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In-vehicle fragrance administration as a countermeasure for driver fatigue

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ABSTRACT

Driver fatigue is a contributing factor in about 10–30% of all fatal crashes. Prevention of fatigue-related crashes relies on robust detection of driver fatigue and application of effective countermeasures. A potential counter-measure is fragrance administration since odors can have alerting effects on humans. The aim here was to investigate if a fragrance incorporating trigeminal components could be used as an in-vehicle countermeasure for driver fatigue.

The fragrance was tested in a driving simulator with 21 healthy but sleep-deprived participants. Each participant performed a monotonous driving task twice, once with active fragrance containing a trigeminal component and once with olfactory fragrance, in a cross-over single-blind design. The order of trigeminal/ol-factory fragrance was randomized and blinded to the participants. Both fragrances (trigeminal/olfactory) were administered either when the participant fell asleep (defined as eye closure > 3 s) or after approximately 45 min if the participant did not fall asleep.

Self-reported sleepiness was assessed using the Karolinska Sleepiness Scale (KSS) every 5 min during driving. Variability in speed and lateral position and line crossing frequency were logged for each drive to measure driving performance. Heart rate measurements (ECG) and eye blinks (EOG) were collected to investigate potential arousing effects of the fragrance and to track objective signs of sleepiness.

Mean blink duration, which was used as an objective measure of sleepiness, decreased significantly, after fragrance exposure, as did the frequency of line crossings, but there were no statistically significant differences between the fragrance with trigeminal stimulus and the pure olfactory fragrance.

The results are in line with the effects found for other commonly used fatigue countermeasures, like playing loud music. These countermeasures can restore alertness and driving performance for a short while. Whether this is sufficient to support driving performance until the driver can make a safe stop in real traffic remains a topic for future studies.

1. Introduction

Driver fatigue is a contributing factor in about 10–30 % of all fatal crashes (Philip and Åkerstedt, 2006, Hallvig et al., 2014, Zwahlen et al., 2016). Most drivers feel sleepy behind the wheel from time to time, but often continue to drive nonetheless (Armstrong et al., 2010, Zwahlen et al., 2016). This behavior can eventually lead to traffic crashes and may result in severe injuries and fatalities (Connor et al., 2002). Prevention of fatigue related crashes is thus a major goal for the automotive industry. To reach this goal, both robust detection and effective

countermeasures are required.

Driver fatigue can arise for several reasons. The most obvious one is sleepiness, which is defined as a physiological drive to fall asleep (Dement and Carskadon, 1982). Sleepiness is affected by sleep depri-vation, extended duration of wakefulness and time of day. Traffic safety wise, subjective sleepiness ratings are highly linked to the likelihood of lane departures in simulators and to line crossings on real roads (Åkerstedt et al., 2014). Another possible contributing factor is task-related fatigue induced by the driving task itself. Fatigue is different from sleepiness in the sense that it is defined as a suboptimal

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psychophysiological condition caused by exertion (Phillips, 2015). Certain characteristics of driving, like task demand and driving environment, can produce task related fatigue in the absence of any sleep-related cause. Task-related fatigue can come from either overload or underload (May and Baldwin, 2009, Phillips, 2015). Overt signs of different types of fatigue may overlap, but the countermeasures are different (May and Baldwin, 2009). If the driver is fatigued due to overload, an appropriate countermeasure would be to stop driving and thus temporarily shut off demands of sustained attention. If fatigue is due to underload, then activation helps more than rest (Oron-Gilad et al., 2008, Gershon et al., 2009, Rayes et al., 2019). When the cause of fatigue is sleepiness, however, the most effective countermeasure is to sleep. One of the most effective ways to alleviate sleepiness is by taking a 15–20 min nap, which has been shown to reduce physiological and subjective sleepiness, and improve driving performance (Horne and Reyner, 1996, Watling et al., 2014). Studies also show an increased alertness and improved performance after caffeine intake (Horne and Reyner, 1996, De Valck and Cluydts, 2001, Reyner and Horne, 2002). A systematic review and *meta*-analysis concluded that caffeine has a positive effect on vehicle control (both lateral and longitudinal parameters of car driving tasks) in sleep restricted/deprived individuals (Irwin et al., 2020). Popular strategies such as opening a window and turning on the radio are relatively ineffective at reducing sleepiness for extended time periods (Reyner and Home, 1998, Schwarz et al., 2012). Despite this, the most common countermeasures used by drivers are to stop to take a walk, turn on the radio/stereo or open a window (Anund et al., 2008a).

The most effective countermeasures, such as taking a nap, are highly intrusive in the sense that you need to make an unplanned stop. Finding less intrusive, yet effective, countermeasures that could be deployed without requiring major replanning would thus provide a significant benefit to car makers who wish to use this type of technology in their vehicles. Other, less intrusive, measures like bright light, blue light and caffeine/energy can be helpful to some extent but do not provide a solution (Horne and Reyner, 1996, Reyner and Home, 1998, Reyner and Horne, 2002, Lowden et al., 2004, Bjorvatn et al., 2007, Schwarz et al., 2012, Taillard et al., 2012).

