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Master Thesis

用眼動馬可夫模型與事件相關電位分析思緒漫遊和專注

Mind-wandering revealed by eye movement hidden Markov model and ERPs

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本論文係陳子翎君（學號 R06454014）在國立臺灣大學腦與心智科學研究所完成之碩士學位論文，於民國 110 年 1 月 14 日承下列考試委員審查通過及口試及格，特此證明

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摘要

隨著現代科技和社群媒體的蓬勃發展，人們身處於一個分心時代，越來越難以專注在當前重要的工作上。當我們把注意力轉移到與作業無關的思緒上，這樣的現象又稱為思緒漫遊，它與作業表現之間有顯著的負向關聯，因此探討思緒漫遊是重要的議題。先前的研究已指出專注和思緒漫遊兩種不同注意力狀態下，有不同的眼動行為，然而目前仍不清楚是否能藉由眼動行為區分不同的注意力狀態。本研究因此想探討是否能透過眼動模式，將人們分成傾向專注和傾向思緒漫遊。在此研究中，受試者會執行持續性注意力作業同時也記錄事件相關電位。持續性注意力作業共有 40 個回合，每個回合有 25 個嘗試次數，其中包含一個需要停下的目標刺激和 24 個需要按鍵反應的非目標刺激。每個回結束時會請受試者自評當下的注意力狀態。本研究利用眼動馬可夫模型將受試者區分成兩種不同的眼動模式：集中型和分散型，並且比較不同眼動模式下的行為表現與事件相關電位。研究以目標刺激出現的行為表現為基準，將目標刺激出現之前的 10 秒作為客觀量測思緒漫遊的時間窗。結果顯示與使用分散型眼動模式的受試者相比，使用集中型眼動模式的受試者有較好的作業表現。同時當受試者錯誤反應目標刺激的當下，量測到 P3 振幅減少以及 N2 振幅變大，另外非目標刺激的 P3 振幅也是減少的。研究也以自評問題的回答為基準，將自評問題出現之前的 10 秒作為主觀量測思緒漫遊的時間窗。結果顯示使用集中型眼動模式的受試者傾向回答專注的比例較高，然而沒有發現回答專注和思緒漫遊之間的非目標刺激 P3 振幅的顯著差別。這些結果表明，專注和思緒漫遊之間存在特定的眼動模式，P3 振幅的減少表明思緒漫遊時降低對作業的認知處理。 本研究揭示眼動和注意力之間的關聯，強調眼動可以區辨不同的專注狀態，也開啟眼動馬可夫模型於視覺注意力研究的新視野。

關鍵字：思緒漫遊、注意力、眼動模式、眼動馬可夫模型

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Abstract

With the development of modern technology and social media, we live in a distracted era that makes us more difficult than ever before to concentrate on the current goal and thus important tasks at hand. It has become imperative to identify mind-wandering, a phenomenon that people sometimes think about things unrelated to the current task, which can potentially cause considerable negative effects on task performance. Since eye movements have been shown to reveal different characteristic between focused attention and mind-wandering, we examined whether eye movement patterns can categorize different groups of people by how prone they are to mind-wandering. Participants performed the sustained attention to response task (SART) with their eye movements and ERPs recorded. The SART comprised 25 trials (one No-go target and 24 go trials) per block and 40 blocks in total. At the end of each block, participants were asked to subjectively rate their state of attention. By applying the eye movement hidden Markov model (EMHMM) to analyze the eye movement data, we differentiated people with two eye movement patterns: centralized vs. distributed pattern. We analyzed the 10-s pre-target time window, which served as an objective measure of mind-wandering based on their performance on the No-go target. Results showed that participants with a centralized-viewing pattern had higher d' than those with a distributed-viewing pattern. Also, the incorrect response to the No-go target were associated with decreased P3 and greater N2. P3 amplitudes for go trials was also reduced prior to the incorrect response to No-go target. The 10-s pre-probe time window was also analyzed, which served as a subjective measure of mind-wandering based on their report on the probe. Participants with a centralized-viewing pattern tended to rate themselves as more focused relative to

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those with a distributed-viewing pattern. However, no difference on P3 for go trials prior to rating the state of focus was found. These results suggest that there are specific eye movement patterns differentiating focused attention and mind-wandering, and P3 amplitude reduction suggests reduced processing of the task during mind wandering. By linking the relationship between eye movements and attention, this study highlights that states of attention can be revealed by eye movements and also provides new insight in utilizing EMHMM to study visual attention.

Keyword(s): mind wandering, attention, eye movement pattern, EMHMM

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Introduction

Mind wandering, a phenomenon refers to the spontaneous shift of one's attention from the current task to task-unrelated thoughts, is a universal experience in our daily thinking time (Smallwood & Schooler, 2006). In a survey over 5000 people, it was estimated that American adults spent 47% of time wandering their mind. Indeed, we live in a distracted era that modern technology and social media have become a pervasive part of our lives, which keep distracting our mind so that people have become more difficult to concentrate on current goal and important tasks. Although mind wandering also benefits creativity, imagination, and plan (Mooneyham & Schooler, 2013; Ottaviani & Couyoumdjian, 2013), it has an emotional cost that a wandering mind is not necessarily a happy mind (Killingsworth & Gilbert, 2010).

Numerous studies have found that mind wandering during a task is negatively correlated with task performance. For example, cellphone notifications disrupted performance during an attention demanding task, even when participants did not check their phone to receive notifications. This suggests that attentional cost of receiving notifications induced task-unrelated thoughts so as to drop the performance by interrupting with the task at hand (Stothart, 2015). Other studies have shown that mind-wandering is negatively correlated with text comprehension (Feng et al., 2013; Schooler et al., 2011) and driving (He et al., 2011).

Thought sampling is a standard measure for mind wandering in which thought probes were inserted into the task to obtain subjective reports of mind wandering (Smallwood & Schooler, 2015). In addition to such a thought sampling measure approach to catch intrinsic thoughts, behavioral markers commonly used with manual responses of

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the cognitive demanding task were also used. In this study, we adopted the Sustained Attention to Response Task (SART hereafter) to measure mind wandering. SART is a go/no-go task requiring participants to withhold response to the target which has a low probability of occurrence. Participants are required to press a button (i.e., the Go trials) as soon as any letter other than C is shown and withhold their response (i.e., the *No-go* trials) when the target (the letter C) is presented. The measures of manual responses to the SART include: reaction time (RT), reaction time variability, sensitivity toward target (d'), and omission error of the go stimulus. These measures at the interval preceding response to the No-go target and other go stimuli are used as an objective measure of mind wandering (Robertson, 1997; Smallwood, 2008). We also inserted a probe question like the thought sampling method to ask participants what they had in mind when the probe appeared. The answers to the probe question and the rating scale about their attention state (focused attention or mind wandering, from 1 to 7) are used as the subjective measure.

In addition to using SART as the manipulation and measure of mind wandering, we also used physiological markers such as ERPs and eye movements to provide the validity for subjective reports and for further cognitive analysis, since these are shown to be able to differentiate the state of mind wandering. For example, an electroencephalography (EEG) study demonstrates that mind wandering is associated with increased theta and delta power and decreased alpha and beta power (Braboszcz & Delorme, 2011). Moreover, eye-tracking studies have shown that mind wandering leads to longer fixations and less sensitivity to word frequency (Foulsham et al., 2013).

