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Behavioural observation as a means of assessing sleepiness related driving impairment in obstructive sleep apnoea
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Abstract

This study compared the temporal pattern of non-verbal behaviours (actions not directly related to task performance) in obstructive sleep apnoea (OSA) drivers under monotonous driving conditions following sleep restriction versus normal sleep. Seventeen patients with untreated severe OSA completed a 90-minute driving simulator task during mid-afternoon under two experimental conditions: prior normal habitual sleep (~8h) and prior sleep restriction (4h time in bed). Steering deviation and crash events were identified using a driving simulator. Non-verbal behaviours (self-centred gestures, non-verbal facial activities, postural adjustments, non-self-centred gestures and eye closures) were identified using video recording and a behavioural ethogram. Participants demonstrated increased steering deviation over the drive (p<0.001) and following sleep restriction (p<0.001). All non-verbal behaviours, except non-verbal facial activities, increased over the drive (all p<0.01). Compared to normal sleep condition, the incidence rate was 2.1 times higher for eye closures (95%CI 1.75-2.60) and 1.5 times higher for postural adjustments (95%CI 1.29-1.72) following sleep restriction, while non-self-centred gestures reduced by 50% (IRR 0.53, 95%CI 0.36-0.78), all p<0.01. In the 10 minute period prior to simulator crash events, eye closure frequency increased compared to equivalent periods without a crash event 2.1 (95%CI 1.4-3.8, p<0.01). Kaplan-Meier analyses showed a progressive cessation of non-verbal facial activities leading up to crash events (X²=6.2, p=0.013). Although eye-closure appears to be a more
sensitive marker of poor vigilance, behavioural observation could provide a novel further method for assessing vigilance failure in OSA and could assist in the development of novel video-based in-car devices for detection of driver sleepiness/fatigue.

Keywords
OSA; Sleepiness; Driving Performance; Nonverbal Behaviour

1. Introduction
Obstructive sleep apnoea (OSA) is a common sleep disorder characterised by excessive daytime sleepiness, poor vigilance and 2–7 times increased risk of motor vehicle accidents (1–3). Current driving risk assessment in OSA is largely based on sleep study determined OSA severity and self-reported sleepiness which is problematic. There is high variation in daytime sleepiness and vigilant performance (e.g. driving performance) between OSA patients and poor correlation between these daytime outcomes with clinical measures of OSA severity (4, 5). Furthermore, many OSA patients may under-appreciate, or under-report their level of sleepiness to avoid potential license restrictions. Thus, more reliable and objective methods are needed to both establish and monitor fitness to drive in OSA (6), perhaps targeting ways to assess driver alertness state in real time. Given the transient and progressive nature of sleepiness, and attendant driving performance deficits and increased accident risks, simple low cost in-car monitoring strategies could play a useful role in improving driving safety in OSA.

The observation of non-verbal behaviours (actions that do not contribute directly to task performance) could provide useful measures of sleepiness related driving impairment in OSA. For example, if passengers are aware of the behavioural signs that impaired performance or even a crash may be likely, they may be able to alert drivers when it is time to stop driving and take a break. Furthermore, information on sleepiness related non-verbal behaviours may aid in the development of novel in car fatigue recognition technologies. In a driving context non-verbal behaviours may be split into 4 categories: (a) ‘non-verbal facial activities’ (non-communicative facial expressions); (b) ‘postural adjustments’ (body movements from an original orientation); (c) ‘self-centred gestures’ (movements of one or both hands towards the body); and (d) ‘non-self-centred gestures’ (behaviours suggesting the manipulation of objects) (7). Though not traditionally considered as a non-verbal behaviour in the literature, eye movements are a strong indicator of increasing sleepiness (8) and may be considered as a fifth behaviour of relevance in assessing sleepiness.

Non-verbal activities increase in frequency during monotonous tasks and following sleep deprivation (9), with specific temporal relationships (10). Non-verbal behaviours have been found to precede periods of low vigilance, while postural adjustments and self-centred gestures occur concurrently and subsequent to periods of low vigilance. Such behaviours may act as defence mechanisms to sleepiness as their stimulatory effect can be reactivating (11). However, despite effectiveness in identifying impaired driver vigilance, behavioural observation has not been applied to the task of identifying specific on-road events.