In the current study, the possibility of using odors to counter driver fatigue has been explored. Odors affect humans through at least two separate routes; the olfactory and the trigeminal (Shusterman and Hummel, 2009). Humans can to some extent use their sense of smell to read emotions and communicate socially (Semin and De Groot, 2013). We produce, transmit, and receive odor messages. Like other senses (visual, auditory, haptic), smell delivers information that triggers a psychological and physiological effect (McClintock et al., 2001, Lundström and Olsson, 2010, Yeshurun and Sobel, 2010, Savic, 2014). Chemosignal-based olfactory solutions that are non-intrusive have been developed and have shown promising effects on vigilance and alertness in laboratory studies (Endevelt-Shapira et al., 2018). The active scents can be subliminal (unconscious) fragrances developed from social chemosignals that act directly on the olfactory system in the brain without the participant's awareness (in other words, the fragrances have no perceivable smell). These can be augmented with trigeminal components that render the stimulus perceptible, and significantly increase its potency. The Trigeminal nerve (CN 5) controls facial muscles and reacts to odors. The effect of trigeminal odors resembles a tingling sensation and sometimes pain (Shusterman and Hummel, 2009). Most fragrances trigger both the olfactory and trigeminal systems simultaneously at some level (Brand, 2006). The two responding systems are independent but they have overlapping activation in the brain and can influence each other (Tremblay and Frasnelli, 2018). A few odorants affect only one system at a time, for example, vanillin exclusively affects the olfactory system and CO2 exclusively affects the trigeminal system (Brand, 2006, Heiser et al., 2012). Unlike most olfactory stimulation, trigeminal stimulation has the potential to wake people up from actual sleep (Heiser et al., 2015). Pure olfactory stimulus has, however, not been effective in waking sleeping persons (Heiser et al., 2012). In a study by

Stuck et al. (2007) participants were exposed to both olfactory and trigeminal stimulation of different concentrations during sleep. They found that participants can be woken up from both light sleep and slow wave sleep using trigeminal manipulations (Stuck et al., 2007). Similarly, a strong trigeminal odor has been incorporated into a fire-alarm for the deaf (Goto et al., 2015). So far, only a few studies have investigated the effects of odors on driver fatigue (Hirata, 2001, Raudenbush et al., 2009, Okazaki et al., 2018). There is some evidence that exposure to cinnamon and peppermint scent leads to increased ratings of alertness, decreased temporal demand, and decreased frustration in drivers (Hirata, 2001, Raudenbush et al., 2009). Several studies have shown that pulsed delivery of odors (e.g., peppermint) can help enhance operator performance (Ho and Spence, 2005, Mahachandra et al., 2015). The impact of olfactory and trigeminal fragrances on severely fatigued drivers, however, remains to be investigated. The aim of the current study was therefore to investigate if administration of a fragrance incorporating trigeminal components had an alerting effect on fatigued drivers.

2. Materials and methods

The fragrance was tested on healthy but sleep-deprived individuals while they performed a driving task in a simulator.

2.1. Participants

Twenty-one night shift workers, 12 male and 9 female, were recruited by advertisements on Facebook and at workplaces. They were 30–60 years old (mean 45, SD 10). A self-report screening procedure ensured that they were healthy and had a normal sense of smell. Specific exclusion criteria were BMI < 18 or > 30, being prone to motion sickness, pregnancy, sleep disorders, diabetes, cardiovascular disease, neurological disease and use of prescription medicine or over-the-counter sleeping medication.

The study was conducted in accordance with the declaration of Helsinki and informed consent was obtained by all participants. The study protocol was approved by the Swedish Ethical Review Authority (dnr 2020–04054). The participants received a compensation of 1000 SEK (about 100 EUR). Data collection was performed between 12 April and 14 May 2021 and infection control procedures were applied to minimize the spread of COVID-19.

2.2. Procedure

All drives were performed in the morning after working a night shift to ensure that participants were sleep deprived. The participants were instructed to abstain from alcohol intake three days before the test and caffeine the night before the test as well as to stay awake the entire night before the test. Each participant performed a monotonous driving task twice. In one drive, participants were exposed to the trigeminal fragrance, i.e., a fragrance that had a combination of olfactory and alerting trigeminal components (the main trigeminal ingredient was allyl isothiocyanate). The formula is Moodify's trade secret and ingredients can be disclosed upon request. In the other drive, participants were exposed to an olfactory fragrance without any trigeminal component (vanilla) in a cross-over single-blind design. The order of trigeminal/olfactory fragrance was randomized between participants, and they were not informed about the type of fragrance they received. Both fragrances (trigeminal/olfactory) were given either when the participant fell asleep (here defined as eye closure for more than 3 s) or after approximately 45 min of driving if the participant did not fall asleep.

The participants performed the driving task in a fixed-base driving simulator. A monotonous scenario was utilized to manipulate driver fatigue, including both sleepiness due to sleep deprivation and task-related fatigue due to underload. The driving scenario was an 80 km/h rural road with randomized traffic in the opposite direction but with

no traffic in the same direction as the participant was driving to avoid takeovers.

