76888300.
E-mail address: m.norrish@coventry.ac.uk (M.I.K. Norrish).

0167-8760/$ - see front matter © 2004 Elsevier B.V. All rights reserved.
doi:10.1016/j.ijpsycho.2004.08.004

empirical studies into these 'invigorating' effects. Several studies have looked at the effects of essential oils on aspects of attention and task performance. Using a visual attention task, Warm et al. (1991) showed that the presence of peppermint significantly increased detection of critical signals but had no effect on the subjective experience of workload or stress. This was further supported by EEG studies showing that presentation of peppermint oil could lead to and increased ability to sustain attention (Parasuraman et al., 1992). However, using a visual vigilance task, Gould and Martin (2001) found that there was a significant effect of bergamot (a relaxing odour) on task performance, with participants detecting fewer targets, but there was no effect of peppermint.

There is greater support for the effect of peppermint oil on sleep itself. By recording EEG sleep stages, Badia et al. (1989) found a circadian 'time of night' effect where participants were less responsive, when administered peppermint oil during stage 2 or towards the middle or end of the night. They suggest that peppermint oil may have an arousing effect but seems not to be pervasive enough to interrupt lower levels of sleep. In subsequent experiments, participants who were exposed to peppermint oil spent a significantly greater percentage of time in stage 1 sleep and experienced more spontaneous awakenings as compared to the air control group (Badia et al., 1990a,b).

There is little doubt that in addition to any direct physiological effect of an essential oil, there are also other factors that may influence both task performance and one's level of alertness. One example of this is the mismatch between the patterns of EEG activity and the perceptual similarities of various essential oils (Lorig and Schwartz, 1988). Furthermore, it has been demonstrated that the perceptual quality of an odour (hedonics) can have an affective reaction on a person's mood (Knasko, 1992). There are many other indirect factors that may influence odour perception in the individual, such as culture, expectations and belief in the qualities of the odour (Broughan, 1998). A useful categorisation of the mechanisms by which odours have their influence has been provided by Jellinek (1997). He identifies four mechanisms: (i) quasi-pharmacological influences on the central nervous system, (ii) semantic influences that are dependent on the individual's experience with that odour, (iii) the influence of the odour's hedonic valence (pleasantness) and (iv) an expectation effect (often referred to as placebo).

This latter expectancy effect was elegantly demonstrated by Ilmberger et al. (2001), where they found that in a control condition with water, if participants rated the water as being more stimulating (than the previous water condition) then their reaction times and motor movements were faster. This expectation effect is thought to play a particularly critical role in mediating attentional processes when low odour concentrations are used (Torii et al., 1998).

In many of the studies mentioned above, the measures are either of an attentional performance task or a direct measure of the effect on stages of sleep. In this study, we investigate the 'invigorating' effects of peppermint oil more directly by using an objective measure of daytime sleepiness. However, most of the commonly used objective measures of sleepiness involve sleep latency and are therefore not appropriate for a study involving an acute presentation of an odour. A pupillary measure of daytime sleepiness was therefore chosen. In sleepy participants, in darkness, there are spontaneous low-frequency pupillary oscillations with increasing amplitude, whereas in alert participants, the pupil is relatively stable with small amplitude oscillations (<0.3 mm) at approximately 1 Hz. Pupillary fatigue oscillations have been shown to be both effective and reliable measures of daytime sleepiness in a variety of experimental conditions (Lowenstein et al., 1963; Yoss et al., 1970), and they correlate well with the most commonly used objective measure of sleepiness: the Multiple Sleep Latency Test (Danker-Hopfe et al., 2001; McLaren et al., 2002). Pupillary fatigue oscillations have been used as a significant indicator of daytime sleepiness for both sleep-related disorders (Wilhelm et al., 1998a) and for sleep-deprived normals (Wilhelm et al., 1998b).

The size of the pupil is determined by the antagonistic pairing of the dilator and sphincter muscles. These muscles are double reciprocally innervated by the sympathetic and parasympathetic nervous systems. The steady-state size of the pupil in darkness is largely dependent on sympathetic activity and paired central parasympathetic inhibition. As alertness decreases, there are reduced levels of central sympathetic activity. It is this reduction in the sympathetic activation of the Edinger–Westphal

nuclei, as well as a reduction in the paired parasympathetic inhibition of the Edinger–Westphal nuclei, that are thought be the primary contributors to the pupillary fatigue oscillations (Wilhelm et al., 2001).

