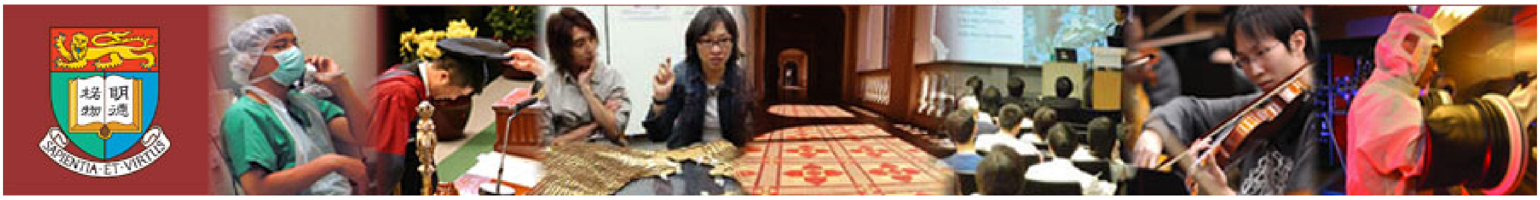

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Analytic Eye Movement Patterns in Face Recognition are Associated with Better Performance and more Top-down Control of Visual Attention: an fMRI Study

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Abstract

Recent research has revealed two different eye movement patterns during face recognition: holistic and analytic. The present study investigated the neural correlates of these two patterns through functional magnetic resonance imaging (fMRI). A more holistic pattern was associated with more activation in the face-selective perceptual areas, including the occipital face area and fusiform face area. In contrast, participants using a more analytic pattern demonstrated more activation in areas important for top-down control of visual attention, including the frontal eye field and intraparietal sulcus. In addition, participants using the analytic patterns had better recognition performance than those showing holistic patterns. These results suggest that analytic eye movement patterns are associated with more engagement of top-down control of visual attention, which may consequently enhance recognition performance.

Keywords: eye movement; functional magnetic resonance imaging (fMRI); face recognition; analytic patterns; Hidden Markov Model (HMM); top-down visual attention.

Introduction

Studies have revealed distinct eye movement patterns in face processing. For example, compared with young adults, older adults fixate more on the lower half of a face (Wong, Cronin-Golomb, & Neargarder, 2005). Some differences seem to be culturally influenced: Caucasians demonstrate more of an analytic pattern, focusing on characteristics of face parts, whereas Asians process faces with a more holistic pattern, with most fixations landed around the face center (i.e., the nose; Kelly et al., 2011). However, it remains unclear whether people adopting different eye movement patterns process faces differently. Findings on the relationship between eye movements and face recognition performance are still mixed. For example, Kelly et al., (2011) found no performance differences between Asians and Caucasians who adopted different eye movement patterns. Mehoudar et al. (2014) reported that individual eye movements were not predictive of performance in face recognition. In contrast, Henderson, William, and Falk (2005) showed that eye movements facilitate face learning since restricting eye movements during face learning was found to impair recognition performance. Goldinger, He, and Papesh (2009) showed that during face learning, eye movements in trials that eventually led to a miss during recognition were more suppressed, with fewer regions visited, shorter scanning distance, and fewer fixations, as compared with those that eventually led to a hit.

This inconsistency may be due to limitations in eye movement data analysis methods for discovering common patterns from individuals. In view of this, Chuk, Chan and Hsiao (2014a) proposed a Hidden Markov Model (HMM) based approach to analyze eye movement data; the model takes individual differences in both spatial and temporal dimensions of eye movements into account. Through clustering participants' eye movement patterns according to their similarities, both holistic and analytic patterns in face recognition were discovered in Asians (Chan, Chan, Lee, & Hsiao, 2015; Cheng, Chuk, Hayward, Chan, & Hsiao, 2015; Chuk et al., 2014a) as well as in Caucasians (Chuk et al., 2014b). In addition, it was found that people who adopted analytic patterns had better recognition performance than those with holistic patterns (Chuk et al., 2014b; Chan et al., 2015). These results demonstrate that the HMM based approach is a powerful analysis tool for discovering common eye movement patterns and their relationship with recognition performance.

Nevertheless, it remains unclear why analytic eye movement patterns lead to better face recognition performance than holistic patterns. Since analytic patterns involve more spread out regions of interest (ROIs) targeting at facial features, and more transitions among them, people with analytic patterns may engage more top-down control of visual attention, which in turn enhances recognition performance.