The fragrance was administered by the test leader when the participant fell asleep, here defined as eye closure for more than 3 s. The event of falling asleep was determined by an experimenter observing the participant. If the participant did not fall asleep, the fragrance was administered anyway after approximately 45 min of driving. Trigeminal and olfactory fragrance were administered by a nebulizer (Life Medical Care, CN-01 W). The tube from the nebulizer containing the fragrance (trigeminal or olfactory) was attached to the participants' chest using Velcro straps and the tube opening was directed towards the nose. At the time of fragrance administration, the experimenter pressed a button which triggered the nebulizer, and it ran for three seconds. The nebulizer was placed in a noise dampening box and the participants wore noise cancelling in-ear headphones to ensure that they could only hear the sound from the driving simulator. The participants were informed that the study included evaluations of different fragrances, but they did not know how many fragrances, at which time point they would be given, and what the expected effects of the fragrances were. After being exposed to the trigeminal/olfactory fragrance, the participants continued driving until they either fell asleep a second time, or for a maximum of an additional 20 min. The experimental procedure took approximately four hours per participant.

2.3. Data collection and processing

Self-reported sleepiness was assessed using the Karolinska Sleepiness Scale (KSS) every 5 min during the driving task. The KSS is a rating scale ranging from 1 (highly alert) to 9 (having to fight to stay awake) (Åkerstedt and Gillberg, 1990). The reported value is meant to correspond to the average feeling during the last 5 min. In the analyses, the last rating before fragrance administration was compared to the first rating after receiving the fragrance. After each drive, the participants answered a brief questionnaire about their experience during the drive. They were asked on 5-point Likert scales whether they perceived the fragrance as tiring/alerting on a scale ranging from 1 (tiring) to 5 (alerting) and pleasant/unpleasant on a scale ranging from 1 (pleasant) to 5 (unpleasant).

Speed variability, lateral position variability and line crossing frequency (the vehicle crossing the lane demarcation line) were logged for each drive to measure driving performance. Line crossings and standard deviation (SD) in lateral position and speed were included in the analyses.

Physiological measurements in the form of heart rate measurements (ECG), eye blinks (EOG) and brain activity (EEG) were collected to investigate potential arousing effects of the fragrance and to track objective signs of sleepiness. Electrophysiological data were recorded with eego sports (ANT Neuro, Hengelo, the Netherlands). Electrocardiogram (ECG, lead II), a vertical electrooculogram (EOG), respiration (chest strap) and a 64-channel electroencephalogram (EEG) were recorded. Results from ECG and EOG recordings are presented here. Physiological data were acquired with a sampling rate of 512 Hz but later downsampled to 256 Hz. The ECG was band-pass filtered between 0.3 and 30 Hz and the EOG was band-pass filtered between 0.3 and 11.5 Hz. All filtering was carried out with zero-phase 5th order Butterworth filters.

Heart beats (R-peaks) were extracted from the ECG using a filterbank approach (Afonso et al., 1999) and an RR time-series was derived as the time difference between heart beats. The corresponding normal to normal (NN) time series was obtained by a recursive procedure where RR intervals were removed if they differed from the mean of the surrounding RR intervals with more than 30 % (Karlsson et al., 2012). Heart rate was here expressed as mean beats per minute (bpm) in each segment and heart rate variability was quantified as the root mean square of successive differences (RMSSD) between normal heartbeats (Shaffer and Ginsberg, 2017).

The blink parameters were extracted from the vertical EOG signal with an automatic blink detection algorithm (Jammes et al., 2008). Two blink duration-based parameters were calculated; the mean blink duration and the number of eye blinks with a duration longer than 0.150 s (Fors et al., 2011).

A PC-based Psychomotor Vigilance Test (PVT) was used to capture attention and cognitive performance before and after the drives (Khitrov et al., 2014). The PVT was set up according to Loh et al. (2004), with random stimuli onsets with an inter stimulus interval of 2–10 s and a total test duration of 10 min. The PVT is a widely used test of vigilant attention with high reliability and predictive validity as well as a lack of aptitude and learning effects (Basner and Dinges, 2011). Increased sleepiness levels typically result in longer mean reaction times (RT) and higher percentages of lapses/misses (here defined as RTs > 500 ms). Responses with RTs < 100 ms were identified as false starts. PVT metrics were aggregated by trial, i.e., a baseline trial and then trials after each drive.

2.4. Statistical analysis

For analysis, simulator and physiological data were aggregated in one-minute segments around the point in time when the fragrance was administered (one segment before and five after). Minute −1 is the minute before fragrance administration and minute + 1 is the minute directly after receiving the fragrance.

Results are generally presented as means with standard deviations (SD). Subjective sleepiness was analyzed with a repeated measures ANOVA. Timepoint (before and after fragrance) was included as the repeated factor and fragrance (trigeminal or olfactory) as an independent factor. The first KSS rating of each drive was included as a covariate. The possible effects of fragrance exposure on physiology and driving performance were analyzed using univariate ANOVA. Separate regression models were created with each of the outcome measures as the dependent variable. Fragrance (trigeminal or olfactory) and time (one-minute intervals from −1 min to + 5 min) were included as within-subjects variables. Participant was included as a random factor. Note that the factor time was in relation to fragrance administration rather than time driven. If the time effect was significant, pairwise comparisons were made between time = -1 and time = +1 through + 5. Bonferroni correction was used to compensate for multiple comparisons in post hoc tests. To analyze if the effect of fragrance exposure differed depending on whether the participant fell asleep or not, ANOVAs with the additional factors sleep (fell asleep or not), fragrance*sleep and fragrance*time*sleep were also performed. PVT was analyzed using a repeated measures ANCOVA with fragrance (trigeminal vs olfactory) as the repeated factor and baseline PVT as a covariate. Questionnaire data was analyzed using chi-square tests and Wilcoxon signed rank test. The significance level was set to 0.05. Statistical analyses were performed in IBM SPSS statistics version 29 (IBM Corp., Armonk, NY, USA).