Measurements of sleepiness from these oscillations are therefore used here to ascertain whether some of the claims made about peppermint oil deserve their popular consensus.

2. Methods

Most normal healthy participants become increasingly sleepy during an 11-min recording of daytime sleepiness. The primary interest of this study was to ascertain whether peppermint oil limits this increase in sleepiness during the recording. The study therefore incorporated a mixed factorial design with presence or absence of peppermint oil as a between-groups factor and time during the recording as a within-group covariate. A passive control condition was used. Daytime sleepiness was assessed by measuring and analysing pupillary fatigue oscillations. Average pupil size and initial subjective sleepiness were used as additional covariates.

2.1. Participants

Twenty participants, all undergraduate students from Coventry University, were recruited. These participants were randomly assigned to control and experimental conditions. The mean ages of these groups were 24 and 21.4 years, respectively. In the control condition, there were five males and five females, in the experimental condition there were four males and six females.

2.2. Materials

A bench-mounted monocular infrared video pupillometer and eye tracker (PM_SCAN system; Barbur et al., 1988) was used to record the pupillary responses. The size of the pupil is calculated with a resolution of 0.01 mm and is output at a rate of 50 Hz. The pupillary fatigue oscillations of the right eye were recorded, while the participant viewed a static fixation target, subtending 2°, presented on computer monitor. Blackout blinds and a sheet were used to ensure that the room was in relative darkness (<1 cd/m^2). The participant was seated comfortably in an adjustable chair, and their head was kept in position with standard chin and forehead rest. An aroma pad was positioned 3 cm from the participant's left nostril. A fixed concentration of undiluted peppermint oil, *Mentha x piperita*, was administered to the aroma pad just before each participant entered the room. The concentration of the essential oil was determined in a preliminary thresholding experiment involving 10 participants from the same student population as the participants used in the main experiment. They each carried out threshold judgments on five concentrations of peppermint oil from the same 'batch' of the product. The condition that corresponded to a concentration just above threshold, for 8 of the 10 participants, was used in the main experiment. The chosen concentration was subthreshold for one of the remaining participants and significantly greater that threshold for the other remaining participant. Thresholds were not determined for the 20 participants in the main study.

It has been noted that sleepiness and the factors affecting sleepiness are not unitary. In order to control for the situational factors that may modify the basal levels that determine sleepiness, Cluydts et al. (2002) suggests that multiple measures are used to assess sleepiness. Indeed, a previous study on the effects of peppermint oil on alertness suggested that the Stanford Sleepiness Scale (SSS) should be used to control for participants' initial subjective level of sleepiness (Ilmberger et al., 2001). Each participant was therefore required to complete the Stanford Sleepiness Scale (SSS) to indicate his or her level of sleepiness at the beginning of the experiment. The SSS is a single-item test scale that provides a reliable indication of a participant's feeling of sleepiness (Hoddes et al., 1973) and has been significantly correlated with vigilance, reaction time and the Multiple Sleep Latency Test (Glenville and Broughton, 1979; Johnson et al., 1988).

2.3. Procedure

On recruitment, participants were screened to ensure that they did not have a cold or nasal allergy. In order to limit the effects of extraneous variables

upon the oil's performance, participants were asked not to smoke, drink coffee or wear strong perfume/aftershave in the hour prior to their participation. All participants were tested separately between the hours of 1 p.m. and 4 p.m.

The experimental room was fully ventilated for at least 2 days between testing participants in the peppermint and no-odour conditions. The room was also briefly ventilated between participants in the peppermint group.

After the SSS had been completed, the aroma pad (with or without the peppermint oil) was brought into the room and fixed in position. Following a brief adaptation to darkness and to the experimental surroundings, the 11-min recording was initiated. The experimenter observed the pupillometer throughout the recording to make sure that the participant did not close their eyes, fall asleep or move out of the camera's focus.

2.4. Preliminary data management

Prior to further analysis, the data were filtered using an artefact rejection algorithm. This involved automated blink interpolation and the filtering out of high-frequency noise (greater than 12.5 Hz) within the data. The blink interpolation is based on the differential of the pupil size—if the rate of change of the pupil exceeds the maximum constriction velocity of the normal pupil, 7 mm/s (Ellis, 1981), then the portion of the trace affected is considered a blink. Data are interpolated across any such portion of the trace. Daytime sleepiness is then evaluated using the standard procedures for calculating the Pupillary Unrest Index (Lüdtke et al., 1998; Wilhelm et al., 1999). The magnitudes of the difference between consecutive complete means of 32 data points (at 50 Hz) are summed and normalised to 1 minute (from the 59.52 s arising from incomplete sets of 32 points) for each minute of the recording. This corresponds to a measurement of pupillary instability (in mm/min) with a sampling frequency of 1.5625 Hz.

