Review

Neuroergonomics of Absent-minded Driving: State of the Art and Future Research Directions

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ABSTRACT Absent-minded driving is far less understood than distracted driving such as texting or talking while driving; therefore, no effective countermeasure for the prevention of risky absent-minded driving has been found. However, new insight into absent-minded driving might be gained as a result of recent advances in neuroscience regarding spontaneous attentional decoupling (SAD). In this study, empirical evidence from the existing neuroscience literature relating to SAD is reviewed, and a neural network model of SAD is proposed. Finally, based on the proposed SAD model, future research directions toward realizing detection and prevention technologies against absent-minded driving are discussed from a neuroergonomics perspective.

KEYWORDS Absentmindedness, Attentional Decoupling, Mind Wandering, Traffic Accident, Road Safety, Brain, Attention, Neuroergonomics

1. Introduction

People often have to focus on a particular operation for a prolonged period of time, and sustained attention plays a critical role in achieving this goal. Unfortunately, however, humans have not yet evolved to the point of being capable of sustaining their attention over prolonged periods of time. Attention is spontaneously decoupled from an ongoing primary task and the mind starts to wander.[1,2] The most obvious example of this spontaneous attentional decoupling (SAD) is mindless reading.[3-5] That is, our eyes will continue scanning text even when our minds are occupied with something totally unrelated to the content. More importantly, SAD occurs in riskier situations, such as car driving[6-8] and medical practice.[9] In fact, Galéra et al.[10] demonstrated in an epidemiological study that absent-minded driving was associated with an increased risk of causing a motor vehicle accident. However, despite its ubiquity, much less is known about SAD; therefore, no effective countermeasure for preventing SAD-related human error in actual work environments has been proposed.

Recent technical developments in the field of neuroscience have contributed to important advances in our understanding of the mind and human behavior. Among these technical developments, functional magnetic resonance imaging (fMRI), a diagnostic imaging technique that produces three dimensional maps of brain activation patterns associated with sensory, perceptual, cognitive and motor processes with a spatial resolution in the order of a few millimeters, undoubtedly plays the most significant role. For instance, the presentation of visual stimuli induces broad activation in the occipital cortices,[11,12] tasks requiring cognitive control of visual attention commonly activate a neural network comprising the lateral prefrontal cortex (PFC) and the parietal lobule along the intraparietal sulcus (IPS).[13,14] In addition to fMRI, noninvasive stimulation techniques for manipulating brain activity have recently received substantial attention as a tool for altering the mind and human behavior. For example, one study reported that transcranial direct current stimulation (tDCS) over the dorsolateral PFC diminishes risk-taking behavior,[15] while another reported that tDCS over the cerebellum facilitates motor learning efficiency.[16]

These advances in our understanding of human behavior and mind from the perspective of neuroscience may provide new insight into the ways that human-related technologies, systems, and societies should develop in the future. In fact, advanced neuroscience knowledge gives rise to a lot of new (or updated) academic disciplines, including neuroeconomics, neuromarketing, and neuroaesthetics. Parasuraman recognized that ergonomics should also be updated on the basis of the level of understanding of the mind and human behavior made possible by neuroscience, and therefore advocated a new research discipline termed neuroergnomics.[17]

In this paper, to consider a possible neural network model of SAD, empirical evidence from the existing SAD-related neuroscience literature is reviewed, followed by a discussion regarding the implications of the proposed SAD model and future research directions toward realizing countermeasure technologies against absent-minded driving from a neuroergonomic perspective.

2. Neuroscience of SAD

2. 1 Maladaptive Brain Activity Preceding Errors

SAD is often coincident with behavioral error. Therefore, maladaptive changes in brain activity preceding error responses in goal-directed tasks might be informative with respect to the neural basis of SAD.

From this perspective, Weissman et al.[18] conducted a pioneering fMRI study in which participants performed a cognitively-demanding task (local/global selective-attention task; **Fig. 1**(a)). Consequently, reduced activity preceding error responses was found in the right inferior frontal gyrus (IFG) and anterior cingulate cortex (ACC) (**Fig. 2**). Error responses were also characterized by reduced deactivation in the precuneus and posterior cingulate cortex (PCC) (Fig. 2).