3. Results

In 17 of the 42 drives, the participant fell asleep. Mean driving time until falling asleep was 26 min (SD = 12). There was no statistically significant difference in the number of participants falling asleep between trials with trigeminal vs olfactory fragrance. Eleven participants received the trigeminal fragrance during the first drive and ten during the second drive. There were no statistically significant differences between men and women in the outcome measures.

Mean subjective sleepiness (KSS) was 6.9 (SD = 1.4) for the first five-minute segment of the drive with olfactory substance and 6.2 (SD = 1.4) for the first five-minute segment of the drive with trigeminal substance. The difference was significant according to a paired samples *t*-test (p = 0.028).

The mean KSS before fragrance administration was 7.9 (SD = 1.3) in the drive with olfactory substance and 7.7 (SD = 1.3) in the drive with

trigeminal substance (Fig. 1). The mean KSS after fragrance administration was 7.7 (SD = 1.4) after olfactory and 7.2 (SD = 1.4) after trigeminal fragrance. In the repeated measures ANOVA testing differences between the before and after KSS ratings, the time effect was significant, indicating that KSS decreased after administration of fragrance (F = 8.154, p = 0.007). In Fig. 1, a larger decrease in subjective sleepiness after administration of the trigeminal fragrance can be seen but the effect did not differ significantly between the trigeminal and olfactory fragrance (F = 0.5845, p = 0.449) and no significant interaction effect between timepoint and fragrance was found (F = 2.816, p = 0.101). KSS scores were lower at the beginning of the trials with trigeminal substance and after controlling for sleepiness at the start of the drive by including the first KSS rating as a covariate, the time effect was no longer significant (F = 3.006, p = 0.091). The main fragrance effect (0.068, p = 0.795) and time*fragrance interaction effect (F = 1.629, p = 0.210) were not significant.

Number of line crossings decreased after fragrance exposure (Fig. 2A). The time effect was significant in the ANOVA of line crossings (F = 5.1, p < 0.001, η^2 = 0.106). There were significantly fewer line crossings in every one-minute segment after fragrance administration (time = +1 to + 5) compared to the minute before receiving the fragrance (time = -1). There was no significant main effect of fragrance type and no interaction between time and fragrance was seen (Table 1). For the two other measures of driving performance, SD of lateral position and speed, there were no significant effects of time, fragrance or time*fragrance (Table 1, Fig. 2B and 2C).

The time effect was significant for mean blink durations (F = 2.8, p = 0.019, η^2 = 0.064) and Fig. 3A shows that blink durations decreased after fragrance exposure. Blink durations were significantly shorter in the first one-minute interval after fragrance administration compared to the minute before fragrance exposure (p = 0.010). There was no main effect of fragrance nor interaction effect between time and fragrance for mean blink duration (Table 1). The number of long blinks (>150 ms) was not affected by fragrance administration (Table 1, Fig. 3B).

Heart rate and heart rate variability (RMSSD) showed no significant time, fragrance, or time*fragrance effects (Table 1).

The ANOVAs including the effect of sleep (fell asleep or not) showed that participants that fell asleep had more line crossings, longer mean blink durations, more long blinks, lower heart rate, and higher RMSSD than participants that did not fall asleep (Table 2). The sleep*time effect

was not significant for any of the dependent variables (Table 2), indicating a similar development over time irrespective of whether they fell asleep or not. The fragrance*sleep and fragrance*time*sleep interaction effects were significant for SD speed (Table 2). None of the other dependent variables showed significant fragrance*sleep or fragrance*time*sleep interaction effects, indicating that the effect of fragrance exposure was similar in the two groups (Table 2).

Psychomotor vigilance performance tests after the drives showed a significant effect of fragrance administration on mean RT after controlling for baseline performance (F = 14.005, p = 0.001). The response times were shorter after the drive with trigeminal fragrance (mean RT 349 ms, SD 96) compared with olfactory fragrance (mean RT 359 ms, SD 131). The number of lapses (F = 0.241, p = 0.629) and false starts (F = 0.073, p = 0.790) were not significantly different between tests.

Wilcoxon signed ranks tests showed that the trigeminal substance was perceived as significantly more unpleasant (W = 119.5, p = 0.040) but the difference in perceived alerting effect was not statistically significant (W = 111.0, p = 0.098).

4. Discussion

Exposing drivers to fragrances when they were fatigued had some clear effects. Subjective sleepiness decreased, and the frequency of line crossings showed a significant improvement that lasted at least five minutes after fragrance exposure. Blink durations also decreased significantly after fragrance exposure and the mean blink durations were significantly lower than before exposure. However, the latter difference only lasted for the first minute after exposure, possibly indicating that the physiological signs of sleepiness (long blink duration) return faster to their previous state after fragrance exposure than behavioral signs of sleepiness (line crossings). In addition, the small difference between conditions in response times from the PVT indicated that the participants were more alert after completing the drive with trigeminal substance compared to the drive with olfactory substance. While the difference is statistically significant, it is unlikely to be relevant in the real world.