3. Results

The recordings from two of the participants, one from each condition, were not included in further analyses, as it became apparent that their pupillary activity had been masked by interference either from noisy estimation of the pupil margin or from prolonged partial eye closures.

A graphical time series representation of the Pupillary Unrest Index (PUI) during the 11-min recording is shown in Fig. 1. For the purposes of further analysis, the first minute was used as an indicator of initial sleepiness and an average of minutes 4 to 11 was used as a general indicator of

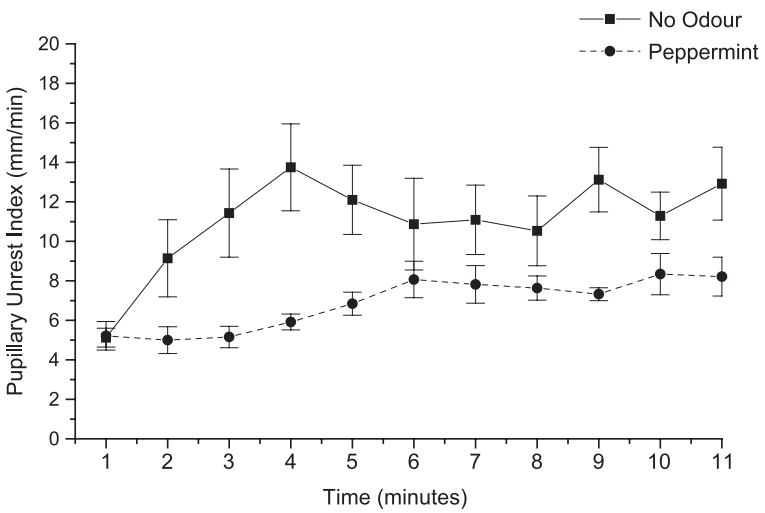

Fig. 1. Time series data for the peppermint and no-odour conditions throughout the 11-min recording of PUI. Each data point represents the mean of nine participants (±S.E.).

sleepiness in that condition. The 4 to 11 minute average was determined a priori on the bases of previous pilot and published studies. In published descriptions of pupillary fatigue oscillations, the maximum magnitude of pupillary unrest in normal sleepy participants is reached in approximately 4 min, and this magnitude is typically maintained for the rest of the recording. (Lüdtke et al., 1998, Wilhelm et al., 1999, 2001).

Scores of initial subjective sleepiness, from the Stanford Sleepiness Scale, ranged from 1 to 4, with mean scores for the peppermint and no-odour conditions being 2.4 (0.8) and 2.7 (0.7), respectively. These are between the ratings for 2 ("*functioning at high levels, but not at peak; able to concentrate*") and 3 ("*Awake, but relaxed; responsive but not fully alert*") on the SSS. This suggests that prior to the recordings of pupillary behaviour, both groups were fairly alert but relaxed. There is no significant difference in the ratings of initial subjective sleepiness between these two experimental groups, t=0.59 (df=16) p=0.56.

In order to control for the moderating effects of pupil size per se, the mean pupil sizes were also considered. The mean initial pupil sizes were 6.67 (0.86) for the control group and 6.42 (0.94) for the peppermint group. The mean pupil size during minutes 4 to 11 was 5.72 (1.35) for the control group and 6.25 (0.80) for the peppermint group. There were no significant difference in pupil size between the groups for either initial pupil size, t=0.60 (df=16) p=0.56, or average pupil size, t=1.01 (df=16) p=0.33.

The effects of time and of the experimental condition can be seen in Fig. 2. During the first minute of the recording (initial PUI), the mean pupillary unrest indices for the peppermint and control groups were 5.22 (2.44) and 5.12 (1.60), respectively. However, the expected increase in sleepiness during the 11-min recording was less in the peppermint condition than in the control condition, with mean indices of 7.68 (1.44) and 11.80 (4.45), respectively.