This driving simulator study is the first of its kind to examine non-verbal behaviours in an OSA patient population, and in relation to specific performance failures (i.e. driving simulator crashes). We hypothesised that the frequency of specific behaviours would increase over time during simulated driving, and to a greater degree following sleep restriction. We hypothesised that simulator crash events would occur more frequently following sleep restriction and be preceded by an increase in eye closures and decrease in reactivating behaviours, since at that point participants would pass beyond the purposeful self-management of vigilance.

2. Materials and Methods

2.1. Study Design
The study used a within-subjects design in untreated patients with severe OSA tested on a driving simulator following normal sleep (~eight h time in bed) and sleep restriction (four h time in bed) conditions in a random order. This study was part of a larger project examining the performance of drivers with OSA and their vulnerability to the effects of sleep restriction and alcohol (12).
2.2. Participants

Patients diagnosed with severe OSA were recruited from the Adelaide Institute for Sleep Health. Inclusion criteria required participants to be 1) aged between 25-70 years, 2) have severe OSA (apnoea hypopnea index, AHI>45 events/h) on laboratory based diagnostic polysomnography (PSG), with 3) no prior treatment for OSA, 4) reside in Adelaide and 5) hold a private driver’s licence for at least 2 years, and averaging at least 2 h driving per week. Exclusion criteria included history of (a) traumatic head injury, central nervous system disease, alcohol or drug abuse, (b) present use of medication that may affect motor skills, such as sedatives, anticonvulsants, or opiates, (c) additional irregular sleep patterns or conditions, such as shift work, narcolepsy, insomnia, or periodic limb movement disorder or (d) significant medical co-morbidities linked to sleep, such as chronic depression or heart failure. During a preliminary visit to the laboratory, patients were introduced to the study aims and protocol, screened for suitability, undergone 30 minute driving simulator familiarisation/practice drive and provided informed written consent for their participation. The study was approved by the Human Research Ethics Committees of the Repatriation General Hospital and University of South Australia.

2.3. Experimental Procedure

All participants slept at home prior to the experimental day. Self-report sleep diaries and activity monitors (Mini Mitter, Actiwatch Co., Model-AW64, Bend, Oregon, USA) were used to confirm a regular sleep/wake cycle and adherence to the sleep restriction regime in the week preceding testing. During the normal sleep condition, participants had their habitual sleep opportunity the night prior to testing, while during the sleep restriction condition their time in bed was reduced to 4hrs (between 2am and 6am) and they were required to call a time and date stamped answering machine before going to sleep and rising to confirm compliance. Participants were instructed not to consume alcohol or caffeine 24 h before testing. The order of conditions was randomised, and the time between testing sessions was at least five days.

Upon arrival to the laboratory at 11.30am, sleep diaries, activity monitors and answering machine records were crosschecked for protocol adherence, and a calibrated breathalyser (Dräger Alcotest 7410Plus, Mississauga, Ontario, Canada) used to confirm a zero blood alcohol concentration (BAC). At 12.15pm, participants were provided with a standardised lunch (two toasted cheese rolls and a glass of water). The driving task began at 2pm.

2.4. Polysomnography

All subjects had overnight PSG approximately one to two weeks before testing, with the following recordings: Electroencephalography (EEG: C3/A2, C4/A1 lead placements), left and right electro-oculograms, submental electromyogram, nasal cannula for pressure-based airflow, limb movement sensors, inductive plethysmography for thoraco-abdominal motion, lead II electrocardiography and arterial oxygen saturation (finger pulse oximetry). All signals were digitised and stored using a Compumedics-E Series sleep system (Melbourne, Australia). Sleep and arousals were scored using standardised methods (13, 14). Apnoeas and hypopneas were scored according to internationally agreed Chicago criteria (13). Hypopnea was defined as (i) >50% reduction from baseline in the amplitude of the nasal pressure signal, or, if this signal was absent or of poor quality, the sum of non-calibrated thoracic and abdominal plethysmography signals; or (ii) a clear amplitude reduction in one of these parameters that was <50% from baseline but associated with either oxygen desaturation >3% or arousal.