In terms of trigeminal versus olfactory fragrance, there were no statistically significant differences in the effects of the two fragrances on physiological and subjective measures of fatigue and driving performance. Important to note is that some measures were not affected at all
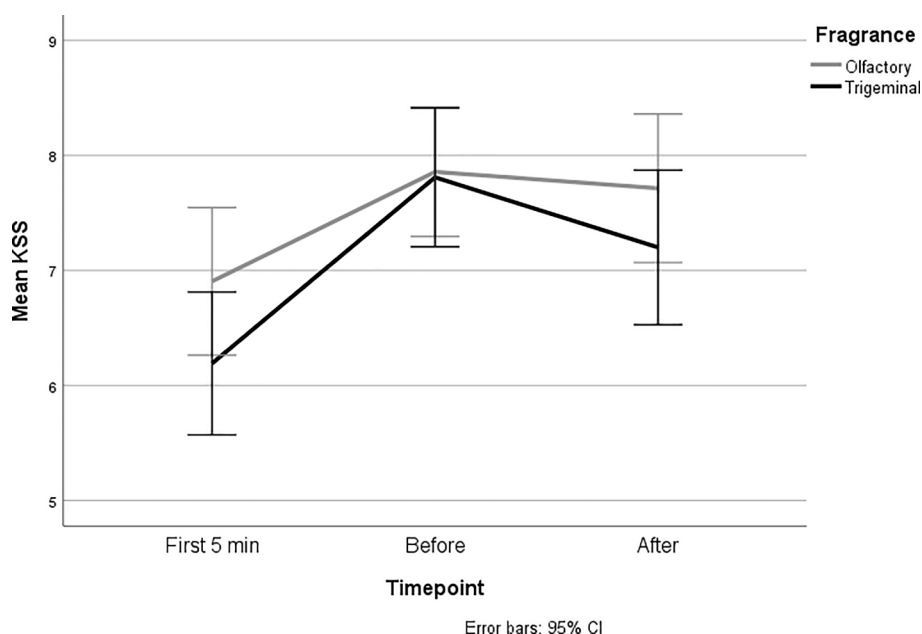

Fig. 1. Descriptive data (mean and CI) of subjective sleepiness (KSS) the first five minutes of the drive and before and after fragrance administration.
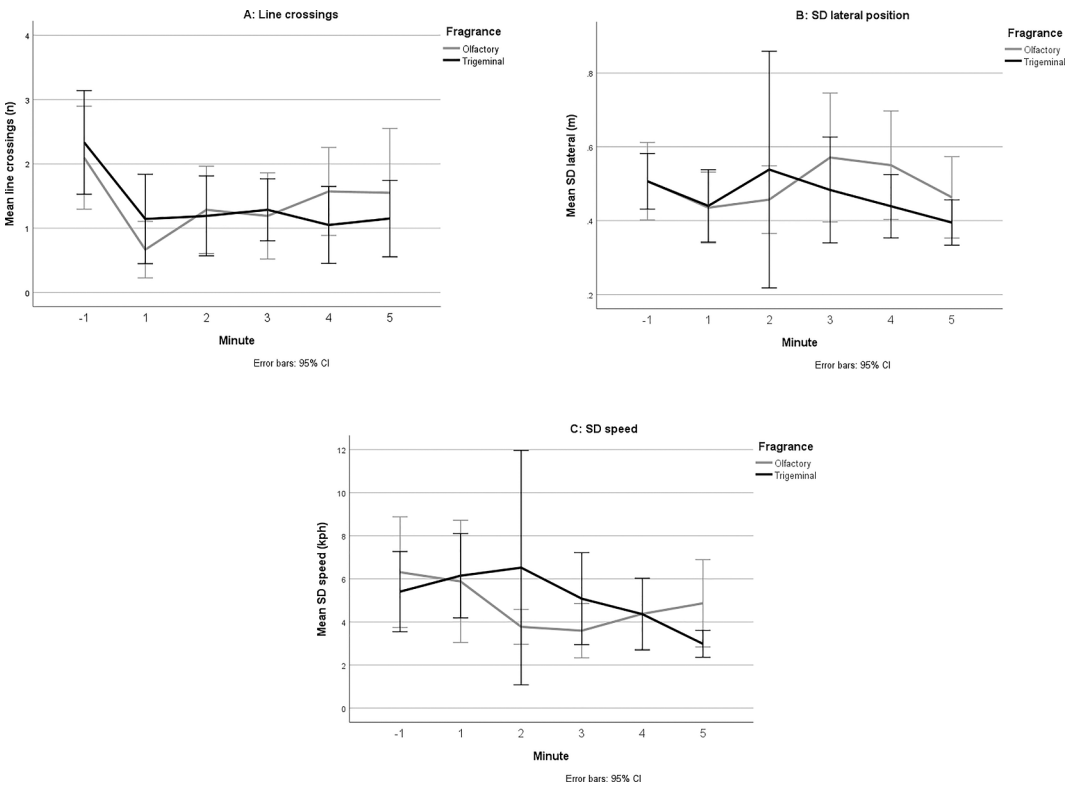
Fig. 2. Descriptive data (mean and CI) of driving performance measures one minute before and five minutes after fragrance administration.