Following this study, Li et al.[19] performed a similar fMRI study using a different cognitive task (stop signal task; Fig. 1(b)). They found greater activity preceding error responses in medial brain regions, including the PCC and medial PFC (Fig. 2); these results were replicated by Christoff et al.[20] Moreover, Eichele et al.[21] performed independent component analysis on fMRI data during another cognitively-demanding task (Eriksen flanker task; Fig. 1(c)). They concluded that reduced activity in the presupplementary motor area (pre-SMA) and right IFG, and increased activity in the PCC, could be a precursor of error responses (Fig. 2).

The majority of previous studies consistently found that error responses in cognitively-demanding tasks are preceded by reduced activity in the right IFG. The right IFG is well known to be important in reactive response inhibition, which is the reactive cancellation

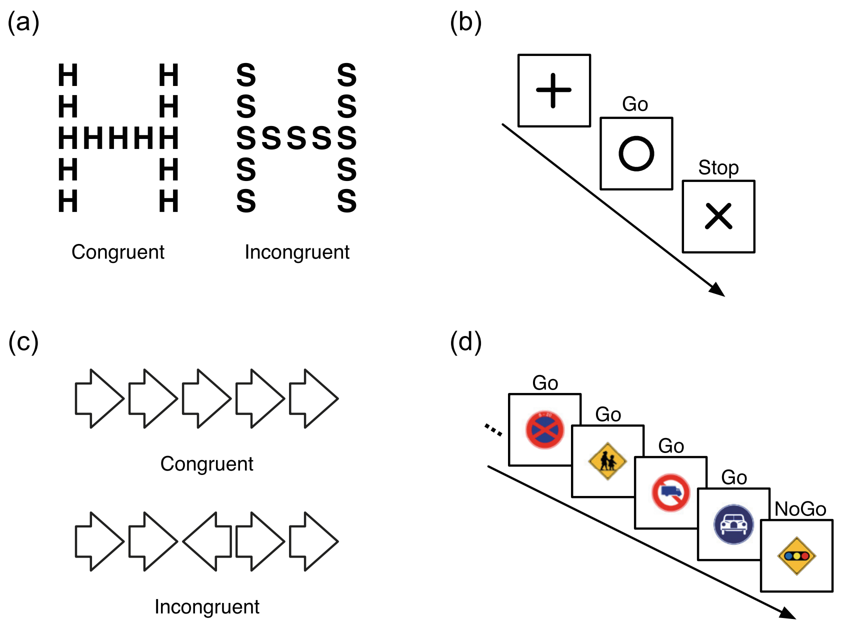

Fig. 1 Cognitive tasks used to explore the neural correlates of spontaneous attentional decoupling. In a local/global selective-attention task (a), the Navon figures (many small letters arranged to form a larger letter) are employed as a visual stimulus. Participants are instructed to focus on a local or global level before stimulus presentation and state the corresponding letter as quickly and accurately as possible. In a stop signal task (b), participants are asked to quickly respond to a visual stimulus (circle), but also to stop the response when a subsequent stimulus (x-mark) is presented. In the Eriksen flanker task (c), participants state the direction of a target arrowhead presented in the center while ignoring flanker arrowheads. In the sustained attention to response task (d), participants quickly respond to successively presented visual stimuli (Go) and to withhold responses to a predetermined specific stimulus (NoGo).

of inappropriate prepotent or habitual actions.[22,23] Other regions showing reduced activity preceding error responses, i.e., the ACC and pre-SMA, are also considered to be associated with reactive response inhibition.[24-27] Therefore, reduced activity preceding error responses in these frontal control regions is most likely associated with impaired reactive inhibition of inappropriate actions for performing tasks. Moreover, previous studies have also reported finding increased activity in additional medial regions, including the PCC and medial PFC. Interestingly, these medial regions are considered to constitute the default mode network (DMN), a group of areas characterized by decreased activity during demanding tasks and increased activity during rest.[28,29]

2. 2 Brain Activity Associated with Automatic Behavior

In SAD, people do not completely stop doing the task at hand, but rather appear to continue doing it in an automatic (careless) manner, as typified by mindless reading and absent-minded driving. Therefore, SAD can be operationally characterized not only as behavioral error, but also as automatic behavior.