Thus, here we aim to investigate the neural correlates of the observed association between eye movement patterns and face recognition performance via functional magnetic resonance imaging (fMRI).

In face recognition, neuroimaging research identified two face-selective perceptual areas, including the occipital face area (OFA) in the inferior occipital gyri and the fusiform face area (FFA) in the lateral fusiform gyrus. OFA is the entry point of the face network and is sensitive to facial features. FFA is related to invariant aspects of face perception such as face identity and is sensitive to the configuration and spacing between facial features (Hoffman & Haxby, 2000; Pitcher, Walsh, Yovel, & Duchaine, 2007). When a task was switched from face to object recognition, functional connectivity decreased significantly between the OFA and FFA (Zhen, Fang, and Liu, 2013), suggesting an important role of these two areas in face recognition.

Brain regions beyond the face-selective network have also been identified, namely the primary visual cortex (V1), frontal eye field (FEF), intraparietal sulcus (IPS), posterior cingulate cortex (PCC), and prefrontal cortex (PFC; Zhen et al, 2013; Leube et al., 2003; Phillips et al., 1998). Some of these regions are greatly engaged in top-down control of visual attention in cognitive tasks in general (Gilbert & Li, 2013; Noudoost, Chang, Steinmetz & Moore, 2010; Leech & Sharp, 2014). For example, the FEF, IPS and PCC are related to saccadic eye movement (Schall, 2004), attention shift (Corbetta et al., 1998) and internally directed attention (Leech & Sharp, 2014) respectively. The PCC was also found to play an essential role in facilitating or monitoring working memory loaded tasks (Hampson, Driessen, Skudlarski, Gore, & Constable, 2006), and early top-down control of visual attention has been shown to be advantageous to performance on working memory and perceptual tasks (Rutman, Clapp, Chadick, & Gazzaley, 2010). The prefrontal cortex (PFC), especially the dorsolateral prefrontal cortex (DLPFC), plays an important role in memory (Braver et al., 1997; Kane & Engle, 2002), goal maintenance (Colvin, Dunbar, & Grafman, 2001), planning and execution (Fincham, Carter, van Veen, Stenger, & Anderson, 2002), and modulates other brain regions by conveying top-down signals in controlling visual attention.

Accordingly, we hypothesized that analytic eye movement patterns in face recognition may be associated with more top-down control of visual attention, as reflected in higher activations in the IPS, FEF, PCC, and DLPFC. To test this hypothesis, here we examined participants' eye movement patterns and brain activations in face recognition and examine the association between them.

Method

Participants

A total of 20 Chinese participants (aged 18 – 24; M = 21.7; SD = 2.36; 11 females) were recruited from the University of Hong Kong. All participants were right-handed. They either had normal or corrected visual ability. Informed consent was collected from each participant; the research protocol was approved by the Ethics Review Board at The University of Hong Kong.

Materials

A total of 120 young Chinese face images (60 females) with neutral facial expressions were used and split into two sets of images. Sixty of them (30 in each set) were used as target faces to be remembered and the other 60 (30 in each set) were used as distractors in the test phase. All face images were 270 × 360 pixels (8 visual degrees) in grayscale, and were adjusted to match for luminosity, contrast, and quality. The distances between the eyes and the mouth were standardized. Each face was a frontal view and was cropped according to the original shape of the face such that hair, ears and the neck were removed, leaving only the face visible.

Experimental Design

Apart from the face recognition task, a verbal and spatial working memory test and an executive functioning test were administered in order to examine possible correlations between eye movement patterns and cognitive abilities.

Face Recognition task. The task included three runs, each of which consisted of a study and a test phase. In each study phase, participants were shown 10 face images one at a time at a rate of 3s each. The face was displayed either at the upper center or at the lower center (see Figure 1) of the screen randomly. Participants were instructed to fixate at a cross "+" located at the center of the screen between the presentation of each image. The stimulus onset asynchrony (SOA) between images varied from 6 to 16s. Participants were instructed to remember all the faces in the study phase. In each test phase, participants were shown 20 face images individually, which consisted of 10 old images and 10 new images. They were asked to judge whether they recognized the displayed images from the study phase previously, within 3s per face. Individual A-prime was computed.