Previous studies suggest that saccade target selection and visual attention are strictly coupled, both temporally and spatially (Deubel & Schneider, 1996). A variety of studies found eye behaviors differ between focused attention and mind wandering such as

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increased allocation of fixations and longer durations prior to reporting mind wandering on the scene viewing task (Ceh et al., 2020; Franklin et al., 2013; He et al., 2011; Krasich et al., 2018; Uzzaman & Joordens, 2011; Zhang et al., 2020). The pupillary response could be used to distinguish between attentional and mind wandering states (Unsworth & Robison, 2016). Eye behavior parameters such as eyeblink, saccade, fixation position, fixation duration, and pupil diameter are sensitive to focused attention. Among these parameters, fixations provide good spatial and temporal information and constitute eye movement pattern. Take the example of face recognition, some people prefer fixating on the face features (e.g., the eyes, the nose, and the mouth, an analytic pattern), whereas others prefer viewing around those features (i.e., a holistic pattern). The temporal information of eye movements could predict either correct or incorrect face recognitions: It is more likely to switch between different regions of interest in correct trials than in incorrect trials (Chuk et al., 2014).

The aim of the current study was to investigate whether we can differentiate two kinds of eye movement patterns (attentive vs. mind wandering) based on the transitions of fixations when participants were conducting the SART. For this purpose, we used the eye movement hidden Markov model (EMHMM) to analyze eye movement data. In addition, we also measured event-related potentials (ERPs). Mind wandering can be considered a decoupling of attention from an external task (Smallwood & Schooler, 2006). We expect to find decreased cortical processing of external information such as the amplitude of a positive event-related potentials (ERPs), known as the P3 component. Indeed, P3 has been shown smaller when participants are off task (Smallwood & Schooler, 2015). N2 is also observed in go/no-go task which requires inhibition response and decreased before the No-go error.

We examined whether there were different ERP amplitudes (i.e., N2 and P3)

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underling the two distinct eye movement patterns for the following reasons. First, P3 amplitude is measured within a 300-600ms time window, which indexes updating of the representation of the previous event in working memory or the amount of attentional resources engaged during dual-task performances (Polich, 2007). Reduced P3 was also observed prior to mind wandering versus on-task reports (Kam et al., 2012; Smallwood, 2008). Second, N2 amplitude is measured within a 250-450 ms time window, which is significantly larger for the No-go trials compared to the go trials and also larger for the No-go correct trials compared to the No-go incorrect trials. The no-go N2 is interpreted as an index of motor inhibition which is located at the pre-motor level in the go/ no-go task such as the SART, and a large N2 is followed by a large late positive wave P**3** reflects the contribution of endogenous sustained attention (Falkenstein et al., 1999).

We hypothesized that eye movement pattern can differentiate people with focused attention or mind wandering when they conducted the SART. Mind wandering measured with response at target (i.e., objective measure of mind wandering) and subjective report (i.e., subjective measure of mind wandering) can be revealed by eye movement patterns respectively. By using EMHMM, we expected that there were distinctive eye movement patterns representing attentional state for either focused attention or mind wandering. Based on the two distinct eye movement patterns we would see whether there are differences between the two groups of participants with different manual response (i.e., d', RT, RTCV), eye behaviors (i.e., fixation dispersion, fixation duration, and pupil size), and ERPs during objective measure (10 secs before target onset). Moreover, we expected people with the two distinct eye movement patterns would have different subjective reports (i.e., self-report focused attention or mind wandering), manual response, eye behaviors, and ERPs during subjective measure (10 secs before the probe question).

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Methods

Participants

Forty-one healthy adults completed this study (M_{age}= 22.61 years, SD= 2.62 years, female= 18). Participants were recruited through posted sign-up sheet in the internet. They were free from psychological or neurological disorders based on self-report. All of them had normal or corrected to normal vision and without wearing contact lenses during the experiment. Participants all received informed consent and this study was conducted according to the guideline of the Research Ethic Committee at National Taiwan University. Ten participants were excluded due to more than 50% rejected trials. Therefore, we performed data analysis on 31 participants. Sample size was examined using G-Power 3.1.9.6 software (Faul et al., 2009), with the level of significance set at $P < .05$ and power $(1- \beta) = 0.8$ to detect a medium effect size. Based on these calculations, a minimum of 13 participants was required for either distributed HMMs or centralized HMMs to obtain sufficient power to observe differences between distributed pattern and centralized pattern.

Materials

Stimuli and Design. We employed the sustained attention to response task (SART), which was first proposed by Robertson (1997) and we adopted the version that was adopted from Hu et al. (2012). In this modified SART, 25 English letters (26 English letters except the letter Z) were presented sequentially at the center of the screen, with a low frequency (4%) of the target letter (i.e., letter C). In each trial, a letter was presented for 2 sec or until the participants gave a response. Each block was embedded with 25

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English letters with one target letter which would be presented pseudo-randomly at one of the trials among the 6th to 15th trial in a block. There were totally 40 blocks.

Thought probes were inserted into the end of a block to obtain subjective reports of mind wandering. The probe asked participants the question: “What was in your mind just now?”. Five options were listed below the question for participants to choose from: 1. Focused on the task; 2. Thinking of task performance; 3. Distracted by task-unrelated stimuli; 4. Thinking of things not related to the task; 5. Blank mind. After choosing the thought contents, there was another question asking participants “How focused were you?” and the participants needed to rate their current state of focus from 1 (completely wandering) to 7 (very focused) regarding the moment before seeing the previous probe (Figure 1). To avoid possible response bias, participants were told to respond honestly and that there was no absolutely correct answer regarding the probe and the subjective rating. Stimuli were shown in black against a gray background, and presented using the program E-prime (Psychology Software Tools, Pittsburgh, PA, USA).