2.5. Driving Simulator

Driving performance was measured using the "AusEd" PC-based driving simulator, developed by Engleman (Edinburgh University), and Grunstein (University of Sydney) (15). The AusEd driving simulator ran on a purpose-built Windows 2000 workstation, 19-inch BENQ FP937s monitor with the Logitech MOMO steering wheel and pedals used to assess the driving parameters. The chosen simulated driving task was a 90-minute rural country night-time drive on a predominantly straight dual-lane highway with bends occurring at five minute intervals, each taking approximately 10 seconds to negotiate. There was no oncoming traffic or traffic lights. The left hand side of the road was chosen to replicate the Australian driving conditions. The simulator was located in a sound attenuated sleep laboratory bedroom to avoid obtrusive distractors, which maintained a constant ambient temperature (22°C) and dimmed light level (10 lux) as per the standard operating procedures for the AusEd driving task.
Phones and watches were removed to blind the participants from all time cues. All participants were instructed to drive continuously for the 90 min of the drive and their steering deviation was measured as the deviation (in cm) from median position within the left hand lane. Participants were instructed to maintain speed within 60-80 km/h, but to apply the brakes as quickly as possible whenever a slow moving truck was presented ahead in the driving lane. The latter occurred a total of seven times during the drive and the braking reaction time was computed for each truck-ahead incident. Crash events were defined and recorded as (a) off-road events (all four wheels deviated completely out of the left or right side of the 3.6 metre road), (b) participant came to a stop and remained stationary for >three seconds, or (c) participants collided with a slow-moving truck.

2.6. Behavioural Analysis

To record behaviours during each drive, a single video camera was placed in the top right hand corner of the simulator booth, above the computer screen. The field of vision was calibrated to provide a frontal image, framing participants when seated from the top of their head to their sternum. Behaviours of interest were defined via an ethogram (Table 1) developed by the authors and based upon an agreed categorisation of non-verbal activity (10, 16). This includes (a) ‘non-verbal facial activities’ (non-communicative facial expressions); (b) ‘postural adjustments’ (body movements from an original orientation); (c) ‘self-centred gestures’ (movements of one or both hands towards the body); and (d) ‘non-self-centred gestures’ (behaviours suggesting the manipulation of objects) (7).

2.7. Behavioural Analysis across the Drive

The 90 min video footage was divided into nine, 10 min epochs with behaviours scored in each epoch to create nine consecutive frequency totals for each drive. In order to maximise scoring consistency, a single researcher responsible for behavioural observation was blinded against condition and completed an intra-rater reliability test on five randomly selected studies scored two weeks apart in random order (r=0.94).
Table 1. Definitions of non-verbal behaviours in OSA patients.