To identify the neural correlates of harmful automatic responding, we conducted an fMRI study to examine brain activity during a sustained attention to response task (SART; Fig. 1(d)).[30] The SART is a cognitively-demanding task originally developed to assess the vulnerability of sustained attention.[31,32] In the SART, participants are asked to quickly respond to successively presented visual stimuli (Go response), and to withhold responses to a specific predetermined stimulus (NoGo response). Previous studies using the SART have demonstrated that patient populations with difficulty in sustained attention exhibit more NoGo commission errors than normal controls.[33,34] More importantly, it is also evident that Go responses followed by NoGo error responses tend to be faster than those followed by NoGo correct responses.[31,32,35] This suggests that faster Go responses represent an absent-minded state without proactive preparation to a NoGo response. Therefore, Go reaction time in the SART can be used as a marker of harmful automatic responding.

We thus explored brain regions in which activity was correlated with Go reaction time. Positive correlations were found in the right dorsolateral PFC and bilateral IPS, and negative correlations were found in the PCC and medial PFC (Fig. 2). For comparison with a previous study that investigated maladaptive brain activity preceding error responses, we further examined brain activity changes associated with NoGo commission errors in the SART. Interestingly, the medial regions (PCC and medial PFC) showed reduced activity preceding errors compared with correct responses; however, no changes in activity were observed in the frontoparietal regions (right dorsolateral PFC and bilateral IPS).

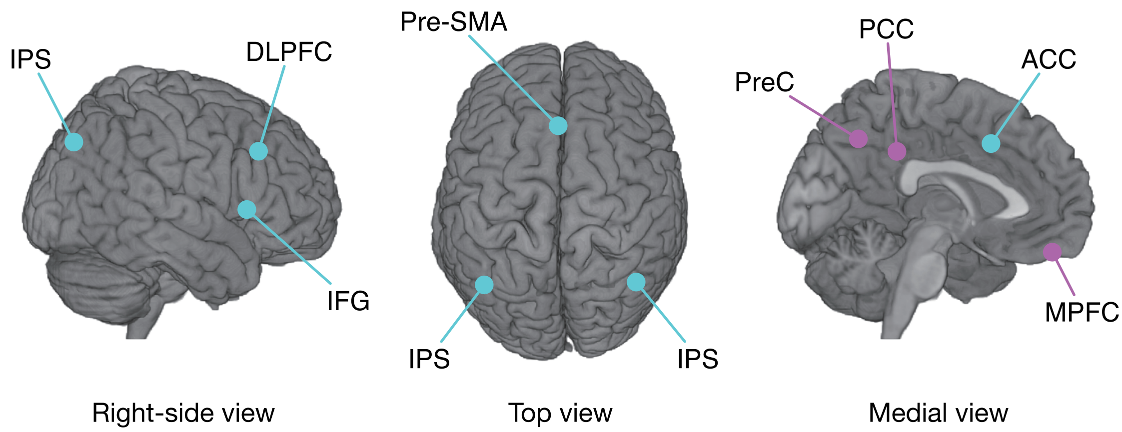

Fig. 2 Brain regions potentially associated with spontaneous attentional decoupling (SAD). Cyan arrows indicate brain regions in which activity would be reduced during SAD; in contrast, magenta arrows indicate brain regions in which activity would be increased during SAD. DLPFC = dorsolateral prefrontal cortex, IFG = inferior frontal gyrus, Pre-SMA = presupplementary motor area, IPS = intraparietal sulcus, PreC = precuneus, PCC = posterior cingulate cortex, ACC = anterior cingulate cortex, MPFC = medial prefrontal cortex.

Our study revealed associations between spontaneously reduced activity in the right dorsolateral PFC and bilateral IPS and the emergence of harmful automatic responding in the SART. This suggests that the right dorsolateral PFC and bilateral IPS are involved in proactive preparation for rare events. In previous studies, these frontoparietal regions were considered to comprise a neural circuit that controls visual attention.[13,14] It can therefore be speculated that the neural circuit of proactive preparation largely overlaps with that of visual attention control, or, more simply, that sustained attention to visual stimuli is a prerequisite for proactive preparation. Meanwhile, no changes in activity were seen in the frontoparietal regions preceding error responses. This suggests that spontaneously reduced activity in the frontoparietal regions is associated with impaired proactive processes, represented by shortened reaction times, but not with impaired reactive processes, represented by commission errors. Thus, the reduced activity in frontal control regions preceding error responses seen in this study is compatible with the results from previous studies.