An ANCOVA was conducted in which the main effect was that of experimental group on the average PUI. Initial PUI, average pupil size and initial subjective sleepiness were included as covariates. There was a significant main effect of group, $F(1,13)=8.77$, $p=0.011$, $\eta_p^2=0.403$. None of the covariates had a significant main effect: initial PUI—$F(1,13)=2.70$, $p=0.12$, $\eta_p^2=0.172$; average pupil size—$F(1,13)=2.60$, $p=0.13$, $\eta_p^2=0.167$; SSS—$F(1,13)=0.39$, $p=0.54$, $\eta_p^2=0.029$.

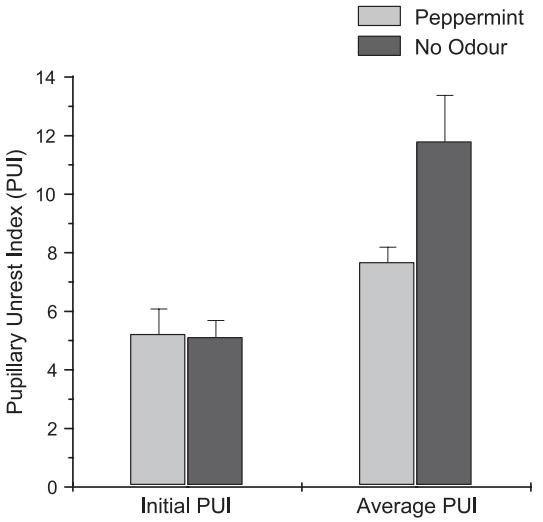

Fig. 2. The initial and average PUIs are shown for the peppermint oil and 'no-odour' conditions.

For the whole participant group, there were no significant correlations between participants' subjective ratings of initial sleepiness (SSS) and their initial PUI, r=0.05 (n=18) p=0.83. Neither was there a correlation between SSS and average PUI, r=0.04 (n=18) p=0.86.

4. Discussion

We have found support for the widely held belief concerning the invigorating effects of peppermint oil. Or more specifically, we have shown that the presence of peppermint oil can have an antisoporific effect in conditions favouring an increase in sleepiness. The expected increase in sleepiness during the 11-min recording was found in both the peppermint and control groups, however this increase was significantly diminished in the peppermint condition. This effect is unlikely to be a result of individual differences in initial sleepiness because there was no significant difference between the ratings of initial subjective sleepiness (SSS) in the two groups. Although it has been suggested that odours will be more effective in subjects who feel inattentive (Nelson et al., 1992), we did not find any relation-

ship between participants' subjective ratings of initial sleepiness (SSS) and either their initial or average PUIs.

It is well-known that the motility of the pupil depends on the size of the pupil. Thus, a smaller pupil will have a reduced PUI irrespective of the underlying sleepiness. The smaller average PUI in the peppermint group compared to the control group is unlikely to have arisen through this type of pupil size effect because there are no significant group differences in mean pupil size, and if anything, the mean pupil size is larger in the peppermint condition. In a similar vein, we do not think that the findings here can have resulted from a generalised orienting response to the presentation of an olfactory stimulus. The mechanism for any such effect on the PUI would be through the pupil size effect considered above. Furthermore, the timeline of the current experiment argues against an orienting explanation because there are no differences in PUI at the presentation of the stimulus (initial PUI), but rather the effect of the odour is several minutes after stimulus onset.

There are often very large variations in the efficacy of particular odours between participants, as has been demonstrated for the effect of peppermint on changes in skin temperature (Satoh and Sugawara, 2003). In this study, however, we found that the condition with the least variance between participants was in the average condition for peppermint. This suggests that the antisoporific effects of peppermint, as assessed by an objective measure of sleepiness, are not subject to the same between-participant variability that has been found for other oils and with other experimental measures. It should be noted that the small sample size makes this assertion difficult to generalise to a wider population.

We started by commenting on the widely held assertion that peppermint oil has invigorating properties. Because, as already noted above, the expectation associated with an odour can have its own effect on performance measures (Ilmberger et al., 2001), it is possible that the 'invigorating' effect of peppermint oil is a result of expectancy rather that any properties of the oil itself. Widespread awareness of these supposed properties makes this possibility all the more likely. Furthermore, the marginally suprathreshold concentrations used here are similar to the low-odour concentrations that have previously been shown to produce optimal expectancy effects (Torii et al., 1998). Expectation, caused by belief in the invigorating properties of peppermint oil, may therefore have been a contributory factor in the significant antisoporific effect reported here. In any future study, this could be further investigated by using a concentration threshold criterion of 50%, rather than the 80% used here. This would then allow for a second between-participants factor relating to expectancy, because approximately half of the experimental group would not be aware of the odour.