<table>
<thead>
<tr>
<th>Behaviour</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Self-centred gestures</strong></td>
<td></td>
</tr>
<tr>
<td>Touching head</td>
<td>Hand touches any point on the face, defined from the jaw line upwards, inclusive of scalp, eyes and ears.</td>
</tr>
<tr>
<td>Touching neck</td>
<td>Hand touches any point on the circumference of the neck, from thorax to nape.</td>
</tr>
<tr>
<td>Touching arms</td>
<td>Hand touches opposite arm, from and inclusive of hand to shoulder.</td>
</tr>
<tr>
<td>Touching torso</td>
<td>Hand touches upper torso - defined from sternum to collarbone and deltoid to deltoid.</td>
</tr>
<tr>
<td><strong>Non-verbal facial activities</strong></td>
<td></td>
</tr>
<tr>
<td>Yawn</td>
<td>Progressive, involuntary opening of mouth during deep inhalation. A closed or open hand may move to cover the mouth during a yawn.</td>
</tr>
<tr>
<td>Stretch face</td>
<td>Extension of facial muscles without hands present. May include: stretching of facial features along horizontal or vertical axes, exaggerated raising of eyebrows, or tightening and slight recession of ears and scalp.</td>
</tr>
<tr>
<td>Licking lip</td>
<td>Extension of tongue onto upper or lower lips, which may be held stationary, or moved horizontally in either direction across the chosen lip.</td>
</tr>
<tr>
<td>Biting lip</td>
<td>Insertion of either upper or lower lip into the mouth until held between upper and lower front teeth. Both lips may be inserted at the same time.</td>
</tr>
<tr>
<td><strong>Postural Adjustments</strong></td>
<td></td>
</tr>
<tr>
<td>Tilt torso</td>
<td>Tilting of torso in any direction, keeping original point of contact on the seat.</td>
</tr>
<tr>
<td>Tilt head</td>
<td>Tilting of head in any direction, keeping original neck position. A tilting behaviour is not to be recorded if it is a function of another behaviour, i.e. tilting head left to scratch the head.</td>
</tr>
<tr>
<td>Shift position</td>
<td>Relocation of seating position marked by the brief rising to fall into a new position on the seat. Rising can occur either through the use of one or two hands pushing down against the armrests, or brief and partial propulsion by the legs.</td>
</tr>
<tr>
<td>Exercise shoulders</td>
<td>Movement of one or both shoulders in a backwards direction, stretching the shoulders and chest. One or both shoulders may also be rotated from the torso in a clockwise or anticlockwise direction, stretching the shoulders and chest.</td>
</tr>
<tr>
<td>Stretch arms</td>
<td>Removal of one or both arms from the steering wheels and full extension of one or both elbow joints, resulting in a stretch of the respective arms muscles.</td>
</tr>
<tr>
<td><strong>Non-self-centred-gestures</strong></td>
<td></td>
</tr>
<tr>
<td>Play with hair</td>
<td>Hand extends to hair on scalp or face and commences one of the following behaviours: wrapping hair around fingers, repetitively stroking hair mass, tugs hair against follicle roots, or moving fingers through or under hair mass.</td>
</tr>
<tr>
<td>Tap fingers</td>
<td>Repetitive initiation and cessation of contact of one or more fingers against a surface. If multiple fingers are in use, they may tap in consecutive motion.</td>
</tr>
<tr>
<td>Touch environment</td>
<td>One or more of digits removed from the steering wheel and placed on an inanimate piece of the surrounding environment, i.e. chair, simulator cupboard.</td>
</tr>
<tr>
<td><strong>Eye closures</strong></td>
<td></td>
</tr>
<tr>
<td>Closed eyes (&gt;1s)</td>
<td>Simultaneous closing of both eyelids for a duration lasting for greater than one second.</td>
</tr>
</tbody>
</table>
2.8. Behavioural Analysis Preceding Crashes

Independent of the behavioural analysis across the drive, pre-crash behaviours were examined by isolating, from the continuous 90 min footage, the ten minutes of video footage preceding each patient’s first simulator crash event. This analysis was performed following the sleep restriction condition only due to very few crash events following normal sleep. To allow behavioural activity comparisons with first crash event, a ten minute period with no crash event and no overlap with the 10 min containing the first crash was randomly selected following at least 20 min into the same drive in each individual. 20 minutes into the drive was chosen because there were no crashes in the first 20 min of any drive. Due to occurrence of multiple crash events in some patients, and to avoid duplicated overlapping periods, only the first crash event and preceding non-verbal behaviours were analysed. The frequency and duration of behaviours occurring in the 10 min epochs prior to crash events and non-crash control periods were determined through video analysis and divided into ten consecutive one min blocks.

The video footage from each 10 min epoch preceding a crash event and non-crash control period was prepared by another investigator who did not contribute to behavioural scoring. Each 10 min file was cut from the continuous 90 min video record such that video footage ceased immediately before visible evidence of crash occurrence (video brightening reflected from the crash screen). All video edited segments were re-labelled and randomised such that the researcher responsible for scoring the data was blinded and could not identify periods that preceded a crash from control periods. Subsequent scoring of the frequency and duration of non-verbal behaviours was then undertaken by the behavioural scorer prior to data un-blinding.