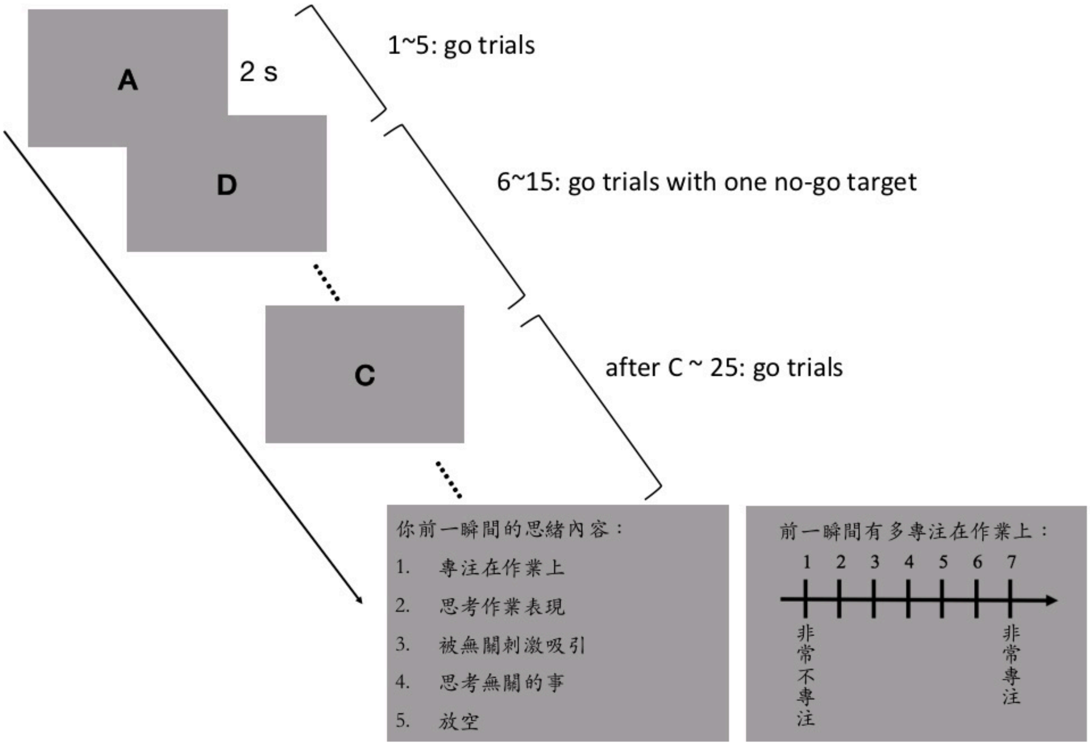

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Figure 1. Experimental paradigm of SART.

Experimental paradigm of SART embedded with experience sampling probes. The probe question was: “What was in your mind just now?”. Five options consisted of the following: 1. Focused on the task; 2. Thinking of task performance; 3. Distracted by task-unrelated stimuli; 4. Thinking of things not related to the task; 5. Blank mind. The current state of focus question was: “How focused were you?” from 1 (completely wandering) to 7 (very focused).

Apparatus. Eye movements data were recorded by Tobii Pro Glasses 2 with Tobii SDK program sampled at 100 Hz. Before the recording session started, participants were instructed to fixate on a supplied bullseye calibration target held at a distance of 1 meter. Once the calibration was successful, no further calibration was required given that Tobii Pro Glasses 2 has a high tolerance to motor movements, which allow participants to conduct the experiment without having to constrain their head movements on a chin-rest. EEG data was recorded with 32-channel Quick-cap sintered Ag/AgCl electrodes placed according to the 10-20 system. All scalp electrodes were referenced to left mastoid (M1), and re-referenced off-line to the average of left mastoid and right mastoid (M2). Vertical electrooculogram (V-EOG) were placed on approximately 2 cm above and below the left eye to monitor for vertical eye movement and blinks. Horizontal electrooculogram (H-EOG) were placed on 2 cm away from left and right eye respectively to monitor for horizontal eye movement. The impedances of all electrodes were kept under 5 kΩ to ensure good quality of data. EEG and EOG signals were amplified by the SynAmps using a 0.05–100 Hz bandpass and continuously sampled at 1000 Hz per channel for offline analysis.

The physiological signals (i.e., blood volume pulse (BVP), galvanic skin response

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(GSR), skin temperature, and respiration) were recorded via Thought Technologies ProComp Infiniti bio sensor system sampled at 256 Hz. BVP sensor was recorded from the left index finger, GSR was recorded from left middle and ring finger, and skin temperature was recorded from left little finger. Also, respiration (rate) was recorded from the belt fastened on participants' abdominal regions without having them feel restricted or under pressure. These physiological signals will be reported in another study and will not be further mentioned here.

Before the experiment started, the experimenter disinfected participants' left hand with alcohol to ensure that signal quality was not contaminated. The eye movements, electroencephalogram (EEG), and physiological signals were synchronized with E-prime triggers by the DB-25 connector.

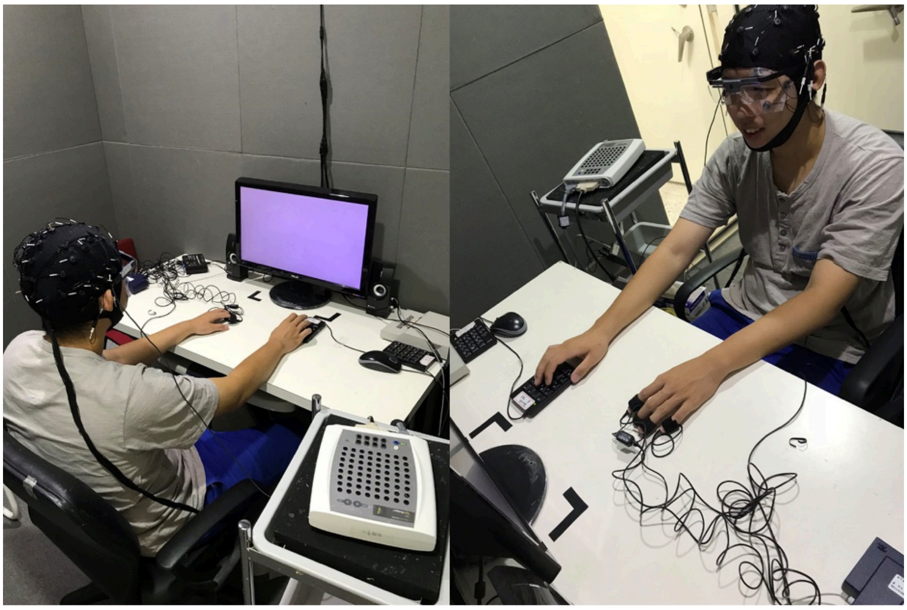

Figure 2. The setup of the experiment.

Participants sat in front of the monitor wearing Tobii Pro Glasses 2, EEG recording cap and ProComp Infiniti bio sensor. Participants used their right hand to give responses.

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Procedure

The experiment was conducted in a sound-attenuated room. Participants were seated with their eyes approximately 80 cm away from the monitor. Their left hand was disinfected with alcohol by the experimenters and equipped with the sensors as well as the EEG cap on their head. After ensuring the impedance of all electrodes were under 5 kΩ, participants were instructed to do the one-point calibration for the Tobii Pro Glasses 2. Then, resting-state signals were recorded respectively with close-eye and open-eye for 3 minutes each session. Before the formal experiment started, participants were given a detailed description of thought probes and task contents. The main experiment was preceded by three blocks of practice trials.

During the main task, participants were instructed to press number 9 with their right hand to initiate a block. Also, they were instructed to press number 8 on the keyboard with their right hand as quickly as possible when they saw an English letter on the screen but to withhold their response when they saw the target letter C. We recorded close-eye resting-state signals and open-eye resting-state signals recording at the end of the experiment. The whole experiment took around 1.5 to 2 hours to complete.

