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Is having similar eye movement patterns during face learning and recognition beneficial for recognition performance? Evidence from hidden Markov modeling

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ABSTRACT

The hidden Markov model (HMM)-based approach for eye movement analysis is able to reflect individual differences in both spatial and temporal aspects of eye movements. Here we used this approach to understand the relationship between eye movements during face learning and recognition, and its association with recognition performance. We discovered holistic (i.e., mainly looking at the face center) and analytic (i.e., specifically looking at the two eyes in addition to the face center) patterns during both learning and recognition. Although for both learning and recognition, participants who adopted analytic patterns had better recognition performance than those with holistic patterns, a significant positive correlation between the likelihood of participants' patterns being classified as analytic and their recognition performance was only observed during recognition. Significantly more participants adopted holistic patterns during learning than recognition. Interestingly, about 40% of the participants used different patterns between learning and recognition, and among them 90% switched their patterns from holistic at learning to analytic at recognition. In contrast to the scan path theory, which posits that eye movements during learning have to be recapitulated during recognition for the recognition to be successful, participants who used the same or different patterns during learning and recognition did not differ in recognition performance. The similarity between their learning and recognition eye movement patterns also did not correlate with their recognition performance. These findings suggested that perceptuomotor memory elicited by eye movement patterns during learning does not play an important role in recognition. In contrast, the retrieval of diagnostic information for recognition, such as the eyes for face recognition, is a better predictor for recognition performance.

1. Introduction

In human vision, the density of photoreceptors on the retina is not uniform. It is extremely high at the fovea, and drops dramatically as visual eccentricity increases. Thus, the fovea has the highest visual acuity, whereas the perifoveal area, which is much larger than the fovea, is of low visual acuity. In order for an individual to see clearly a region of interest in a cognitive task, the fovea has to be constantly relocated to the region (Tovée, 1996). Consequently, our eyes are constantly moving, and eye movements are shown to reflect underlying cognitive processes, or more specifically the way information is sampled from the environment (Antrobus, Antrobus, & Singer, 1964; Grant & Spivey, 2003; Heremans, Helsen, & Feys, 2008; Yarbus, 1967). Thus, it is reasonable to speculate that different eye movement patterns may lead to different performances in cognitive tasks.

Consistent with this speculation, it has been reported that in a cognitive task, experts and novices typically exhibited different eye movement patterns. For instance, Charness, Reingold, Pomplun, and Stampe (2001) reported that expert and intermediate chess players have different eye movement patterns. Experts made significantly more fixations at empty squares on the board. They also fixated significantly more often at pieces relevant to the current task than did the intermediates. Waters and Underwood (1998) compared the eye movement patterns of expert and novice musicians when they participated in a simple music reading task. The participants were shown two melodic fragments successively, and asked to judge whether the two fragments were the same or different. It was found that experts made significantly

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more fixations at the first fragment than novices and that their initial fixations were of significantly shorter duration than the novices. Similar findings were also reported in the research on reading. Siyanova-Chanturia, Conklin, and Schmitt (2011) compared the eye movement patterns of native and non-native English speakers when they were asked to read idioms and novel phrases. It was found that native speakers made significantly fewer and shorter fixations at idioms than novel phrases. In contrast, the number and duration of fixations that non-native speakers made at idioms and novel phrases were similar to each other. This demonstrated that native speakers had a processing advantage for idioms over novel phrases, which was not presented among non-native speakers. Hyönä, Lorch, and Kaakinen (2002) compared eye movement patterns of native Finnish speakers when they were reading Finnish texts and found that those who fixated more often at the headings and topic-final sentences performed significantly better than those who showed other eye movement patterns when they were required to summarize the texts.

Nevertheless, in the literature on face recognition, it remains controversial whether different eye movement patterns are associated with different recognition performances. For example, Goldinger, He, and Papesh (2009) found that in a face recognition memory task, participants made fewer fixations, visited fewer regions of interest, and had shorter scanning distances on the trials in which they failed to recognize a learned face as compared with those that led to successful recognition. Glen, Crabb, Smith, Burton, and Garway-Heath (2012) found that among people who suffered from central visual field defects, those who performed better in face recognition demonstrated a different eye movement strategy as compared with the ones who performed worse. These findings suggest that eye movement patterns are associated with performance in face recognition. In contrast, Blais, Jack, Scheepers, Fiset, and Caldara (2008) found that in face recognition, although Asian participants looked primarily at the center of the faces (i.e., a holistic scanning pattern) whereas Caucasian participants looked more frequently at facial features such as the two eyes and the mouth (i.e., an analytic pattern), the two cultural groups showed comparable recognition performance. This finding was later replicated in Caldara, Zhou, and Miellet (2010). Similarly, Mehoudar, Arizpe, Baker, and Yovel (2014) found that participants showed idiosyncratic eye movement patterns in face recognition that were highly stable over time; however, these patterns were not predictive of their recognition performance.