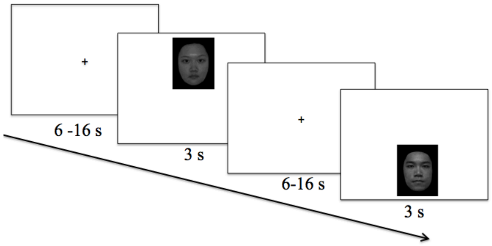


Figure 1. Display of images in the study and test phases.

Working memory test. Both verbal and spatial working memory abilities were measured via a computerized two-back test (Lau, Ip, Lee, Yeung, & Eskes, 2013). For verbal two-back, a sequence of 100 single digit numbers was displayed at the screen center. Starting from the third number, participants had to judge whether each displayed number was identical to the one displayed two items ago. For the spatial two-back task, a sequence of 100 symbols was displayed at several different locations around the screen center. Starting from the third symbol, participants had to judge whether each displayed symbol was in the same position as the one displayed two items ago. Accuracy (%) was calculated for verbal and spatial tasks separately.

Executive functioning test. Executive functioning, specifically planning and execution ability, was measured via a computerized Tower of London (TOL) test (e.g., Phillips, Wynn, McPherson, & Gilhooly, 2001). Three beads and three pegs of different heights were shown on screen. Participants had to move the beads from peg to peg one at time to match the bead positions on a target board while adhering to certain rules. Participants were told to complete it as quickly as possible using the fewest number of moves. The planning and execution ability was measured by performance scores (a total of 10 trials; 1 mark for every trial finished with minimal moves) and number of extra moves (actual minus minimal moves). .

Procedure

The study consisted of three parts: an eye tracking experiment, a set of cognitive tests, and an fMRI experiment. In the eye tracking experiment, participants sat in front of a computer screen with their head on a chinrest and their eye level adjusted via a chinrest to approximately the mid-level of the screen. Prior to the experiment, 9-point calibration was conducted repeatedly until the errors were lower than 0.3° and 0.5° visual degree for the dominant eye and the non-dominant eye respectively. Then, they performed the face recognition task while their eye movement was recorded. After the eye tracking experiment, participants performed cognitive tests including the verbal and spatial two-back, and TOL tasks, followed by the fMRI experiment. Throughout the whole fMRI experiment, participants had to perform the same face recognition task during the eye tracking experiment but with a different set of images.

Eye Data Acquisition, Processing and Analysis

Eye movements were recorded with an SMI REDn eye-tracking system (60 Hz), which was connected to a 17" monitor with screen resolution 1280 × 768 pixels (with a 60 cm eye-monitor distance). Both eyes were tracked with the 'Smart Binocular' tracking mode; only data from the dominant eye was used in analysis. We analyzed participants' eye movement data in the test (recognition) phase.

A Hidden Markov Model (HMM) based approach was used to analyze eye movement data. First, each participant's eye movement data was modeled by an HMM with a variational Bayesian approach. Each HMM included three Gaussian components (i.e. ROIs), as indicated by different colors in Figure 2. The overlapping area of two or more ROIs indicates that the fixations around that area have similar probabilities of belonging to those ROIs. The prior values in the matrices represent the probability that an initial eye fixation is located at each of the ROIs. The rest of the matrix represents the transition probabilities among the three ROIs. Next, we applied a variational hierarchical EM algorithm (VHEM; Coviello, Chan, & Lanckriet, 2014) to cluster the individual HMMs into two subgroups according to their similarities. According to our previous studies (e.g., Chuk et al., 2014), a holistic pattern and an analytic pattern would be shown. Finally, for each individual HMM, we calculated the difference between the log-likelihood of being classified as the holistic pattern and the log-likelihood of being classified as the analytic pattern, to represent the degree of similarity of one's eye movements to the two patterns (named "H-A Scale" in later sections).

Image Data Acquisition, Processing and Analysis

Imaging was performed on a 3-Tesla Phillips scanner head scanner with a standard eight-channel head coil. A total of 580 volumes (190 × 3 runs) of functional data were collected as echo-planar images (128 × 128 matrix; 40 slices with in-plane resolution of 3 × 3 mm^2 and slice thickness 3.5mm; TE 30 ms; TR 2000 ms; FOV 230 × 230 mm^2; flip angle 90°). A T1-weighted spin-echo pulse sequence with a spatial resolution of 1 × 1 × 1 mm^3 data set was collected for anatomical reference.