Data processing and analysis

We separated the analyses in two parts: objective measure and subjective measure of mind wandering. In terms of objective measure, the 10-s pre-target intervals preceding the target (a No-go response was required) was categorized according to the participant's response as either a correct withhold (without key press) or a commission error (with a key press). In terms of subjective measure, the 10-s pre-probe intervals was categorized according to the participant's response as focused attention or mind wandering. Focused

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attention was defined as giving the thought content: 1. Focused on the task; 2. Thinking of task performance; 5. Blank mind and rating state of focus 5-7 on the 7-point scale. Mind wandering was defined as giving the thought content: 3. Distracted by task-unrelated stimuli; 4. Thinking of things not related to the task; 5. Blank mind and rating state of focus 1-3 on the 7-point scale. Blank mind was defined as a neutral state; it can be either focused attention or mind wandering. 7-point scale that were responded to 4 were excluded from analysis.

Eye behavior and movements data. We used Tobii pro lab to obtain eye behavior data (i.e., fixation position, fixation duration, and pupil diameter) and R for further processing. Fixations with duration above 3 standard deviation of the individual mean were eliminated. For calculation of pupil baseline and dilation, the data were down sampled to 50Hz and averaged across both eyes. Pupil baseline were calculated as the average pupil diameter in the 500ms pre-stimulus. Pupil dilation were computed by subtracting from pupil baseline and averaged 10-s before both objective and subjective measures across over blocks.

Eye movements were analyzed by a program called Eye Movement Hidden Markov Model (EMHMM), with a toolbox available online at http://visal.cs.cityu.edu.hk/research/emhmm/. The time windows of modeling data were taken from the 10-s pre-target intervals and 10-s pre-probe intervals respectively for objective and subjective measure of mind wandering. The EMHMM method is a data-driven machine-learning approach that accounts for individual differences in both spatial (i.e., fixation location) and temporal dimensions (i.e., transitions among fixation locations) of eye movements (Chuk et al., 2014). A hidden Markov model (HMM) is composed of numbers of hidden states (i.e., region of interest) and observed data (i.e., the current

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fixation). The model assumes that the region of interest (ROI) of the current fixation is determined by the previous ROI. The association among the current fixations and ROIs are summarized using transition probability in a transition matrix. The prior value for an ROI indicated the probability that the first fixation began within the region. The HMM parameters, including the Gaussian emission densities, the transition matrix, and the vector of priors were estimated by a variational Baysian approach. According to this approach, given the model parameter Ks then the best model with highest log-likelihood (LL) is selected to determine the optimal number of ROIs for each participant. Therefore, there is no need to predefine temporal segments or spatial ROIs.

We performed clustering EMHMM and produced a representative HMM model for each subgroup to reveal whether certain patterns of eye movements are associated with mind wandering. In order to examine the correlation between eye movement patterns and cognitive measures, we quantify the degree of similarity of individual HMMs to the representative HMMs. The mean-log-likelihood (MLL) of participants' eye movements data was being generated by the representative distributed pattern and centralized pattern HMM. The difference of distributed pattern and centralized pattern MLL divided by the sum of the two MLL:

$$\frac{\mathrm{D}\ \ MLL \quad - C\ \ MLL}{|D \quad MLL| + |C\ \ MLL|}$$

D indicates distributed pattern and C indicates centralized pattern. The more positive value represents a pattern that is more similar to distributed HMM, and vice versa for centralized HMM (Chan et al., 2018).

ERPs data. The ERPs data were processed under Matlab using the EEGLAB toolbox with plug-in ERPLAB (Delorme & Makeig, 2004). Continuous EEG data was

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applied low-pass filter at 30 Hz cutoff, re-referenced to the average of left mastoid and right mastoid (M2). Then we segmented the EEG data into 10-s pre-target epochs by two stimulus categories (i.e., correct withheld vs. commission error), time-locked to stimulus-onset and was aligned to a 200 ms pre-stimulus baseline. The epochs data applied the independent component analysis and artifacts rejection to remove eye blinks, eye movements, and other muscle activities. We only excluded participants who had more than 50% artifact-free epochs. Finally, we included 31 participants in further EMHMM and ERPs analysis. We used mean amplitude which is an average amplitude over a time window to compute ERPs amplitude. We measured P3 amplitude within a 300-600ms time window and N2 amplitude within a 250-450ms time window. The No-go errors in the SART can be used to index periods of attentional disengagement from the task(Seli, 2016); therefore, the N2 amplitude was examined on the No-go trials in the period of objective measure. The P3 amplitude of No-go trials and go trials are typically maximal at the parietal-central midline electrode, whereas the N2 amplitude of No-go trials is typically maximal at the frontal and frontal-central midline. The statistical analysis of the ERPs data thus were restricted to the electrodes at frontal (Fz) and parietal (Pz).

Behavioral and eye behavior data. For manual response data (i.e., d', hit rate, RT, and RTCV) and eye behavior data (i.e., fixation dispersion, fixation duration, and pupil baseline), we used the lme4 package in R (Bates, 2007) to conduct a mixed-effect model to model the data averaged across go trials during the 10-s intervals before the No-go target. For the objective measure of mind wandering, condition (i.e., correct or error to the target) interacts with clustered eye movements patterns as the fixed effects and participants are a random effect. The same procedure was conducted on the 10-s before probe intervals for the subjective measure of mind wandering. Approximation of p values

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came from the lmerTest package.

Our data is stored in the MM-SART database and can be accessed through the provided link (http://mmsart.ee.ntu.edu.tw/NTU_SART/download.html) (Chen et al., 2020).

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Results

Eye movement data during the 10-s pre-target period

Participants' 10-s pre-target intervals individual HMM were modeled by EMHMM. First, we trained individual HMM with the number of hidden states (K) ranging from 3 to 6 separately. We then selected the HMM within this set with the highest model log-likelihood and determined the number of ROIs for both individual and clustered HMM. The representative HMMs of the two groups are shown in Figure 3. One group consisted of 16 participants and the other one consisted of 15 participants. We termed them "distributed pattern" and "centralized pattern" respectively. Figure 3A indicates that the distributed pattern had similar prior transitional probabilities among the red ROI and the blue ROI. Sometimes participants would look at the red ROI first and still view the same region. They sometimes would look at the center (the blue ROI) and then look everywhere. Figure 3B indicates that participants of the centralized eye movement pattern had a high probability first to view the center (the red ROI), and then remained to view the same region. Sometimes they performed scan out of the stimuli (the green ROI) and probably made a transition to the center again.

Pairwise t test showed that the log-likelihood of participants with distributed pattern generated by the two representative HMMs were significantly different, $t(15) = 4.33$, $p < .001$. The same procedure was conducted on the participants with centralized pattern; pairwise t test was also significantly different, $t(14) = 7.63$, $p < .001$. The results suggest that the distributed and centralized HMMs represent two distinctive eye movement patterns.