Our study also revealed associations between the emergence of harmful automatic responding in the SART and spontaneously increased activity in the PCC and medial PFC. Increased activity in these regions was also observed preceding commission errors, which is in line with previous studies examining maladaptive activity changes preceding error responses. These results suggest that, in contrast to reduced activity in the frontoparietal regions, increased activity within the DMN is associated with SAD-induced behavior in a general rather than specific manner. This may be explained by the occurrence of mind-wandering accompanied by SAD. An abundance of evidence has been generated to link activity within the DMN to stimulus-independent/task-irrelevant thoughts.[20,36-39] Thus, increased activity within the DMN may be associated with mind-wandering during task performance.

3. Neural Network Model of SAD

As described above, fragmentary evidence regarding neural correlates of SAD-induced behavior has been accumulated. In combination with such fragmentary evidence, it is therefore tempting to speculate about a neural mechanism underlying SAD.

A schematic diagram of the neural network model of SAD proposed in this study is shown in **Fig. 3**. Even during resting periods with no task demands, the living brain is never silent; several brain regions belonging to the DMN are dominantly active, although the functional significance of this activity remains unknown. When people start to perform a cognitively-demanding task such as driving, specific brain regions for goal achievement are systematically engaged and form a task-positive network (TPN), whereas DMN activity is reciprocally suppressed. Within the TPN, the sustained activation of neural circuits critical for reactive and proactive control of behavior may be key for stable task performance. The relative dominance of the TPN, however, is vulnerable, particularly in monotonous situations, because there is an intrinsic driven force for getting a task-positive brain activation pattern back to the relative dominance of the DMN. In turn, this spontaneous transition from the TPN to the DMN during task performance results in decoupling attention from external environments, sometimes with inappropriate behavior and/or mind-wandering.

4. Implications for Road Safety

In this review, empirical evidence related to SAD from the field of neuroscience was reviewed, and a state-of-the-art neural network model of SAD was proposed. Implications of this SAD model for road safety is discussed below.

One of the most direct applications of the neural-level understanding of SAD is the monitoring of a driver's brain activity to detect risky absent-minded driving. Functional near-infrared spectroscopy (fNIRS) is a noninvasive neuroimaging technique that may be suitable for this purpose, mainly due to its high portability. Because fNIRS can measure brain activity in the lateral as opposed to ventral surface of both cerebral hemispheres, it might therefore be able to be used to detect reduced activity in, for example, the right PFC, while driving. Several recent studies have already demonstrated that fNIRS is capable of measuring PFC activity while driving;[40-42] however, technical limitations must be kept in mind when applying fNIRS to actual driving environments. One possible limitation is the influence of ambient sunlight, which contains a substantial amount of near-infrared radiation, while driving; this could compromise fNIRS

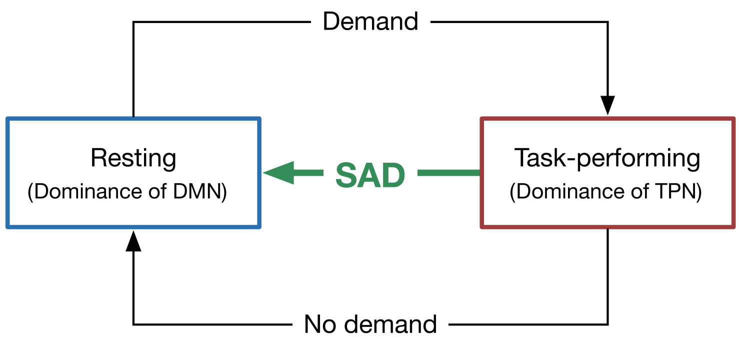

Fig. 3 Schematic diagram of the proposed neural network model of spontaneous attentional decoupling (SAD). Even in a resting state, the brain is never idle; regions belonging to the default mode network (DMN) are dominantly active. When people start to perform a cognitively-demanding task such as driving, the task-positive network (TPN) and the DMN alternate in dominance. However, the relative dominance of the TPN is vulnerable, particularly in monotonous situations, because there is an intrinsic driving force for getting a task-positive brain activation pattern back to the relative dominance of the DMN. This spontaneous transition from the TPN to the DMN during task performance causes decoupling attention from external environments.

signals. Another limitation is the motion of the vehicle, which involves changes in acceleration. fNIRS signals at the forehead have been shown to be greatly affected by skin blood flow.[43] Due to the law of inertia, as well as the driver's posture changes, vehicle motion could lead to changes in skin blood flow in the forehead.