The FSL software package was used for image preprocessing. Functional images were corrected for head motion with FSL's intra-modal motion correction tool (MCFLIRT), high-pass filtered at 100s and spatially smoothed with a Guassian filter (full-width-half-maximum = 5mm). T1 anatomical images were co-registered at participant level and to a standard brain Montreal Neurological Institute template (MNI152; 2 mm). A general linear model was used to analyze functional imaging data incorporating predictors, which corresponded to the particular experimental conditions. The onset times were set as the stimulus onset and the durations were set as 1s for all predictors.

To examine the neural correlates of different eye movement patterns, we examined the correlations between participants' H-A Scales and the event contrasts of non-missed test trials (i.e. trials with either correct or incorrect responses) against the fixation baseline. Significant signal changes were reported if they exceeded a p-value of 0.05 corrected at a whole-brain level.

Result

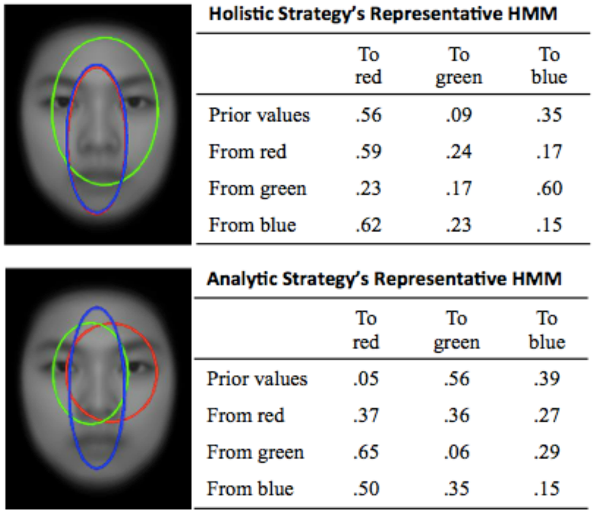
Cognitive Test and Behavioral Performances

The average face recognition performance in A' was .85 (SD = .07). The average number of fixations per trial was 2.56 (SD = .85) and the average reaction time was 1.64s (SD = .85s). The mean accuracy of the verbal 2-back task was 76.6% (SD = 18.0%) and that of the spatial 2-back task was 77.5% (SD = 11.5%). The average correct score and number of extra moves in the TOL test were 5.3 (SD = 2.6) and 24.3 (SD = 16) respectively.

Eye Movement Pattern Analysis

Participants' eye movement patterns were clustered into two groups via the HMM-based approach, as shown in Figure 2. Each group consisted of 10 participants. H-A Scale was computed, with a positive value representing a holistic pattern (M = .04; SD = .56; ranging from -.65 to 1.31).

In Figure 2, the top figure shows a typical holistic eye movement pattern. The ROIs were around the face center. The first fixation was located most commonly at the vertical and center of a face (red; prob. = .54). The subsequent eye fixations usually stayed at the same position (red to red = .56), although sometimes they also transited to the surrounding region (red to green = .24; blue to green = .23). In contrast, the bottom figure shows a typical analytic eye movement pattern. The ROIs were relatively more clearly located at different facial features, the left eye (green), the right eye (red), and the center/mouth (blue) of a face. The first fixation was most commonly located near the left eye (green; prob. = .56). Most eye gaze transitions appeared between the two eyes (red to green = .36; green to red = .65, see e.g. Chuk et al., 2014a).



Holistic Strategy's Representative HMM

	To red	To green	To blue
Prior values	.56	.09	.35
From red	.59	.24	.17
From green	.23	.17	.60
From blue	.62	.23	.15

Analytic Strategy's Representative HMM

	To red	To green	To blue
Prior values	.05	.56	.39
From red	.37	.36	.27
From green	.65	.06	.29
From blue	.50	.35	.15

Figure 2. The representative HMMs of the two subgroups, holistic (top) and analytic (bottom) patterns, and the corresponding transition probability matrices.