2.9. Statistical Analysis

Steering deviation data were divided and averaged into nine bins across the 90 min drive, with the exclusion of the first minute to allow for acceleration and initial lane positioning. Mixed model analysis specifying subject as a random effect was used to examine condition (normal sleep and sleep restriction), time on task (9 bins), and interaction effects using an autoregressive covariance structure to allow for serial correlation of neighbouring time points (SPSS Inc, Version 16.0, Chicago).

Regression for count data was used to analyse differences in the incidence of behaviours across the drive to test the effects of condition (sleep restriction vs normal sleep) and time (one to nine) and their interaction with repeated measurements taken into account by specifying subject ID as a panel variable (Stata v10.0). Regression for count data was also used for pre-crash analysis examining the differences in the incidence of behaviours occurring 10 min prior to crash vs non-crash events across time (1-10 minutes). Negative binomial regression models were used to account for over dispersion (higher than expected variance). In order to more specifically examine the cessation of behaviours prior to crashes, Kaplan-Meier analyses were used to examine the proportion of patients exhibiting each behaviour and the temporal distribution of the final behaviour relative to the end of each 10 min period preceding crash events versus and non-crash controls. Data are presented as mean±SEM, unless otherwise indicated. p<0.05 was considered statistically significant.
3. Results

Seventeen OSA patients were recruited into the study. Their anthropometric characteristics, sleep study results, estimated sleep time (actigraphy) during normal sleep and sleep restriction conditions are shown in Table 2. All patients complied with the sleep restriction protocol and had a blood alcohol concentration of 0.0 g/dL upon arrival to the laboratory on each experimental day.

Table 2. Patient characteristics, sleep study results, time In bed (actigraphy).

<table>
<thead>
<tr>
<th>Variable</th>
<th>N/Mean(SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Males/Females (N)</td>
<td>14/3</td>
</tr>
<tr>
<td>Age (yrs)</td>
<td>53.2 (11.6)</td>
</tr>
<tr>
<td>Body-Mass Index (BMI)</td>
<td>36.8 (8.0)</td>
</tr>
<tr>
<td>Apnea Hypopnea Index (AHI: events/hr)</td>
<td>64.6 (18.0)</td>
</tr>
<tr>
<td>% of sleep time with SaO2&lt;90%</td>
<td>9.9 (15.1)</td>
</tr>
<tr>
<td>Average SaO2 desaturation</td>
<td>4.9 (2.3)</td>
</tr>
<tr>
<td>Epworth Sleepiness Scale (ESS)</td>
<td>10.6 (5.4)</td>
</tr>
<tr>
<td>Time in Bed (mins)</td>
<td>Normal Sleep</td>
</tr>
<tr>
<td></td>
<td>Sleep Restriction</td>
</tr>
</tbody>
</table>

3.1. Driving Performance

Steering deviation increased significantly over time in both conditions (F8,(196) =4.9 p<0.001), with a greater level of impairment present during the sleep restriction condition (F(1,33) = 20.7, p=0.001) (Figure 1). There were forty nine driving simulator crash events during normal sleep and sleep restriction combined (11 following normal sleep and 38 following sleep restriction). The crash incidence rate was approximately 3.4 (95%CI 1.74 - 6.84) times higher following sleep restriction compared to normal sleep condition (Table 3 and Figure 2A).

Figure 1. Mean (SEM) steering deviation throughout the 90 minute drive in severe OSA patients following normal sleep and sleep deprivation.
3.2. Behaviour Across the Drive

There were no significant condition (normal vs sleep restriction) by time interaction effects in any behaviour. However, eye-closures and postural behaviours occurred more frequently and non-self-centred gestures less frequently following sleep restriction compared to normal sleep (p<0.01). Except for non-verbal facial behaviours, all other behaviours significantly increased in frequency over time (p<0.01, Table 4 and Figure 2). Compared to normal sleep, the incidence rate was approximately 2.1 times higher for eye closures (95%CI 1.75-2.60) and one and a half times higher for postural adjustments (95%CI 1.29-1.72) following sleep restriction. In contrast, the incidence rate of non-self-centred gestures was reduced by nearly 50% in the sleep restriction compared to the normal sleep condition (95%CI 0.36-0.78).

