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Lapses of Responsiveness: Characteristics, Detection, and Underlying Mechanisms

Richard D. Jones, *Senior Member, IEEE,* Govinda R. Poudel, *Member, IEEE,* Carrie R. H. Innes, Paul R. Davidson, *Member, IEEE,* Malik T. R. Peiris, Amol M. Malla, T. Leigh Signal, Grant J. Carroll, Richard Watts, and Philip J. Bones, *Senior Member, IEEE*

Abstract—**Lapses in responsiveness ('lapses'), particularly microsleeps and attention lapses, are complete disruptions in performance from ~0.5-15 s. They are of particular importance in the transport sector in which there is a need to maintain sustained attention for extended periods and in which lapses can lead to multiple-fatality accidents.**

A central aim of our Lapse Research Programme is to better understand the neural activity underlying lapses so as to maximally detect, and even predict, the onset of lapses as the basis for a non-invasive early-warning systems with the potential to save many lives.

We are on the cutting edge of research into lapses in terms of behavioural characterization and detection, EEG-based characterization and detection, and determination of the underlying mechanisms in the brain via simultaneous recordings of whole-brain BOLD fMRI, 64-ch. EEG, eye video, and EOG, while performing a visuomotor tracking task.

This paper provides an overview of our methods, findings, achievements, and remaining challenges in this fascinating and important area.

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R. D. Jones is with the Department of Medical Physics and Bioengineering, Christchurch Hospital, the Departments of Electrical & Computer Engineering, Communication Disorders, and Psychology, University of Canterbury, and the Department of Medicine, University of Otago, Christchurch, New Zealand (phone: +64-3-378-6077, fax: +64-3-378-6080, e-mail: richard.jones@vanderveer.org.nz).

G. R. Poudel is with the Department of Medical Physics and Bioengineering, Christchurch Hospital, Christchurch, New Zealand (e-mail: govinda.poudel@vanderveer.org.nz).

C. R. H. Innes is with the Department of Medical Physics and Bioengineering, Christchurch Hospital, Christchurch, New Zealand (e-mail: carrie.innes@vanderveer.org.nz).

P. R. Davidson was with the Department of Medical Physics and Bioengineering, Christchurch Hospital, Christchurch, New Zealand. He is now with S.L.I. Systems, Inc., Christchurch, New Zealand (e-mail: pdavidson@orcon.net.nz).

M. T. R. Peiris was with the Department of Electrical & Computer Engineering, University of Canterbury, Christchurch, New Zealand. He is now with Fisher & Paykel Healthcare Ltd, Auckland, New Zealand (e-mail: malikpeiris@gmail.com).

A. M. Malla was with the Department of Electrical & Computer Engineering, University of Canterbury, Christchurch, New Zealand. He is now with Fisher & Paykel Healthcare Ltd, Auckland, New Zealand (e-mail: amolmalla@hotmail.com).

T. L. Signal is with the Sleep-Wake Research Centre, Massey University, Wellington, New Zealand (e-mail: T.L. Signal@massey.ac.nz).

G. J. Carroll is with the Department of Neurology, Christchurch Hospital, Christchurch, New Zealand (e-mail: grant.carroll@cdhb.govt.nz).

R. Watts is with the Department of Physics & Astronomy, University of Canterbury, Christchurch, New Zealand (e-mail: richard.watts@canterbury.ac.nz).

P. J. Bones is with the Department of Electrical & Computer Engineering, University of Canterbury, Christchurch, New Zealand (e-mail: phil.bones@canterbury.ac.nz).

I. Introduction

LAPSES in responsiveness (*lapses*) are complete transient/phasic disruptions in sensory-motor/cognitive performance, from ~0.5–15 s, during an active task. They include (i) behavioural microsleeps (*microsleeps*) [1], during which individuals have a brief episode of suspension of performance and appear to fall asleep momentarily, (ii) *sustained-attention lapses*, which are not directly related to level of arousal and can occur when alert, fatigued, or drowsy, and (iii) *diverted-attention lapses*, due to loss of task-orientated attention. *Sleep episodes* ('nodding off' for >15 s) can have the same adverse consequences as microsleeps but are considered physiologically distinct due to their duration (notwithstanding the arbitrariness of the 15-s demarcation) and the recovery of responsiveness after a brief period in microsleeps.

Lapses are of particular importance in occupations and activities in which there is a need to maintain sustained attention for extended periods and in which lapses can cause accidents and, in the worst cases, can involve multiple fatalities (e.g., truck & car drivers, pilots, air-traffic controllers, train drivers, health professionals, and process control workers) [2, 3].