Relationship between Eye Movement Pattern and Recognition Performance/Cognitive Ability

With regards to the relationship between eye movement pattern and face recognition performance, a negative correlation was found between the H-A Scale and face recognition A-prime scores, r = -.47, p = .036 (Figure 3). People who used a more analytic (holistic) strategy yielded a better (worse) face recognition performance. This finding is consistent with previous studies (e.g., Chuk et al., 2014b; Chan et al., 2015; Cheng et al., 2015). H-A Scale was neither correlated with average number of fixations per trial (r = .05, n.s.) nor reaction time (r = .30, n.s.). Thus, participants with holistic patterns did not necessarily make fewer fixations or had shorter viewing times on the faces. When examining the relationship between eye movement patterns and cognitive abilities, we found that spatial working memory performance was marginally correlated with the H-A Scale, r = -.41, p = .073, indicating that people who possessed higher (lower) spatial working memory tended to employ a more analytic (holistic) eye movement pattern. However, the results were not significant for verbal working memory (r = -.08, n.s), and executive functioning (scores: r = -.26, n.s.; extra moves: r = .15, n.s.).

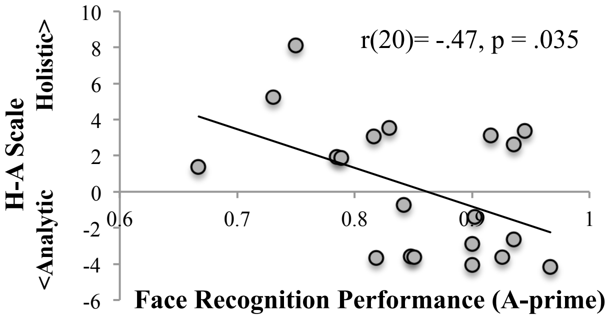


Figure 3. Correlation of H-A Scale and face recognition performance.

Relationship between Strategy and Neural Activity

Correlation analysis between participants' H-A Scales and the event contrast of non-missed test trials against fixation baseline was conducted for all 20 participants. It was found that the more holistic the eye movement patterns, the higher the brain activation in some face-selective perceptual areas (Figure 4), including the left OFA ([-34, -76, -10]; z > 2.3, p < .05) and the right FFA (BA 37; [42, -55, -18]; z > 2.3, p < .05). Higher activation was also found in the left pars triangularis of the inferior frontal gyrus (BA 45; [-55, 26, 6]; z > 2.3, p < .05).

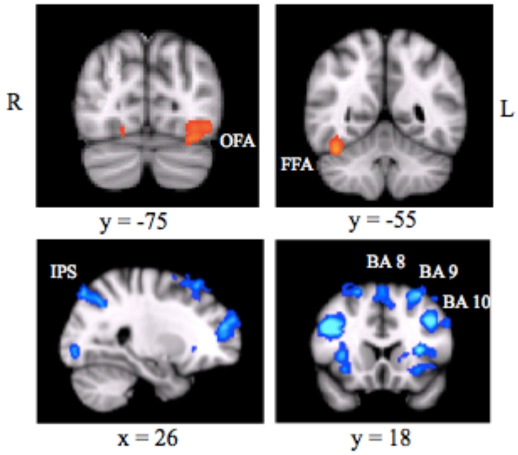


Figure 4. Holistic patterns: more activation in the left OFA (top left) and the right FFA (top right). Analytic patterns: more activation in bilateral IPS (bottom left) and the prefrontal cortex (bottom right)

When people had more analytic eye movement patterns, there was significantly higher activation in the V1 ([±14, -92, 4]; z > 2.3, p < .05), eye movement planning and attention control related areas including the IPS ([±30, -64, 46]; z > 2.3, p < .05), PCC ([±2, -30, 40]; z > 2.3, p < .05), and FEF (encompassed in DLPFC; BA 8; [±30, 18, 58]; z > 2.3, p < .05), and executive functioning related areas including the DLPFC (BA 9; [±46, 44, 30]; z > 2.3, p < .05) and the frontalpolar prefrontal cortex (FPPFC; BA 10; [±24, 52, 18], $z > 2.3$, $p < .05$).