Table 1
Results from the ANOVAs of driving performance and physiology, analyzing the effects of fragrance type and time.

|	Fragrance	p-value	Time	p-value	Fragrance*Time	p-value	Participant	p-value
Line crossings	0.035	0.852	5.146	<0.001	0.915	0.472	5.983	<0.001
SD lateral position	0.7774	0.380	0.877	0.497	0.737	0.597	5.097	<0.001
SD speed	0.277	0.599	1.432	0.214	1.395	0.227	5.317	<0.001
Blink duration	2.859	0.092	2.779	0.019	0.457	0.808	8.421	<0.001
Long blinks	0.931	0.336	0.707	0.619	0.701	0.623	6.902	<0.001
Heart rate	0.467	0.495	0.470	0.798	0.932	0.461	103.170	<0.001
RMSSD	2.150	0.144	1.051	0.389	0.947	0.452	25.992	<0.001

by fragrance administration. These included heart rate related measures, the number of long blinks, SD of lateral position and SD of speed. Participants that fell asleep showed significantly more objective signs of fatigue (longer blink durations, more long blinks, lower heart rate and higher RMSD) and worse driving performance (more line crossings) compared to the participants that were awake during fragrance exposure. However, the effect of fragrance exposure was not significantly different between participants who were asleep and those who were awake when analyzing the fragrance*sleep and fragrance*time*sleep effects for the measures that were affected by fragrance exposure.

There are no previous studies on pure trigeminal stimulation in drivers, but certain olfactory stimulation has been proven to have a positive effect on driver fatigue (Hirata, 2001, Funato et al., 2009, Raudenbush et al., 2009, Yoshida et al., 2011). Most of the stimuli used act on both olfactory and trigeminal nerves. An example is peppermint, which has been repeatedly shown to increase alertness (Stuck et al., 2007, Funato et al., 2009, Raudenbush et al., 2009, Yoshida et al., 2011, Tang et al., 2021a). In a simulator driving test, 30 s interval presentation of peppermint kept drivers alert for 16 min (Yoshida et al., 2011). In their study, alertness was determined through measurements of eye-blink frequency and SD of lateral displacement.

Previous studies have used fragrances to maintain alertness rather than to counteract fatigue (Hirata, 2001). In most cases, the participants

have not been sleep-deprived before the trial and they have reported much lower levels of subjective sleepiness than in the present study. The fragrance used here was specifically designed to wake people up after falling asleep, based on results from previous laboratory studies (Stuck et al., 2007, Heiser et al., 2015). To ensure high levels of sleepiness and a high proportion of drives where the participants fell asleep, all participants had been awake the entire night preceding the trials. The mean KSS ratings were > 6 the first five minutes of the drives, confirming that the participants had some signs of sleepiness at the start of the drives. All measures except RMSSD showed a significant deterioration from the start of the drive to the time of fragrance exposure (data not shown).

It is possible that the fragrance would have had different effects on subjective sleepiness, physiological measures, and driving performance in less fatigued drivers. However, trigeminal stimulus gives a tingling sensation that was perceived as unpleasant by some participants. Therefore, trigeminal stimulation might be more suitable for waking people up from actual sleep, whereas olfactory stimulus is more suitable for maintaining alertness. Waking drivers from actual sleep could be a relevant application in partly automated vehicles where the driver needs to be fit to take over control of the vehicle when it approaches the end of the operational design domain (ODD) for autonomous driving. Both these applications presuppose that one first can establish that the tingling sensation as such does not lead to an overly negative user
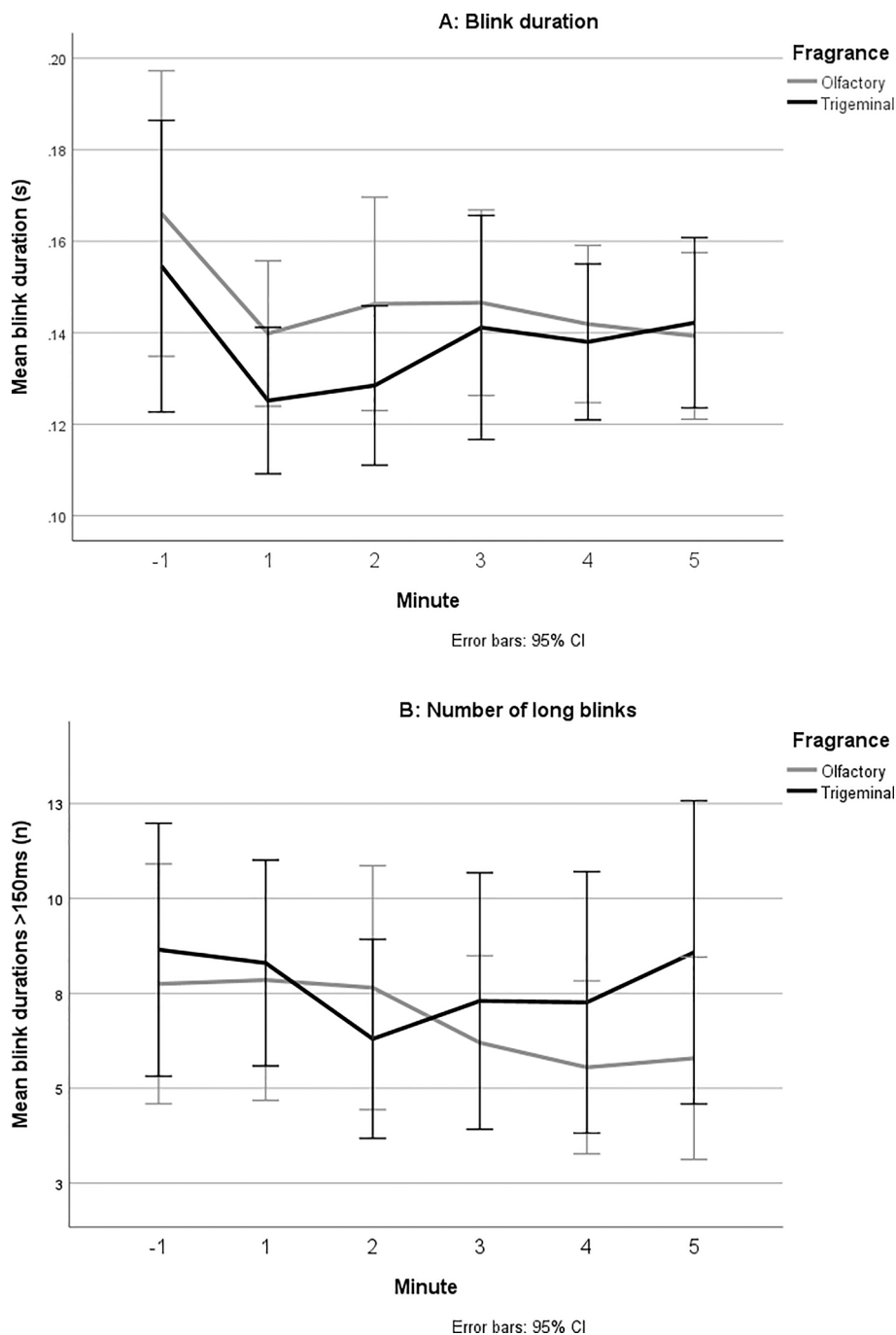
Fig. 3. Descriptive data (mean and CI) of blink duration and number of long blinks (>150 ms) one minute before and five minutes after fragrance administration.