Response failure and prolonged reaction times during discrete auditory/visual detection tasks are commonly used in research to identify performance lapses [4-7]. In the case of the psychomotor vigilance task, reaction times > 500 ms are commonly arbitrarily defined as 'lapses' [7]. In a discrete task, a lapse is identified by a delayed or absent response to a stimulus and the onset of the lapse is arbitrarily marked as commencing at the same time as the stimulus. Thus, using a discrete response task means that it is not possible to accurately determine lapse onset or duration. Lapses can also be missed if they occur completely between the discrete stimuli (commonly 2–10 s). One way researchers have countered this is by using a continuous performance task, such as visuomotor tracking [1, 8] or driving simulation [9]. Studies investigating the neural processes underlying lapses are particularly reliant upon

accurate measurement of the time a lapse begins and ends, especially those using physiological measures such as EEG or fMRI.

An additional problem with most previous lapse studies is that non-task behavioural characteristics concomitant with prolonged or absent reaction times are not recorded. This means that it is not possible to differentiate between different types of lapses. Differentiation of different types of lapses can be addressed by video recording of the behavioural characteristics surrounding the lapse [1, 10].

Our Lapse Research Programme is working towards increasing our understanding of lapses and, ultimately, reducing accidents due to lapses through (1) behavioural identification of the presence and start- and end-points of lapses, (2) differentiation between different types of lapses, (3) the study of within- and between-subject differences in lapse characteristics, (4) techniques and devices for detection, and even prediction, of lapses from EEG, eye-closure, and other features, (5) determination of the underlying neural mechanisms of lapses and the recovery from such, and (6) study of the relationships between lapses and drowsiness, measures of sleep, sleep deprivation, age, gender, excessive daytime sleepiness, etc.

Our Lapse Research Programme aims to better understand the neural activity underlying lapses so as maximally detect, and even predict, the onset of lapses as the basis for a non-invasive early-warning systems with the potential to save many lives.

We are on the cutting edge of research into lapses in terms of behavioural detection and characterization, EEG-based characterization and detection, and determination of the underlying mechanisms in the brain via simultaneous recordings of whole-brain BOLD fMRI, 64-ch. EEG, eye video, and EOG, while performing a visuomotor tracking task.

II. Behavioural Detection of Lapses

Accurate identification and temporal quantification of lapses via behavioural cues from pursuit tracking and face video have proven of critical importance in the analysis of data from our experimental studies. We have developed the following operational definitions for lapses (EC = full eye closure, excepting normal blinks):

- Sleep – Flat tracking and full EC > 15 s.
- Microsleep – Flat/incoherent tracking > 500 ms + EC + clear behavioural indications of drowsiness.
- Attention lapse (sustained or diverted) – Flat/incoherent tracking > 500 ms but no EC.
- Drowsiness-related impaired responsiveness event (DIRE) – Transient epoch of poor, but not incoherent, tracking (relative to pre- and post-DIRE tracking) > 500 ms + full or partial EC.
- Voluntary eye closure (VEC) – Usually flat/incoherent tracking > 500 ms + EC clearly voluntary to relieve visual fatigue.

In our first study [1, 11-16], subjects undertook a 60-min session of 1-D preview random tracking [17]. This task generally works well except for an intrinsic weak point in that the target has flat-spots during which it can be unclear whether or not a response flat-spot is a lapse.

For our second major study [18-21], we developed a novel 2-D random tracking task [8] in which there are no flat-spots, by ensuring that the minimum speed of the 2-D target never falls below a certain positive value (Fig. 1).

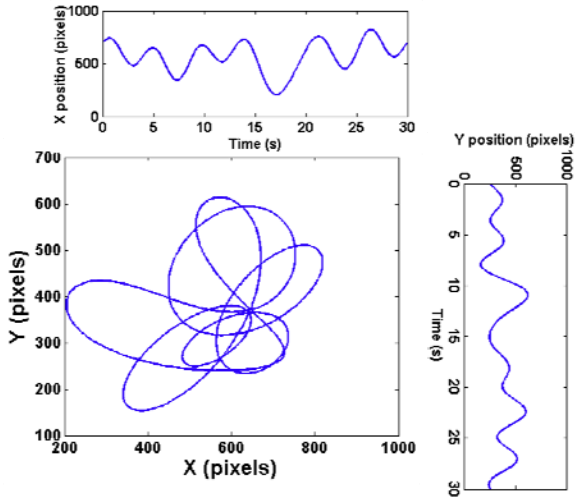

Fig 1. The target trajectory of the 2-D tracking task comprises independent horizontal and vertical components produced by summing 7 sinusoids with frequencies evenly spaced from 0.033 to 0.231 Hz. This produced a 2-D periodic target trajectory (T = 30 s) with a velocity range of 63–285 pixels/s (screen = 1024 x 768 pixels).