3.3. Behaviour Preceding Crashes

Pre-crash behaviours under normal sleep conditions could not be meaningfully analysed as only three participants exhibited crashes during this condition. However, during sleep restriction, seven of the 17 participants experienced simulator crash events; all off-road crashes (crash criterion (a); all four wheels deviating from the road). The incidence and frequency of eye closures were 2.1 (95%CI 1.4-3.8) time higher in the 10 min preceding crash events compared to non-crash control periods (Figure 3C, Table 4). There was a trend for a significant rise in the incidence of eye-closure over time, but this did not reach statistical significance (p=0.09). There were no other significant condition, time or interactions.

Despite no difference in incident rate (Table 4), Kaplan-Meier analysis showed that in the 10 minutes (600 sec) preceding the first crash event, the fraction of OSA patients exhibiting non-verbal facial behaviours was significantly diminished compared to non-crash control periods (Figure 4, hazard ratio 0.2, 95%CI 0.05-0.80, *p*=6.2, p=0.013), particularly over the last five minutes preceding the crash event. There were no changes in other behaviours over time in crash events versus non-crash control periods.
Figure 2. Mean frequency (SEM) of behaviours observed per 10 min block throughout the 90 minute simulated drive in severe OSA patients under normal and sleep restriction conditions.

A  Simulator Crashes

B  Self-Centered

C  Non-Verbal Facial

D  Eye Closure

E  Postural

F  Non Self-Centred Gestures
Figure 3. Mean frequency (SEM) of behaviours observed per 1 minute time block in the 10 minutes prior to the first crash or non-crash event in severe OSA patients under sleep restriction condition.
### Table 3. Incident rate ratio for exhibiting behaviour.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Time</th>
<th>IRR</th>
<th>95%CI</th>
<th>95%CI</th>
<th>Z</th>
<th>IRR</th>
<th>95%CI</th>
<th>95%CI</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crash</td>
<td></td>
<td>3.44</td>
<td>1.74</td>
<td>6.84</td>
<td>3.54**</td>
<td>1.24</td>
<td>1.09</td>
<td>1.40</td>
<td>3.40**</td>
</tr>
<tr>
<td>Self-centred</td>
<td></td>
<td>1.02</td>
<td>0.87</td>
<td>1.21</td>
<td>0.26</td>
<td>1.08</td>
<td>1.05</td>
<td>1.12</td>
<td>4.69**</td>
</tr>
<tr>
<td>Non-verbal facial</td>
<td></td>
<td>1.12</td>
<td>0.96</td>
<td>1.31</td>
<td>1.38</td>
<td>1.03</td>
<td>0.99</td>
<td>1.06</td>
<td>1.73</td>
</tr>
<tr>
<td>Eye closure</td>
<td></td>
<td>2.13</td>
<td>1.75</td>
<td>2.60</td>
<td>7.48**</td>
<td>1.24</td>
<td>1.19</td>
<td>1.29</td>
<td>10.82**</td>
</tr>
<tr>
<td>Postural</td>
<td></td>
<td>1.49</td>
<td>1.29</td>
<td>1.72</td>
<td>5.48**</td>
<td>1.11</td>
<td>1.08</td>
<td>1.41</td>
<td>7.42**</td>
</tr>
<tr>
<td>Non-self-centred gestures</td>
<td></td>
<td>0.53</td>
<td>0.36</td>
<td>0.78</td>
<td>-3.28**</td>
<td>1.11</td>
<td>1.03</td>
<td>1.19</td>
<td>2.90**</td>
</tr>
</tbody>
</table>