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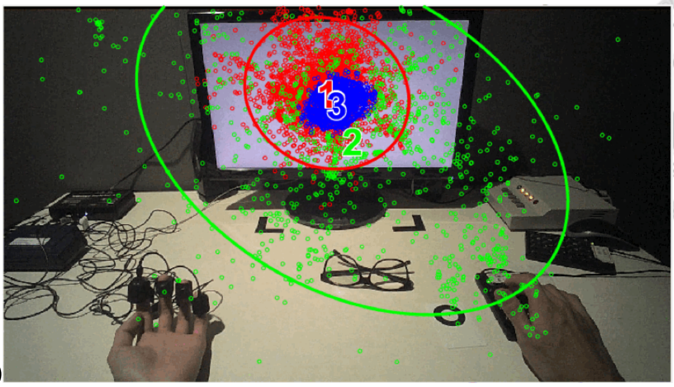
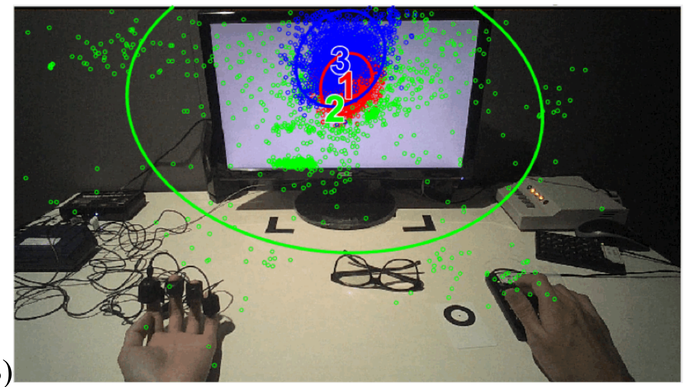
(A) 

Representative HMM of distributed pattern (N= 16)

Prior values	Red	Green	Blue
	.49	.06	.45
Transition probabilities	To Red	To Green	To Blue
From Red	.96	.04	.00
From Green	.11	.47	.41
From Blue	.00	.27	.73

(B) 

Representative HMM of centralized pattern (N= 15)

Prior values	Red	Green	Blue
	.66	.09	.25
Transition probabilities	To Red	To Green	To Blue
From Red	.88	.12	.00
From Green	.37	.57	.06
From Blue	.00	.04	.96

Figure 3. The two eye movement patterns.

(A) The one on top shows a distributed eye movement pattern and its transition metrics.

(B) The one on the bottom shows a centralized eye movement pattern and its transition metrics.

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Manual data during the 10-s pre-target period

Performance. We compared the task performances in the following aspect of those who had been classified as one of the two eye movement patterns using the correct response to the target (i.e., d'). Participants with centralized pattern made significantly more correct responses than those with distributed pattern (Table 1). This result suggested that participants moved their eyes with a centralized pattern during the 10-s pre-target period were beneficial for target detection. Furthermore, d' were negatively correlated with eye movement patterns scale, r = -.45, p = .01, suggesting that the lower the performance, the more distributed the eye movement pattern.

Table 1

Means for d'

	Mean（*SD*）		*df*	*t*	*p*
	Centralized pattern (N=15)	Distributed pattern (N=16)			
d'	3.70(0.50)	3.06(0.74)	29	-2.74	.01**

* p<.05 ** p< .01

Reaction time (RT). No significant difference was observed in reaction times between participants with the two types of eye movement patterns. However, participants were faster preceding No-go errors than No-go correct, β = 38.12, SE = 6.69, t = 5.70, p < .001. It was consistent with previous studies , which has shown an decreasing in RT when the response to the No-go target was incorrect (Hu et al., 2012; Robertson, 1997).

Reaction time coefficients of variation (RTCV). RTCV is defined as variation within the normal range of RT and can be estimated using the ratio of the RT standard deviation to the RT means. The difference was not significant between participants with

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centralized and distributed eye movement patterns, β = -.04, *SE* = .03, *t* = -1.19, *p* = .24. When the response to the No-go target was correct, RTCV also did not significantly differ from when the response was incorrect, β = -.01, *SE* = .02, *t* = -.55, *p* = .59.

Fixation dispersion. Fixation dispersion is a measure of the spread of fixations and can be computed as the root mean square of the Euclidean distance from each fixation to the average of all fixations. The difference was not significant between the two eye movement patterns, β = -18.26, *SE* = 17.07, *t* = -1.07, *p* = .29. There were no significant differences in fixation dispersion during the intervals before the No-go target response was correct, and the No-go target response was incorrect, β = 4.29, *SE* = 8.43, *t* = .51, *p* = .62.

Fixation duration. The difference was not significant between the two eye movement patterns, β = -29.22, *SE* = 176.94, *t* = -.17, *p* = .87. There were no significant differences in fixation duration during the intervals before the No-go target response was correct, and the No-go target response was incorrect, β = 26.60, *SE* = 33.22, *t* = .80, *p* = .43.

Pupil baseline. Participant's left and right eye pupil diameter were used. Pupil baseline is computed as the average pupil diameter in the 500ms interval before stimuli appeared. No significant difference was observed in pupil baseline between distributed pattern and centralized pattern, β = .30, *SE* = .23, *t* = 1.31, *p* = .20. Participants' pupil baseline was larger when the response to the No-go target was incorrect than when the response to the No-go target was correct, β = -.07, *SE* = .03, *t* = -2.29, *p* = .03.

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Pupil dilation. No significant difference was observed in pupil dilation between distributed pattern and centralized pattern, $\beta = .01$, $SE = .01$, $t = .61$, $p = .55$. Pupil dilation in the No-go target correct trials did not significantly differ from the incorrect trials, $\beta = -.001$, $SE = .005$, $t = -.27$, $p = .79$.

Eye movement data during the 10-s pre-probe period

The processing was identical to 10-s pre-target intervals and the representative HMMs of two groups were shown in Figure 4. One group consisted of 18 participants and the other one consisted of 13 participants. We termed them "distributed pattern" and "centralized pattern" respectively. The distributed pattern was depicted in Figure 4A, showing a transition of initial fixation among the three ROI. Participants had distributed pattern demonstrated a wider range of viewing. Figure 4B showed that centralized pattern with high probability first to view at the center (the red ROI), and then remained to view the same region. Sometimes they performed a wide range scan (the green ROI) and probably transition to the center. Pairwise t test showed that the log-likelihood of participants with distributed pattern generated by the two representative HMMs were significantly different, $t(17) = 5.79$, $p < .001$. The same procedure was conducted on the participants with centralized pattern; pairwise t test was also significantly different, $t(12) = 5.51$, $p < .001$. The results suggested that the distributed and centralized HMMs represented two distinctive eye movement patterns.