To facilitate the identification of lapses, a custom-built *SyncPlayer*™ program was used to replay synchronized eye-video, VEOG, and target x and y position, response x and y position, target and response velocity, and error (Fig. 2). An expert rater visually inspected all of the data, second-by-second, to identify events using pre-defined criteria. The rating criteria were based on the knowledge gained from previous work [1].

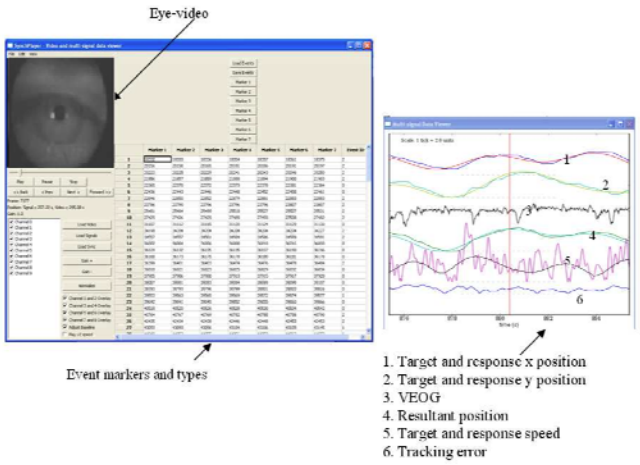

Fig 2. *SyncPlayer* during the visual rating process.

III. Primary Studies

A. Study 1

In Study 1 [1, 11-16], we investigated the occurrence of lapses in 15 non-sleep-deprived subjects (males, aged 18-36 years) performing a 1-D tracking task between 1–4 pm. Tracking behaviour, facial video, and 16-ch. EEG were recorded simultaneously during two 1-h sessions.

A. Study 2

Study 2 [18-21] comprised 20 healthy normally-rested participants (10 males and 10 females, aged 21–45 years). Experimental sessions were conducted between 1–4 pm. Subjects were required to keep a detailed diary of their sleep habits and to wear an Actiwatch to measure their sleep-wake activity during the 6 days and 5 nights prior to the experimental session.

Between 1–4 pm, subjects undertook the 2-D tracking task for 50-min while simultaneous whole-head fMRI (GE 3T, TR 2.5 s), 64-ch. EEG (MagLink), and eye video (Visible Eye) were recorded.

Microsleeps were identified (see Sec. II) and their associated BOLD activity determined from fMRI data using the FMRIB expert analysis tool (www.fmrib.ox.ac.uk/fsl). The onsets of microsleeps were modelled as impulse functions convolved with a double-gamma haemodynamic response function. fMRI data was linearly modeled on voxel-by-voxel basis using FMRIB's improved linear model. Average group statistical maps were generated using mixed-effect models and a cluster-based correction of the z-statistic images was performed and threshold at z scores > 2.3 and $p = 0.05$. It is possible to discriminate between the neural activity due to microsleeps and that associated with intentional eye closure and loss of responsiveness (i.e., stopping tracking) [18, 21].

IV. Key Findings

1. Lapses are a frequent phenomenon in healthy subjects – even when not sleep-deprived – engaged in an extended monotonous visuomotor task.

- On a 1-h 1D tracking task, 14 of 15 subjects had one or more lapses, with an overall mean rate of 39 /h and mean duration of 3.4 s [1].
- Even in a noisy and uncomfortable MRI scanner, while performing a 50-min 2D tracking task [8], 16 of 20 subjects had microsleeps, at an overall mean rate of 79 /h and mean duration of flat/incoherent tracking of 3.3 s [18, 19], with 8 subjects having sleep episodes (> 15 s).

2. In a study of performance on a 10-min psychomotor vigilance task (PVT), 10 air traffic controllers had a total of 101 lapses (reaction times > 500 ms). Of these, only 6 lapses could be identified from EEG and EOG by one or more of 4 expert EEG raters [22]. Thus, expert EEG raters are generally unable to identify lapses based only on EEG and EOG.

3. During microsleeps there is an overall but inconsistent increase is EEG spectral power in the delta, theta, and alpha bands, and a decrease in the beta, gamma, and higher bands (Fig. 3).

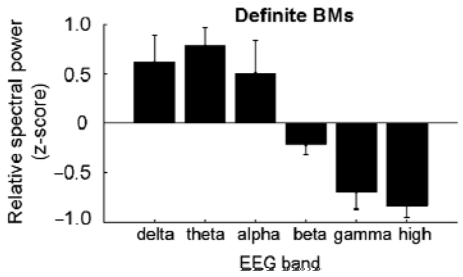

Fig 3. Changes in EEG spectral power during behavioural microsleeps in terms of *z*-scores (mean ± SE) relative to power during the non-lapsing state averaged across all channels and both sessions.