**p<0.01

### Table 4. Incident rate ratio for exhibiting behaviour preceding crash or non-crash events.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Time</th>
<th>IRR</th>
<th>95%CI</th>
<th>95%CI</th>
<th>Z</th>
<th>IRR</th>
<th>95%CI</th>
<th>95%CI</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Self-centred</td>
<td></td>
<td>0.86</td>
<td>0.52</td>
<td>1.42</td>
<td>-0.57</td>
<td>0.98</td>
<td>0.9</td>
<td>1.07</td>
<td>-0.37</td>
</tr>
<tr>
<td>Non-verbal facial</td>
<td></td>
<td>1.02</td>
<td>0.57</td>
<td>1.81</td>
<td>0.06</td>
<td>0.97</td>
<td>0.88</td>
<td>1.08</td>
<td>-0.53</td>
</tr>
<tr>
<td>Eye closure</td>
<td></td>
<td>2.13</td>
<td>1.42</td>
<td>3.78</td>
<td>3.37**</td>
<td>1.07</td>
<td>0.99</td>
<td>1.17</td>
<td>1.68</td>
</tr>
<tr>
<td>Postural</td>
<td></td>
<td>0.91</td>
<td>0.59</td>
<td>1.41</td>
<td>-0.41</td>
<td>0.97</td>
<td>0.89</td>
<td>1.05</td>
<td>0.04</td>
</tr>
</tbody>
</table>

**p<0.01

Figure 4. Kaplan-Meier curves showing the cessation of non-verbal facial activities in the 10 mins prior to crash events versus control period prior to non-crash events.
4. Discussion

4.1. Behaviour and Driving Performance

The main findings of this study were that increased driving impairment over time, particularly following sleep restriction, was generally accompanied by more frequent non-verbal behaviours in patients with OSA. With the exception of non-verbal facial activities, these findings in severe OSA patients are consistent with data from young, healthy drivers (10). A novel finding from this study was that driving simulator impairment as a consequence of sleep loss in severe OSA patients was associated with more frequent extended eye closure and postural adjustments, but not other non-verbal behaviours. However, in addition to more frequent eye closure, patients who experienced a simulator crash event following sleep restriction also showed greater cessation of non-verbal facial activities prior to first crash event. Consequently, behavioural observations could provide a useful early marker of impending vigilance failure risk.

Contrary to expectations, and in contrast to more frequent self-centred gestures and non-verbal facial activities following sleep restriction compared to normal sleep in healthy sleepers (9, 17), we found minimal changes in these behaviours between conditions. For example, one sleep deprivation study (17) in healthy subjects found that compared to rested condition, sleep deprivation resulted in attenuated emotional facial expressiveness to positive stimuli, findings that support the notion that sleep loss leads to lowered emotional expression (de-arousal hypothesis). The lack of a difference between habitual and restricted sleep in the current study may be due to pre-existing habitually higher levels of sleepiness in untreated OSA and may reflect the cumulative effect of habitual poor sleep due to OSA and exposure to additional sleep leading to participants succumbing to sleepiness during the drive (18), rather than resisting it through behavioural reactivation (i.e. self-centred gestures). In this study partial sleep restriction increased the rate of eye closure in OSA patients, consistent with increased sleepiness, with relatively little impact on the frequency of other behaviours. The unexpected similarity of non-verbal facial activities between conditions in this study may be the result of a higher frequency of sleep-related behaviours (i.e. yawning, face stretching, licking/lip-biting) in OSA patients, even under normal habitual sleep conditions compared to previous studies in healthy participants (9, 10). This may also reflect a ceiling effect in self-centred gestures and non-verbal facial activities over a given time period.

Extended eye closures are indicative of succumbing to sleep onset (16, 19) and are often accompanied by postural adjustments (i.e. nodding head, slumping posture) (20). Thus, it appears that participant drowsiness, was mediated by partial sleep restriction, with eye closures and postural adjustments the most sensitive measures of hypovigilance. The difference in behaviours (both performance and non-verbal) between normal and restricted sleep conditions may be related to the severity of this hypovigilance state. Although the difference in postural adjustments was unexpected, Roge et al (9) demonstrated greater frequencies of postural adjustments following sleep restriction that approached statistical significance, which would suggest that the current results support previous research.

Non-self-centred gestures did not provide an insight into the state of vigilance, nor appear to have a reactivating function for OSA patients, despite common driver perception (21). The minimal frequency of non-self-centred gestures in either condition may be explained by the lack of objects within the testing environment. Unlike car cabins, the simulator did not have a radio, dashboard, (items within an) ashtray, windows or passenger with whom to interact, and therefore may be a limitation of the simulated environment compared with the real car cabin.