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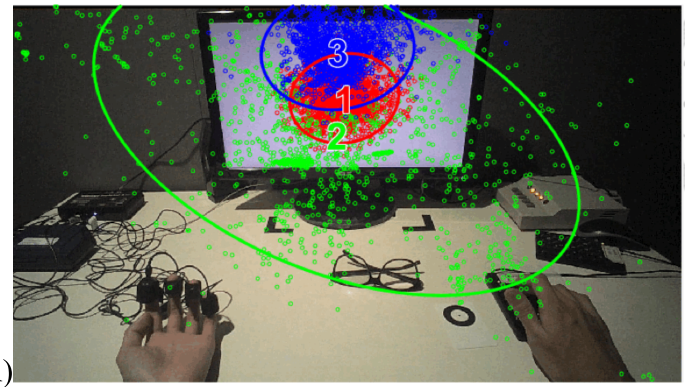
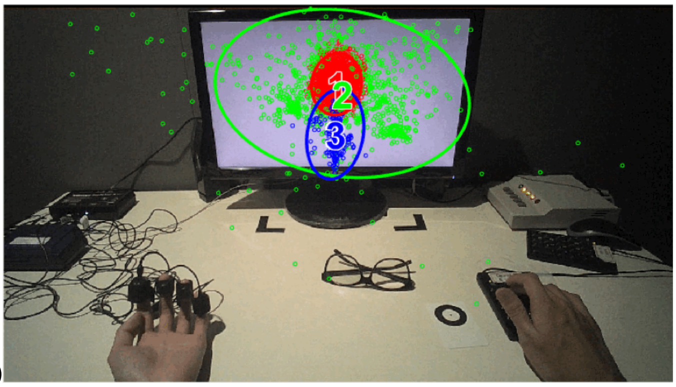
(A) 

Representative HMM of distributed pattern (N= 18)

Prior values	Red	Green	Blue
	.57	.21	.22
Transition probabilities	To Red	To Green	To Blue
From Red	.82	.17	.00
From Green	.28	.71	.01
From Blue	.01	.02	.97

(B) 

Representative HMM of centralized pattern (N= 13)

Prior values	Red	Green	Blue
	.79	.13	.08
Transition probabilities	To Red	To Green	To Blue
From Red	.81	.19	.00
From Green	.45	.55	.00
From Blue	.00	.04	1.0

Figure 4. The two eye movement patterns.

(A) The one on top shows a distributed eye movement pattern and its transition metrics.

(B) The one on the bottom shows a centralized eye movement pattern and its transition

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metrics.

Manual data during the 10-s pre-probe period

Performance. We compared the task performance of two eye movement patterns using proportion of rating focused attention and the omission error of go trial. This difference was not significant between distributed pattern and centralized pattern (Table 2.). For the proportion of rating focused attention, we found a marginal difference between distributed pattern and centralized pattern, $t(29) = -1.76$, $p = .09$. Participants' task performance in omission error were not correlated with eye movement patterns scale. The proportion of rating focused attention were negatively correlated with eye movement patterns scale, suggesting the lower report focused attention, the more distributed pattern, $r = -.38$, $p = .03$.

Table 2
Means for proportion of rating focused attention and omission error

	Mean（SD）		*df*	*t*	*p*
	Centralized pattern (*N*=15)	Distributed pattern (*N*=16)			
Proportion of rating focused attention (%)	56.35(29.4)	39.58(23.63)	29	-1.76	0.09
Omission error	0.25(0.14)	1.69(0.15)	29	1.58	0.13

* p<.05　** p< .01

Reaction time (RT). No significant difference was observed in reaction time between the two eye movement patterns, $\beta = -3.69$, $SE = 27.92$, $t = -.13$, $p = .90$. RT, when participants reported being focused attention did not significantly differ from when they

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reported being mind wandering, β = 21.07, *SE* = 17.03, *t* = 1.24, *p* = .23.

Reaction time coefficients of variation (RTCV). Participants used the centralized pattern had smaller RTCV, β = -.09, *SE* = .05, *t* = -1.97, *p* = .05. RTCV was smaller when participants reported being focused attention than being mind wandering, β = .17, *SE* = .03, *t* = 5.18, *p* < .001. The interaction between the two factors was significant, β = -.15, *SE* = .06, *t* = -2.58, *p* = .02. In the self-rating focused attention condition, participants of the centralized pattern with smaller RTCV than distributed pattern, *t*(28) = 3.15, *p* = .004.

Fixation dispersion. Centralized pattern displayed smaller fixation dispersion than distributed pattern, β = -52.25, *SE* = 16.80, *t* = -3.11, *p* = .003. Fixation dispersion was smaller when participants reported being focused attention than being mind wandering, β = 30.52, *SE* = 11.16, *t* = 2.73, *p* = .02.

Fixation duration. Centralized pattern had longer fixation duration than distributed pattern, β = 365.86, *SE* = 169.40, *t* = 2.16, *p* = .04. There were no significant differences in fixation duration during the intervals before reporting being focused attention, and before reporting being mind wandering, β = -192.01, *SE* = 106.36, *t* = -1.81, *p* = .09.

Pupil baseline. Participants' pupil baseline was larger in the centralized pattern, β = .48, *SE* = .20, *t* = 2.38, *p* = .02. There were no significant differences in pupil baseline during the intervals before reporting being focused attention, and before reporting being mind wandering, β = .09, *SE* = .06, *t* = 1.36, *p* = .19.

Pupil dilation. No significant difference was observed in pupil dilation between

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distributed pattern and centralized pattern, β = -.008, *SE* = .02, *t* = -.49, *p* = .63. There were no significant differences in pupil dilation during the intervals before reporting being focused attention, and before reporting being mind wandering, β = .003, *SE* = .01, *t* = .34, *p* = .74.

ERPs data

P3 amplitude during the 10-s pre-target period. P3 amplitudes in 10s period before the onset time of the target C (for the no-go trial) were obtained by averaging the go trials onset in the period of 10s before the target across blocks. There was no significant difference on averaging P3 between distributed pattern and centralized pattern, β = .50, *SE* = 1.13, *t* = .44, *p* = .66. Consistent with the previous study (Smallwood, 2008), we measured a greater averaging P3 amplitudes when the response to the No-go target was correct than the response to the No-go target was incorrect, β = -1.59, *SE* = .60, *t* = -2.64, *p* = .009 (see Figure 5).

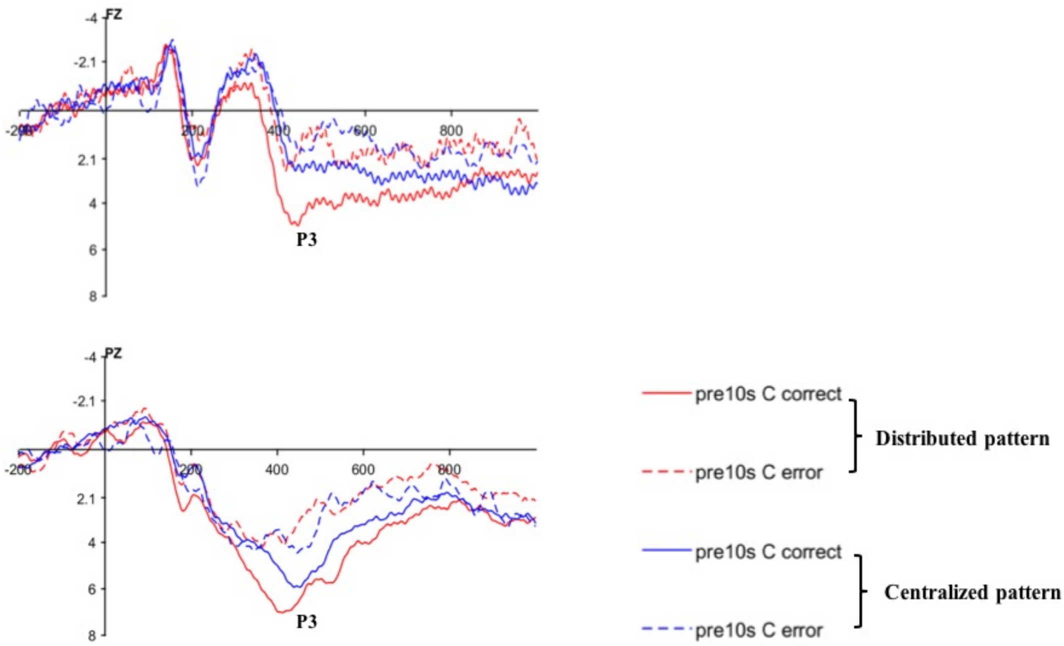

Figure 5. Time course of go trials P3 amplitude during the 10-s pre-target period. Time

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point 0 indicates the point of go trials presentation. Correct indicates the correct response to the No-go target. Error indicates the erroneous response to the No-go target.