There are additional methodological factors that would also need to be considered in order to more fully support the role of peppermint oil in reducing daytime sleepiness. As a preliminary investigation in a novel area, this study incorporated a passive control. It would now be desirable to rule out other factors unrelated to the peppermint through the use of an active control condition, such as whether the arousal effect was caused by the presence of an odour per se. Through careful selection of the active control, it may also be possible to further investigate the expectation effect by choosing a control odour with supposed soporific effects or one without a related expectation. It would also be advantageous to use a repeated measures design in any such replication in order to control for the individual variability that is common in both olfactory perception and in response to sleepiness inducing situations.

It is not uncommon to find a dissociation between subjective and objective measures of daytime sleepiness. Indeed, this was one reason for the inclusion of both a subjective and an objective measure of initial sleepiness as covariates in the analyses. However, in order to ascertain whether the peppermint is indeed subjectively invigorating, it may be worth including a postrecording SSS in any future studies.

Although the presence of peppermint oil diminishes the increase in daytime sleepiness that is associated with sitting in dark room, it is not clear from this study that peppermint oil has truly antisoporific properties or the capability to delay the onset of sleep. Therefore, although the beliefs about the 'invigorating' effects of peppermint oil can be supported, further empirical investigation is required for some of the more specific claims relating to its ability to keep people awake, for example during a night shift.

It seems that several of the oft quoted assertions about the ability of peppermint oil to ward off sleepiness now have some evidential support. However, further investigation is needed in order to confirm that the effect is indeed attributable to the peppermint oil and in order to identify the candidate mechanisms (Jellinek, 1997) through which peppermint has its antisoporific effect.

References

Badia, P., Wesenten, N., Lammers, W., Hughes, R., Boecker, M., 1989. Olfactory sensitivity in sleep. Sleep Research 18, 151.

Badia, P., Boecker, M., Lammers, W., 1990a. Some effects of different olfactory stimuli on sleep. Sleep Research 19, 195.

Badia, P., Wesenten, N., Lammers, W., Culpepper, J., Harsh, J., 1990b. Responsiveness to olfactory presented in sleep. Physiology and Behavior 48, 87–90.

Barbur, J.L., Thomson, W.D., Forsyth, P.M., 1988. A new system for the simultaneous measurement of pupil size and two-dimensional eye movements. Clinical Vision Sciences 2, 131–142.

Broughan, C., 1998. Fragrant mechanisms: the impact of odours—direct and indirect effects. International Journal of Aromatherapy 9, 166–169.

Buckle, J., 1997. Clinical Aromatherapy in Nursing. Arnold, London.

Cluydts, R., De Valck, E., Verstraeten, E., Theys, P., 2002. Daytime sleepiness and its evaluation. Sleep Medicine Reviews 6, 83–96.

Danker-Hopfe, H., Kraemer, S., Dorn, H., Schmidt, A., Ehlert, I., Herrmann, W.M., 2001. Time-of-day variations in different measures of sleepiness (MLST, pupillography, and SSS) and their interrelations. Psychophysiology 38, 828–835.

Devereux, C., 1993. The Aromatherapy Kit: Essential Oils and How To Use Them. Headline Books, London.

Ellis, C.J.K., 1981. The pupil light reflex in normal subjects. British Journal of Ophthalmology 65, 754–759.

Glenville, M., Broughton, R.J., 1979. Reliability of the Stanford Sleepiness Scale compared to short duration performance tests and the Wilkinson auditory vigilance task. In: Passouant, P., Oswald, I. (Eds.), Pharmacology of the States of Alertness. Pergamon, Oxford, pp. 235–244.

Gould, A., Martin, G.N., 2001. 'A good odour to breath?' The effect of pleasant ambient odour on human vigilance. Applied Cognitive Psychology 15, 225–232.

Hoddes, E., Zarcone, V., Smythe, H., Phillips, R., Dement, W.C., 1973. Quantification of sleepiness: a new approach. Psychophysiology 10, 431–436.

Hopkins, C., 1991. Aromatherapy: Remedies for Everyday Ailments. Parallel Books, London.

Ilmberger, J., Heuberger, E., Mahrhofer, C., Dessovic, H., Kowarik, D., Buchbauer, G., 2001. The influence of essential oils on human attention: I. Alertness. Chemical Senses 26, 239–245.