Table 2
Results from the ANOVAs of driving performance and physiology, analyzing the effects of fragrance type, time, and whether the participant fell asleep or not.

	Line crossings		SD lateral		SD speed		Blink duration		Long blinks		Heart rate		RMSSD	
	F	p-value	F	p-value	F	p-value	F	p-value	F	p-value	F	p-value	F	p-value
Fragrance	0.110	0.741	0.761	0.384	0.833	0.363	3.355	0.069	0.199	0.656	0.527	0.469	2.676	0.103
Time	4.998	<0.001	0.836	0.525	1.246	0.289	2.906	0.015	0.413	0.839	0.439	0.821	1.097	0.364
Sleep	4.392	0.037	0.982	0.323	2.113	0.148	19.293	<0.001	38.023	<0.001	54.185	<0.001	7.627	0.006
*Fragrance*Time*	1.120	0.351	0.655	0.658	1.125	0.348	0.787	0.560	1.145	0.338	1.185	0.318	1.418	0.219
*Time*Sleep*	1.667	0.144	0.288	0.919	0.874	0.499	0.359	0.876	0.817	0.539	0.944	0.454	0.546	0.741
*Fragrance*Sleep*	1.198	0.275	0.209	0.648	4.250	0.041	0.368	0.545	2.941	0.088	0.004	0.948	0.792	0.374
*Fragrance*Time*Sleep*	1.483	0.197	0.487	0.785	2.473	0.034	2.073	0.070	1.411	0.222	0.412	0.840	1.380	0.233
Participant	4.832	<0.001	3.717	<0.001	5.870	<0.001	8.422	<0.001	8.057	<0.001	125.341	<0.001	24.660	<0.001

experience, as that would prohibit fleet deployment.

Olfactory interfaces have been introduced in driving for other safety relevant purposes than alertness, for instance to reduce speeding, to notify drivers of relevant events, and to reduce driving-relevant mistakes (Spence, 2021). Pleasant scents (such as rose and peppermint) could be able to shift the emotion of the driver towards the positive valence (Dmitrenko et al., 2020). In a driving simulator study, Dmitrenko et al. (2020) found that pleasant scent (rose) was shown to calm angry drivers and improve driving performance whereas unpleasant scent (civet) was associated with worse driving performance (more collisions). Moreover, Baron and Kalsher (1998) showed that exposure to a pleasant ambient fragrance (lemon aroma) can enhance some aspects of driving performance in a simulated driving task. Odors have also been used in partly automated driving to enhance takeover performance (Tang et al., 2021b).