P3 amplitude locked on target. P3 amplitude were computed from averaging target onset across trials. No significant difference was found on target-locked P3 between distributed pattern and centralized pattern, β= 1.28, *SE* = 1.97, *t* = .65, *p* = .52. A larger target-locked P3 when the response to the No-go target was correct, β = -3.79, *SE* = 1.33, *t* = -2.86, *p* = .005. (see Figure 6)

N2 amplitude locked on target. N2 amplitude were computed from averaging target onset across trials. No significant difference was found on target-locked N2 between distributed pattern and centralized pattern, *β* = 1.31, *SE* = 1.75, *t* = .75, *p* = .46. A larger target-locked N2 when the response to the No-go target was incorrect, *β* = -4.63, *SE* = 1.25, *t* = -3.70, *p* < .001. (see Figure 6)

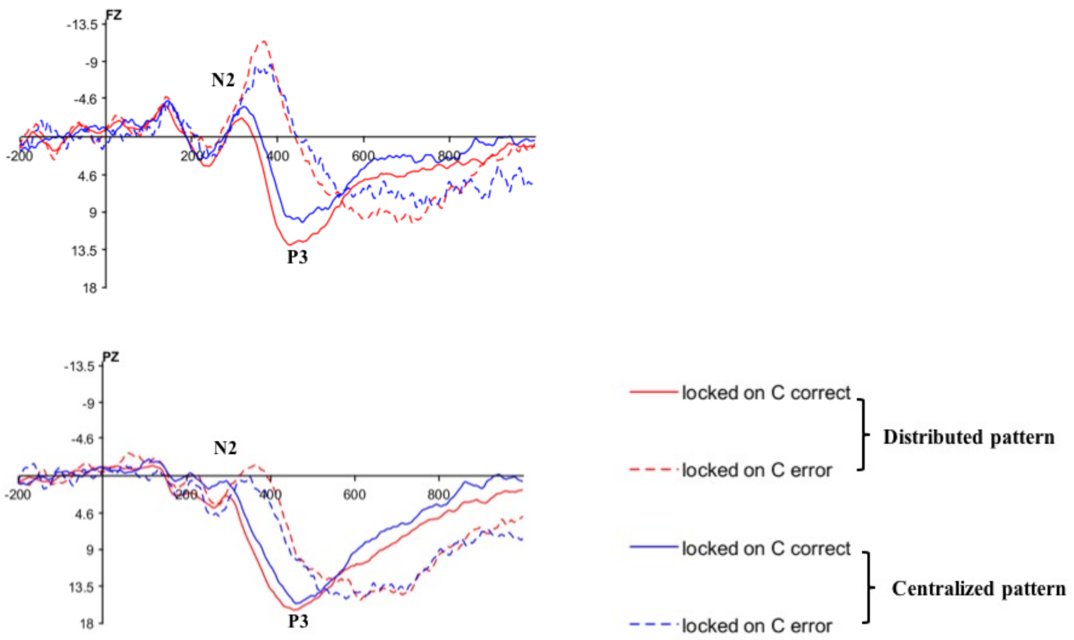

Figure 6. Time course of No-go target P3 and N2 amplitude.

Time point 0 indicates the point of the No-go target presentation. Correct indicates the

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correct response to the No-go target. Error indicates the erroneous response to the No-go target.

P3 amplitude during the 10-s pre-probe period. P3 amplitude were computed from averaging go trials onset across trials. No significant difference was observed on averaging P3 between distributed pattern and centralized pattern, β = -1.40, *SE* = 1.22, *t* = -1.14, *p* = .26. An averaging P3, when participants reported being focused attention did not significantly differ from when they reported being mind wandering, β = -.35, *SE* = 1.04, *t* = -.34, *p* = .73. (see Figure 7).

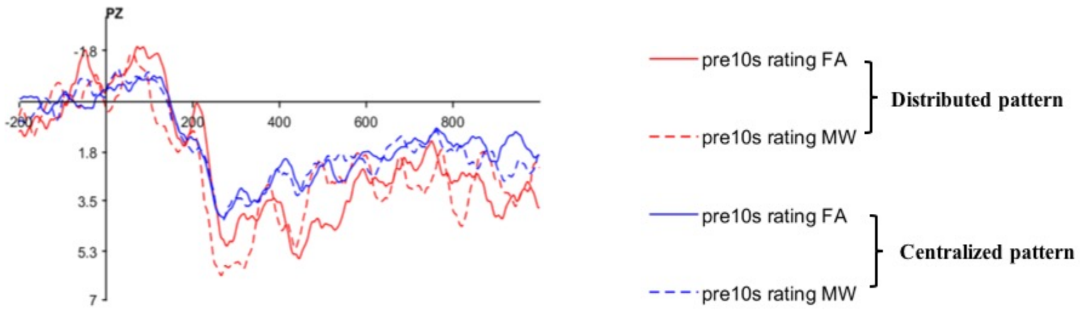

Figure 7. Time course of go trials P3 amplitude during 10-s pre-probe period. Time point 0 indicates the point of go trials presentation. FA indicates the self-rating focused attention. MW indicates the self-rating mind wandering.

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Discussion

The current study found evidence that mind wandering can be revealed by eye movement patterns. Our study was a novel way to measure mind wandering using EMHMM in the SART. We categorized eye movement pattern into distributed pattern and centralized pattern. We found that participants using a distributed pattern were associated with mind wandering state indexed by behavioral data and eye behavior data. Conversely, participants using a centralized pattern were associated with focused attention state also indexed by behavioral data and eye behavior data. These findings were summarized in Table 3 and Table 4.