Jellinek, J.S., 1997. Psychodynamic odour effects and their mechanisms. Cosmetics and Toiletries 112, 61–71.

Johnson, L.C., Freeman, C.R., Spinwebber, C.L., Gomez, S.A., 1988. The relationship between subjective and objective measures of sleepiness (Report No. 88–50). Naval Health Research Center, San Diego.

Knasko, S.C., 1992. Ambient odour's effect on creativity, mood and perceived health. Chemical Senses 17, 27–35.

Lorig, T.S., Schwartz, G.E., 1988. Brain and odour: 1. Alteration of human EEG by odour administration. Psychobiology 16, 281–284.

Lowenstein, O., Feinberg, R., Loewenfeld, I.E., 1963. Pupillary movements during acute and chronic fatigue: a new test for objective evaluation of tiredness. Investigative Ophthalmology 2, 138–157.

Lüdtke, H., Wilhelm, B., Adler, M., Schaeffel, F., Wilhelm, H., 1998. Mathematical procedures in data recording and processing of pupillary fatigue waves. Vision Research 38, 2889–2896.

McLaren, J.W., Hauri, P.J., Lin, S.-C., Harris, C.D., 2002. Pupillometry in clinically sleepy patients. Sleep Medicine 3, 347–352.

Nelson, W.T., Grubb, P.L., Warm, J.S., Dember, W.N., Mayleben, D.W., Parasuraman, R., 1992. The effects of fragrance administration and attentiveness of vigilance performance. Paper presented at the Annual Meeting of the Southern Society for Philosophy and Psychology, Memphis, TN.

Parasuraman, R., Warm, J.S., Dember, W.N., 1992. Effects of olfactory stimulation on skin conductance and event related potentials during visual sustained attention. Progress Report No. 6, The Fragrance Research Fund.

Raudenbush, B., Corley, N., Eppich, W., 2001. Enhancing athletic performance through the administration of peppermint odor. Journal of Sport and Exercise Psychology 23, 156–160.

Satoh, T., Sugawara, Y., 2003. Effects on humans elicited by inhaling the fragrance of essential oils: sensory test, multichannel thermometric study of forehead surface potential wave measurement on basil and peppermint. Analytical Sciences 19, 139–146.

Sugawara, Y., Hino, Y., Kawasaki, M., Hara, C., Tamura, K., Sugimoto, N., Yamanishi, Y., Miyauchi, M., Masujima, T., Aoki, T., 1999. Alteration of perceived fragrance of essential oils in relation to type of work: a simple screening test for efficacy of aroma. Chemical Senses 24, 415–421.

Torii, S., Fukada, H., Kanemoto, H., Miyanchi, R., Hamauzu, Y., Kawasaki, M., 1998. Contingent negative variation (CNV) and the psychological effect of odour. In: Van Toller, S., Dodd, G.H. (Eds.), Perfumery: The Psychology and Biology of Fragrance. Chapman and Hall, London.

Warm, J.S., Dember, W.N., Parasuraman, R., 1991. Effects of olfactory stimulation on performance and stress in a visual sustained attention task. Journal of the Society of Cosmetic Chemists 42, 199–210.

Wilhelm, H., Lüdtke, H., Wilhelm, B., 1998a. Pupillographic sleepiness treating in hypersomniacs and normals. Graefes Archive for Clinical and Experimental Ophthalmology 93, 446–450.

Wilhelm, B., Wilhelm, H., Lüdtke, H., Streicher, P., Adler, M., 1998b. Pupillographic assessment of sleepiness in sleep-deprived health subjects. Sleep 21, 258–265.

Wilhelm, B., Lüdtke, H., Wilhelm, H., 1999. Spontaneous pupillary oscillations: an objective measure for the level of tonic central nervous system. In: Kuhlmann, J., Bottcher, M. (Eds.), Pupillography: Principles, Methods and Applications. W. Zuckschwerdt Verlag, New York.

Wilhelm, B., Giedke, L., Lüdtke, H., Bittner, E., Hofmann, A., Wilhelm, H., 2001. Daytime variations in central nervous system activation measured by a pupillographic sleepiness test. Journal of Sleep Research 10, 1–7.

Yoss, R.E., Norma, J., Moyer, R.N., Hollenhurst, M.D., 1970. Pupil size and spontaneous pupillary waves associated with alertness, drowsiness and sleep. Neurology 20, 545–554.