Discussion

The current study investigated the neural correlates of different eye movement patterns in face recognition. Through the HMM-based approach for eye movement data analysis, we identified holistic and analytic eye movement patterns in the participants (e.g. Chuk et al., 2014a). By calculating participants' H-A Scale according to the likelihood of each individual's eye movement being classified as a holistic or an analytic pattern, our neuroimaging results demonstrated that a more holistic pattern is associated with increased activation in face-selective perceptual areas OFA and FFA. In contrast, a more analytic pattern is associated with increased activation in areas related to top-down control of visual attention, including FEF, IFS, and PCC. In addition, consistent with previous studies, we found that people using analytic patterns recognized faces better than those with holistic patterns (Chan et al., 2015; Chuk et al., 2014a).

The regions whose activations are associated with analytic eye movement patterns included the V1, IFS, FEF, PCC, DLPFC (BA 9), and FPPFC (BA 10). The V1 is one core region of visual attention. The DLPFC (BA 9) is involved in planning (Fincham et al., 2002) and delivering top-down signals to other brain regions. The FEF was previously reported to be active during voluntary saccades of eye movement (Schall, 2004). The PCC was reported to monitor visual attention shift during post-saccadic eye movement (Olson, Musil & Goldberg, 1993) and resetting the visual attention plan in anticipating the next attentional shift (Small et al., 2003). The Right IPS is shown to be involved in serial attention processes and the left IPS acts as an attentional modulator to maintain the activities of initial perception and processing of selective information in the working memory as well as long-term memory network (Majerus et al., 2007; Noudoost et al., 2010). Taken together, the elevated activation of these regions suggests that people adopting analytic patterns may be engaging active eye movement planning and top-down control of visual attention during face recognition. This is consistent with the behavioral finding that analytic patterns involved more spread out ROIs and transitions among ROIs than holistic patterns. Since top-down visual attention allows us to filter out irrelevant information and improve the efficiency of information processing by selecting useful visual information, it has been found to be associated with better cognitive task performance (Rutman, Clapp, Chadick, & Gazzaley, 2010). Thus, it is possible that participants adopting analytic eye movement patterns were engaging more top-down control of visual attention, and consequently had increased accuracy in face recognition.

On the other hand, some face-selective perceptual areas, including the left OFA and right FFA, were found to be more active when people adopted holistic patterns. The OFA plays a major role in face part processing while the FFA is concerned with the processing of face configurations (e.g. Pitcher et al., 2007). Thus, our finding suggested that people who adopted holistic eye movement patterns may have relied more on perceptual areas for face recognition with less engagement of eye movement planning and visual attention control. This is consistent with their eye movement behavior, which focused on the face center and lacked transitions among facial features.

In a previous study, Chan et al. (2015) showed that in face recognition, more old adults adopted holistic eye movement patterns, and more young adults exhibited analytic patterns. In addition, they found that the likelihood of old adults' eye movements being classified as holistic was negatively correlated their cognitive status: the higher the likelihood, the lower the cognitive ability. Our current results suggest that this effect may be due to ageing-related cognitive decline in old adults, affecting their ability to actively engaging top-down control of visual attention. Our results also suggest that the adoption of different eye movement patterns may be related to limitations of cognitive capacity, rather than merely a matter of preference or motivation.

Note that the term "holistic" here refers to the specific eye movement pattern described here, and is different from the term "holistic processing" frequently described in the face perception literature (e.g., Taubert et al, 2011). Thus, having a holistic eye movement pattern does not necessarily leads to more engagement of holistic face processing. Indeed, although here we found holistic eye movement patterns are associated with high activations in the OFA and FFA, recent research has suggested both holistic and featural representations may be found in these areas (e.g., Goffaux, Schiltz, Mur, & Goebel, 2013). Using the Expanding Spotlight technique, Miellet et al. (2013) showed that Westerners, who exhibited analytic eye movement patterns, used local high-spatial-frequency information of facial features for recognition, whereas Easterners, who had holistic eye movement patterns, used global low-spatial frequency information. Future work will examine whether similar results can be obtained between the analytic and holistic patterns identified here through the HMM approach.

In summary, here we showed that holistic eye movement patterns in face recognition are associated with increased activation in the face-selective perceptual areas, whereas analytic patterns are associated with increased activation in areas involved in top-down control of visual attention. As previous studies have shown that analytic patterns lead to better performance in face recognition, the current results suggest that this advantage in performance may be a consequence of more engagement of active eye movement planning and visual attention control during the task. This finding thus provides strong evidence for a close relationship between eye movement patterns and cognitive performance.

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