Electroencephalography (EEG) can also be used to detect SAD-related brain activity. Asada et al.[44] reported that the source of theta-band EEG signals (4 to 8 Hz) is localized at the medial regions of the PFC. Moreover, Scheeringa et al.[45] have shown that spontaneous fluctuations of theta-band power in the medial frontal region correlate negatively with DMN activity measured using fMRI. These results suggest that decreased frontal midline theta activity can be an indicator of SAD while driving. In fact, recently developed commercial devices such as the Emotive EPOC headset (www.emotiv.com) enable highly-flexible, low-cost, portable EEG recording. Nevertheless, applying EEG to actual driving environments does have some limitations. In general, signals measured using EEG electrodes are contaminated by noise and various kinds of artifacts. Electronic devices in vehicles, for instance, can be a source of EEG noise, and the blinking and eye movements of drivers produce large artifact potentials that compromise EEG recording.

Noninvasive brain stimulation could be used to prevent risky absent-minded driving. More specifically, our fMRI study[30] indicates a possibility that sustained activation of the frontoparietal network associated with proactive action control is essential for preventing absent-minded driving; this might be actualized by applying noninvasive brain stimulation to drivers. A few studies have already employed brain stimulation techniques for modulating driving behavior in simulated environments. Beeli et al.[46] published the first study in this line of research. They showed that excitation (upregulation) of the dorsolateral PFC through the application of tDCS leads to a marked tendency to avoid risky driving, i.e., longer inter-vehicle distance and a reduced number of speeding events. More recently, we have further investigated the effect of tDCS over the dorsolateral PFC on driving behaviors.[47] Our results showed that upregulation of the right dorsolateral PFC accompanied by downregulation of the left dorsolateral PFC improves fundamental vehicle control abilities such as car-following and lane-keeping performance. Since lane-keeping performance is well known to be susceptible to drivers' attentional states,[48-50] it can be said that our tDCS study indirectly supports the possibility of tDCS as a tool for preventing absent-minded driving.

Furthermore, the neural-level understanding of SAD is expected to facilitate experimental studies of absent-minded driving. The principle factor responsible for the difficulties encountered in conducting experiments to investigate absent-minded driving is the inability to operationally control the participants' attentional states. The only viable method is to rely on the participants' retrospective reports regarding their own attentional states. For example, He et al.[51] examined gaze behavior during simulated driving shortly before a thought probe in which participants reported whether their attention had been oriented to external or internal events (i.e., attentive driving vs. mind-wandering). Results showed that the participants exhibited less gaze dwell time on side mirrors before mind-wandering than before attentive driving. In contrast, according to the proposed neural network model of SAD, a situation without any rigorous demand for driving in which the DMN is assumed to be dominantly active can be employed as an experimental condition corresponding to absent-minded driving. Under this assumption, our behavioral study[52] revealed that drivers' gaze allocation is biased more to salient loci in traffic scenes during passive viewing (no demand) conditions compared with active inspection (demand for driving) conditions. This suggests that the gaze allocation of drivers is a potential predictor of risky absent-minded driving.

5. Future Research Directions

Absent-minded driving has long been a problem in transportation research. Recently, the significance of this problem is expected to increase because drivers in newly manufactured automated cars are predicted to experience absent-minded events more frequently. Therefore, in this paper, empirical evidence in the existing neuroscience literature relating to SAD was reviewed, and its implications for road safety were discussed. In the final section, future research directions toward realizing countermeasure technologies against absent-minded driving from a neuroergonomics perspective are addressed.

As several reports have shown,[40-42] one possible future research direction is to produce reliable detection systems for risky absent-minded driving by monitoring the brain activity of drivers. To realize such systems, the development of accurate, robust, and, if possible, non-contact measurement devices for brain activity is necessary. Along these lines, an alternative approach is to explore substitutional (behavioral) indicators that reflect specific brain activation patterns associated with SAD. For example, gaze allocation is a promising candidate as a biological marker of absent-minded driving.[51,52]

Another possible future research direction is the development of risky absent-minded driving prevention technologies. As demonstrated in our tDCS study,[47] noninvasive brain stimulation could be a viable option. However, the application of noninvasive brain stimulation to actual work environments has only just begun, and is still in an exploratory phase in terms of not only technical maturity, but also social acceptability for neural enhancement. Further fundamental research in laboratory settings is needed. Pharmacological intervention is another possible option, as drugs for combatting motion sickness are already accepted worldwide. Consuming caffeine drinks to combat drowsiness while driving is also a type of pharmacological intervention. To this end, it is important to consider the molecular basis of absent-minded driving.

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