Table 3

A summary of results during the 10-s pre-target period

		Eye movement patterns (better)	*Respond to target*
Manual data during the 10-s pre-target period	*d'*	Centralized	
	RT	=	C longer than Inc
	RTCV	=	=
Eye behavior during the 10-s pre-target period	*Fixation dispersion*	=	=
	Fixation duration	=	=
	Pupil baseline	=	C greater than Inc
	Pupil dilation	=	=
ERPs amplitude	*Target-locked P3*	=	C greater than Inc
	Target-locked N2	=	Inc greater than C
	Averaging P3	=	C greater than Inc

"=" =no significant difference; C= the correct response to the No-go target; Inc= the incorrect response to No-go target

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Table 4
A summary of results during the 10-s pre-probe period

		Eye movement patterns	*Respond to probe*
Manual data during the 10-s pre-probe period	*proportion of rating focused attention*	=	
	omission error	=	
	RT	=	=
	RTCV	C smaller than D	=
Eye behavior during the 10-s pre-probe period	*Fixation dispersion*	C smaller than D	MW greater than FA
	Fixation duration	C longer than D	=
	Pupil baseline	C greater than D	=
	Pupil dilation	=	=
ERPs amplitude	*Averaging P3*	=	=

"=" = no significant difference; C = Centralized pattern; D = Distributed pattern; FA = focused attention; MW = rating mind wandering

Association between mind wandering and eye movement patterns

Our results showed that participants with a centralized pattern had better d' during the 10-s pre-target period. It is possible that participants with a centralized pattern more often looked nearby where the stimulus appeared (i.e., at the center) than those with a distributed pattern. In the daily activities (e.g., tea-making and sandwich-making), the proportion of task-related object viewed is much higher than task-unrelated objects. This is because top-down information from the task on hand will guide eye movement to the task-related information (Land, 2006). Following this idea, a centralized pattern may be speculated using top-down control of eye movement in the SART.

Although we did not find a significant difference in the proportion of rating focused attention between centralized pattern and distributed pattern, participants with a centralized pattern had more blocks to report attention than a distributed pattern. We found that a distributed pattern more often transferred initial fixations than a centralized pattern, but it may not lead to a difference in fixation dispersion. This result was consistent

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with Faber et al. (2020) observing fixation dispersion during mind wandering in the SART. Contrary to their perspective on the association between fixation pattern and mind wandering in tasks with central spatial allocation (e.g., SART), we suggest that fixation patterns and mind wandering were related. We found that eye movement patterns were related to participants' d', suggesting that EMHMM may overcome spatial allocation demands of tasks and make fixation patterns reliable indicators of mind wandering.

Pupil diameter and mind wandering

Pupil baseline diameter is an index of tonic locus coeruleus (LC) activity, which correlates with task performance in an inverted U-shape pattern. Performance is poor when the LC tonic level is either low or high. Performance is optimal when the LC tonic level is intermediate (Aston-Jones & Cohen, 2005). Our participants showed a larger pupil baseline before No-go errors. First, it is in accord with the inverted U-shape pattern, which offered more extensive tonic LC activity associated with poor performance. Second, it may indicate that our participants were disengaged from the current task, with attention drifted into their internal thoughts before the No-go error. Studies from Unsworth and Robison (2018) and Groot et al. (2020) suggest that situations prone to an external focus of attention are associated with exploratory mind wandering, which is high arousal levels and with large tonic pupil diameter (i.e., pupil baseline). During the 10-s pre-probe period, participants with a distributed pattern showed a smaller pupil baseline than those with a centralized pattern. This finding indicates that distributed pattern at low arousal level and may be associated with non-alert mind wandering.

Pupil dilation refers to the pupil dilates relative to baseline levels due to increases in cognitive processing load (Beatty & Lucero-Wagoner, 2000). We did not observe the difference of pupil dilation during either objective measure or subjective measure. A

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possible explanation for these results is that cognitive processing had done before stimuli onset so that we did not find the change of pupil dilation. Future studies should be undertaken to determine how pupil diameter is affected by mind wandering.

ERPs and mind wandering

Consistent with Smallwood (2008), P3 amplitude was reduced before the behavioral report of mind wandering. We found that the P3 amplitude decreased before the No-go error and stimulus-locked on the No-go error. This finding suggests a reduction of attention to external information during the No-go error. Here, we found a larger N2 amplitude on the No-go error than on No-go correct, which contradicts earlier findings (Falkenstein et al., 1999). Zordan et al. (2008) suggested that the N2 component reflects inhibitory processing, which may interrupt motor preparation but not motor execution. Therefore, our results indicated participants were unsuccessful in inhibiting motor response even though they made more effort to inhibit inhibition. This finding may be attributable to mind wandering before the No-go target.

We did not find a significant difference in ERPs between the centralized and distributed patterns neither on an objective nor subjective measure. A possible explanation is that eye movement data were extracted from the 10-s interval either before the target or before the probe, implying that eye movement patterns reflect a state. The ERPs are a small part of the continuous EEG activity evoked by an interesting event such as target onset (Nidal & Malik, 2014). It suggests that ERPs reflect the online processing of attention and yet not a state. EEG frequency band is sensitive to a condition that is a continuum of states such as alertness to sleep. For instance, beta waves are dominant during a normal state of wakefulness with open eyes. In resting with eyes closed alpha waves raise, and if sleep appears theta waves increase (Teplan, 2002). Thus, the time-

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frequency band during the 10-s interval may be used instead in future works.

Limitations of the study

Due to individual difference, the number of the reporting mind wandering trials included in the analysis was fewer in some participants. The signal-to-noise ratio improves as a function of the square root of the number of trials included in the average. All else being equal, the more trials included in the average, the better the data quality (Luck, 2014) which may explain why we did not observe ERPs' effect during subjective measures. Although the ERPs results of our study are not conclusive, they are certainly steps in the right direction.

Applications and future works

According to Johnson et al. (2020)'s finding, the random SART commission error is a sensitive measure of cognitive attention and response inhibition that relates to both day-to-day classroom behaviors (i.e., direct observation form) and teachers' and parents' ratings of everyday behaviors. Future research could furthermore examine the association between eye movement patterns and classroom behaviors. We expect that the eye movement patterns can assist teachers to directly observe inattentive behaviors in the classroom.

Online learning has shown significant growth over the last decade; it allows students to access the learning programs at their convenience. One of the biggest challenges of online learning for many students is the struggle with focusing on the screen for long periods. With online learning, there is also a greater chance for students to be easily distracted by social media or other sites. There is a detective system that, after 10-mins

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idle time (when no mouse movement or keyboard activity is detected), a pop-up window will ask students whether they want to keep going or the program will stop logging in 3-mins. The way to monitor students' performance is disturbing and may cause dual-task (i.e., taking notes and using a mouse), which leads to a more significant cognitive overload (Pashler, 1994). An eye tracking attention system would be an alternative strategy for supervision without interrupting learning. We expect that eye movement patterns detect whether students concentrate on online learning. If they are mind wandering, the system will adapt to the difficulty in courses to keep them learn the materials effectively. If they are focused, the system will give feedback to enhance the focused attention experience. We also expect that students rely on eye movement patterns to identify their attentional state. After a period of practice, students will be more aware of and regulate their attentional state by themselves.

Conclusion

Overall, the results of the current study suggest that eye movement patterns are associated with mind wandering. For the objective measure, focused attention and mind wandering can be distinguished by differences in eye movement patterns, behavior, pupil size and ERPs. For the subjective measure, focused attention and mind wandering can be distinguished by differences in eye movement patterns, behavior and pupil size. The current study highlights that states of attention can be revealed by eye movements and also provides new insight in utilizing EMHMM to study visual attention. We believe that the findings from our study are intriguing enough to invite further research on topic of mind wandering, as well as further research on other attention-related topics that will make use of eye movement patterns.

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