These inconsistent findings in the literature may be due to substantial individual differences in eye movement pattern that were not adequately reflected in the data analyses. Indeed, recent studies have shown that there are considerable individual differences in eye movement that persist over time and across different stimuli when people perform cognitive tasks. For instance, Castelhano and Henderson (2008) showed that during picture viewing, the characteristics of fixation durations and saccade amplitudes in eye movement differed across individuals but were stable within an individual across different types of visual stimuli. Risko, Anderson, Lanthier, and Kingstone (2012) found that curiosity was a significant predictor of participants' eye movement patterns in scene viewing. Peterson and Eckstein (2013) showed that participants differed significantly in where to first move their eyes in a face identification task, and they performed better when being forced to look at their preferred viewing locations than other locations. Kanan, Bseiso, Ray, Hsiao, and Cottrell (2015) showed that the identity of participants could be inferred based on their eye movements across different face perception judgment tasks. These findings provided stronger evidence for the existence of substantial individual differences in eye movement.

In order to account for individual differences in both spatial (i.e., fixation locations) and temporal dimensions (i.e., transitions among fixation locations) of eye movement in the data analysis, in our previous study (Chuk, Chan, & Hsiao, 2014), we proposed to use a hidden Markov model (HMM) to summarize an individual's eye movement pattern in face recognition. The hidden states of the HMM represented the individual's regions of interests (ROIs) for eye fixations. The individual's eye movements among the ROIs were summarized through the HMM's transition matrix, which represents the probability of each ROI being viewed next conditioned on the currently viewed ROI. The process of learning the individual HMMs was completely data driven. The individual HMMs could then be clustered based on their similarities to discover common patterns shared by individuals. The similarity of an individual pattern to a common pattern discovered through clustering could be measured as the likelihood of the individual pattern being classified as the common pattern. Through this approach, we discovered two common eye movement patterns in face recognition within our Asian participants that resembled the holistic and analytic patterns found in Asian and Caucasian participants respectively in Blais et al. (2008) and Caldara et al. (2010). This finding showed that both eye movement patterns could be observed within a cultural group, demonstrating substantial individual differences in eye movement pattern. In our follow-up study (Chuk, Luo, et al., 2014; Chuk, Crookes, Hayward, Chan, & Hsiao, submitted), we found that analytic and holistic patterns could be observed in both Asians and Caucasians, and the two cultural groups did not differ significantly in the percentage of group members being classified as using holistic or analytic patterns. Also, the participants who showed analytic eye movement patterns performed significantly better than those who showed holistic patterns, and there was a positive correlation between the likelihood of participants' pattern being classified as analytic and their recognition performance. These findings were not possible without taking individual differences in eye movement into account, demonstrating well the advantage of our HMM approach.

Our results from previous studies suggested that analytic eye movement patterns, which involved eye fixations specifically to the two eyes in addition to the face center, were beneficial for face recognition. This result was consistent with the previous studies showing that the eyes are the most important features for face recognition (e.g., Gosselin & Schyns, 2001; Vinette, Gosselin, & Schyns, 2004). For example, using the Bubbles technique, Gosselin and Schyns (2001) found that the two eyes were the most diagnostic features for recognizing the identity of an individual. Vinette et al. (2004) further showed that the left eye was the earliest diagnostic feature that participants used in face recognition. Afterwards, both the left and right eyes were used effectively.

Nevertheless, it remains unclear whether analytic eye movement patterns are also beneficial for face learning. Henderson, Williams, and Falk (2005) found that when participants' eye movements were restricted to be at the face center during the learning phase of a face recognition task, their performance in the recognition phase was impaired significantly. This result suggested that the eye movements during the learning phase were related to recognition performance. Sekiguchi (2011) further showed that participants who had high face recognition memory performance moved their eyes between the left and right eyes more frequently (i.e., an analytic eye movement pattern) during face learning than those with low recognition performance. This result suggests that, similar to eye movements during face recognition, analytic eye movement patterns during face learning may also be associated with better recognition performance.

In addition, in the literature, it has been suggested that during visual recognition, participants showed similar eye movements to those generated during visual learning. For instance, the scan path theory posits that in pattern perception, the mental representation of visual patterns includes the perceptuomotor cycle