4. There are subtle and inconsistent changes in EEG spectral power during lapses [1, 12-15, 22, 23] which can be used to detect lapses with high temporal resolution. We have explored several linear and nonlinear approaches [11-16] and were the first to detect the lapse state with high temporal resolution (1 s) [14]. This was via a long short-term memory (LSTM) recurrent neural network and EEG from 2 bipolar EEG channels (P4-O2, P3-O1). Detection of the lapse/non-lapse state with a phi correlation of 0.38 and AUC_{ROC} = 0.84. We have also extended this to detection of lapse events [16]. Despite this achievement, the accuracy of detection of lapses from the EEG is still at a level too low for effective implementation in real-world lapse detection devices. The incorporation of other cues, particularly eye-closure, is a

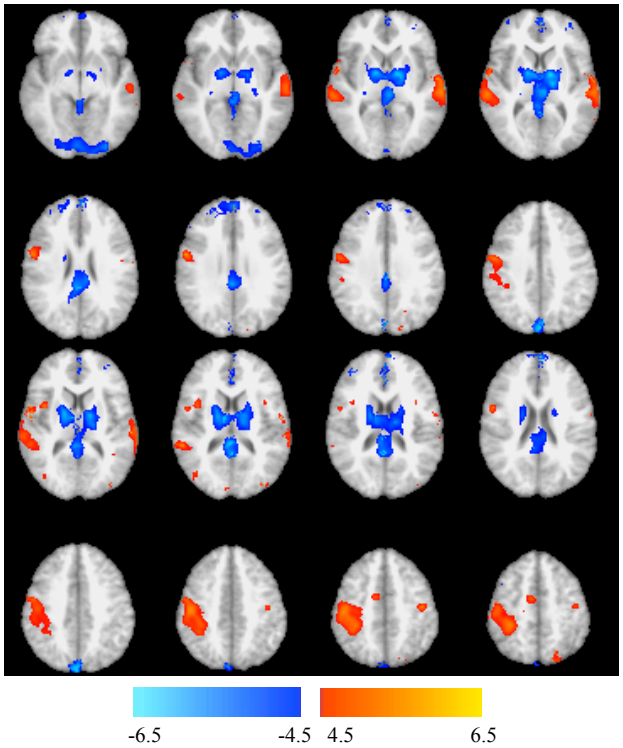

Fig. 4. The spatial pattern of group level BOLD activation and deactivation during lapses of responsiveness. Images have been registered into the standard MNI space and are shown in radiological convention.

promising pathway to increased accuracy of detection of lapses [9, 24].

5. During microsleeps, the BOLD signal (and, hence, neural activity) decreases bilaterally in the thalamus, posterior cingulate cortex, and striate cortex but increases in several cortical brain regions including the inferior frontal cortex, posterior parietal cortex, and occipital cortex (Fig. 4) [18]. Furthermore, the extent of the decrease in neural activity in the thalamus increases with the duration of microsleeps [18]. The thalamus is involved in the maintenance of arousal with decreased activity associated with transition into sleep [22], time-on-task [23], and slowed reactions after sleep deprivation [24]. Similarly, the posterior cingulate gyrus and frontal cortex are part of the default mode region which shows decreased activity during transition into sleep [22], suggesting the important role of wake-sleep neural mechanisms in microsleeps.

6. In addition to microsleeps, there is a less severe but distinct drowsiness-related impaired responsiveness event (DIRE) [20]. This is a discrete epoch in which responsiveness is transiently poor relative to pre- and post-DIRE tracking but, unlike microsleeps, is not absent. DIREs also occur frequently during an extended continuous task and, like microsleeps, rates are highly variable between participants, with a mean rate of 61 /h (range 0–161 /h) and mean duration of 1.9 s.

7. Arousal-related events such as microsleeps, DIREs, and Sleep episodes play an important role in the fluctuations observed in both performance and EEG theta activity during an extended task [20]. Consequently, these events need to be taken into account when studying tonic drowsiness.

8. Propensity for, and duration of, microsleeps and DIREs are correlated with scores on the Epworth Sleepiness Scale (a subjective estimate of daytime sleepiness) but with no other sleep measures, such as sleep quality, disturbance, duration, and efficiency, and circadian type [19]. This indicates that propensity to fall asleep in situations in which sustained performance is required may be primarily a trait characteristic in normally-rested people [19].

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