4.2. Behaviour Preceding Crashes

More frequent eye closures were associated with the occurrence of simulator crash compared to non-crash events, while the frequency of other behaviours did not differ between crash vs non-crash events. This is in agreement with other reports showing that involuntary eye closures are a strong predictor of sleepiness-related vigilance failure (16, 22) and driving incidents (23, 24). This suggests ocular motion may be a promising correlate reflecting arousal state in real time and has certainly received attention as a potential tool for monitoring fatigue/sleepiness in operational environment (e.g. commercial drivers) (25). Employing a Kaplan-Meier analysis strategy, focusing on the time at which OSA patients ceased displaying non-verbal behaviours prior to a crash/non-crash event, we found that OSA patients ceased displaying non-verbal facial activities earlier prior to crash events compared to non-crash events.
Careful temporal monitoring of non-verbal behaviours could potentially complement ocular measures and assist with earlier detection of impending vigilance failure than with ocular measures alone.

In this study, methods of reviving oneself during low vigilance were likely limited to self-centred gestures. In on-road conditions, participants may wind down a window, or regulate the radio in order to more effectively revive themselves to restore vigilance. However, these countermeasures appear of limited benefit in reducing driving impairment (26). Our results derived from a sleep-conducive environment (i.e. monotonous driving conditions with minimal consequences for impaired driving) may overestimate the presence of attentional lapses. Future research could address this issue by using simulator equipment that locates participants within an interactive car cabin and projects the road scenario in front, or by extending the study into real-world driving. On the other hand, a more sleep conducive and challenging simulator environment could be advantageous for assessing driving safety, and discriminating OSA patients most at risk of vigilance failure.

A comparison of behavioural activities with physiological measures of vigilance (EEG) in previous studies has found specific temporal relationships under normative driving conditions (9). Consequently, replicating current methodology with the inclusion of electrophysiological measures could aid in determining the robustness of such relationships in individuals with OSA. Moreover, it would clarify the extent to which these relationships are present preceding critical performance failures, and thus, whether or not holistic behavioural observation may be applied to crash prevention applications.

4.3. Study Limitations

The current study examined a population of OSA patients and did not have data from a healthy control group. Though some inferences may be drawn via comparisons with previous research in healthy participants (10), further research is required to compare OSA patients to a healthy subjects of similar age, under identical procedures. Despite the sample size (n=17) being comparable to similar studies (10, 11), only seven participants experienced crash events. Crashes often occurred in clusters, limiting analysis to the first crash event. The numbers of events available for analysis was thus low, reducing study power to detect behavioural differences. Nevertheless, some differences were detected warranting further validation in a larger sample. Further research using larger samples and perhaps strategies to facilitate vigilance-related crash events (e.g. greater periods of sleep restriction, longer drives, or changes to simulation parameters such as speed, obstacles, and road design) would therefore be useful. Simulated driving in a laboratory environment does not accurately replicate real on-road driving conditions. Nevertheless, previous studies support that driving simulators usefully replicate the major features of driving (27, 28), even though it is a constructed environment (29).

4.4. Conclusions

Non-verbal activities in severe OSA patients appear to be similar to that in young, healthy subjects during monotonous simulated driving tasks. Within these activities, postural adjustments and eye closures showed the largest changes following sleep restriction and with time on task. Taken together, these results suggest that a sleepy driver with OSA is likely to fidget and move in their seat more than usual, and to show more frequent prolonged eye-closures and facial changes associated with sleepiness and sleep avoidance. Several minutes prior to simulator crash events, these changes in facial expression significantly diminished, and may be useful indicators that continuing to drive would be a safety risk.

The deterioration of driving performance and consistency of behavioural outcomes with previous research (10, 11) suggest that behavioural observation may provide useful insight into the state of vigilance not only in healthy drivers, but also in drivers with OSA. Behavioural observation represents a novel and unobtrusive method of assessment that utilises multiple sources of data measurement (i.e. different types of non-verbal activity). From a vigilance detection perspective, such qualities are desirable (30), and could assist in the development of novel video-based in car devices for early detection of driver sleepiness/fatigue.
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7. References