Previous studies on odors and performance of non-driving tasks have reported improved (Warm et al., 1991, Millot et al., 2002, Ho and Spence, 2005), or no change (Gilbert et al., 1997, Ilmberger et al., 2001) in performance in response to various types of odors as compared to no-odor control conditions. Ho and Spence (2005) found improved performance of a dual task when peppermint odor was delivered periodically for 35 s in every 315 s. In a study by Warm et al. (1991) cognitive performance in a sustained visual attention task improved when participants were periodically exposed to either peppermint or muguet (lily of the valley) odor (30 s bursts every 5 min). Millot et al. (2002) reported that the presentation of an ambient odor, no matter whether it was the pleasant odor of lavender or the unpleasant odor pyridine, resulted in significantly decreased reaction time in simple tasks (responses to visual or auditory stimulation) relative to a no-odor baseline condition. Thus, several studies have found similar results as in the present study, i.e., that different types of odors can have similar effects.

The administration route and strength of the trigeminal fragrance was determined through pilot testing in a laboratory setting. It is possible that a different set-up for fragrance exposure could have given different results. There was a startle effect resulting from the flow of air from the nebulizer tubes. This effect was similar for the trigeminal and olfactory fragrance and may have dominated over the effect of the trigeminal component in the trigeminal fragrance. Future studies should investigate and compare alternative routes of administration as aspects such as distance, volume, and speed of fragrance delivery differ between devices (Dmitrenko et al., 2016). It is also possible that a longer exposure, or repeated hits of trigeminal substance could have given stronger effects. Studies using olfactory stimulation have found that intermittent release of fragrance is most effective for maintaining alertness (Hirata, 2001, Funato et al., 2009). Olfactory adaptation is a well-known phenomenon that needs to be taken into consideration when using olfactory stimuli. Desensitization to a stimulus over time is, at least to some degree, similar in the olfactory and trigeminal system (Scheibe et al., 2009) and the risk of adaptation should thus be handled also when using trigeminal stimulus. The present study was designed to avoid carry over effects for the participants exposed to trigeminal fragrance in the first drive. A greater exposure to trigeminal fragrance could have resulted in arousal effects that lingered on for too long, affecting the alertness in the second drive. Longer exposure of trigeminal stimuli could potentially trigger negative effects such as pain even if the fragrance used in this study had shown no negative side effects in pilot trials. The trigeminal fragrance was perceived as more unpleasant by the participants and adverse effects should thus be taken into consideration in future studies.

As the study was designed as a proof-of-concept study, a relatively small sample size was considered sufficient. One reason for that is that previous studies of 10–16 participants have shown significant differences between alert and fatigued conditions in the same outcome measures related to fatigue and driving performance as used in this study (Ingre et al., 2006, Anund et al., 2017). To justify further research and development, a large effect size related to the alerting fragrance would have been required (i.e. large enough to be captured in a small

sample like this study). Here, a crossover design was used to increase the statistical power and thus 20 participants was set as the target number. Still, in many aspects the study is likely underpowered. For example, the lack of statistically significant differences between men and women in the outcome measures should not be given too much weight.

The alerting effect of fragrance exposure was similar to the effect of other fatigue countermeasures commonly used by drivers (Reyner and Home, 1998, Schwarz et al., 2012, Gaspar et al., 2017). Listening to music has shown moderate acute effects on subjective sleepiness and blink durations during real road driving (Schwarz et al., 2012). Various types of fatigue warnings (visual, auditory, and haptic) have been shown to reduce lane departure frequency in drowsy drivers. These countermeasures have modest effects on subjective and objective fatigue measures and the effects were generally short-lasting. Similarly, Anund et al., (2008b) investigated the effects of hitting a milled rumble strip in sleep-deprived drivers. They reported significant effects on blink durations, SD of lateral position and EEG measures and the effects lasted up to four minutes after hitting the rumble strip. Thus, fragrance exposure could be added to the list of countermeasure strategies that can be used alone or in combination to elicit short-term alerting effects in fatigued drivers. Other popular countermeasures such as opening a window (Anund et al., 2008a) have not proven to be effective against driver fatigue (Schwarz et al., 2012).

5. Conclusions

Subjective sleepiness decreased slightly after fragrance administration, irrespective of whether the fragrance contained the trigeminal alerting substance or not. Mean blink duration, which was used as an objective measure of sleepiness, decreased after administration of either fragrance, as did the frequency of line crossings. In summary, exposing drivers to fragrances had a small but significant effect on some but not all measures related to driver fatigue, but there were no significant differences between the trigeminal and olfactory fragrances.

The results for the fragrance administration per se are in line with the effects found for other countermeasures that have temporary effects on fatigue, like rolling down the window to get some cold air, turn on bright lights or play loud music. These types of countermeasures can buy the driver some time, in the sense that driving performance might be restored for a short while. Whether this is sufficient to support driving performance until the driver can make a safe stop in real traffic conditions remains a topic for future studies. It is possible that a different dose or strength of the trigeminal fragrance, longer duration of exposure or repeated administration could have given a stronger or longer lasting effect on driver sleepiness and performance.

CRediT authorship contribution statement

Anna Sjörs Dahlman: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing - original draft, Visualization, Project administration, Funding acquisition. **Mikael Ljung Aust:** Methodology, Writing - review & editing, Funding acquisition. **Yaniv Mama:** Methodology, Resources, Writing – review & editing. **Dan Hasson:** Conceptualization, Methodology, Writing – review & editing. **Anna Anund:** Conceptualization, Methodology, Investigation, Writing - review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal

relationships which may be considered as potential competing interests: Yaniv Mama is the CTO and co-founder of Moodify. The remaining authors have no conflicts of interest to declare.

Data availability

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