# Emotion influences behavioral outcomes and attention during goal-directed reading

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**Abstract**

Recent studies on the interaction between emotion and reading comprehension provide a murky picture with contradictory claims. Here, we offer one explanation for this phenomenon. By utilizing an advanced eye movement analysis method EMHMM with co-clustering, we discovered two representative attention patterns from eye fixations: an expanded, globalized attentional pattern and a more focused, localized attentional pattern. The subsequent analysis shows that these two attention patterns were differentially associated with comprehension accuracy in questions that required either globalized (summative questions) or localized (detailed questions) attentional needs. Moreover, the emotional state influenced the use of the two attentional strategies, as well as reading performance, measured as accuracy and reading time. Our findings demonstrate how emotion may have facilitated or interfered with cognitive processing during reading comprehension that requires different attentional needs, which provides valuable insight into the intertwining relationship between emotions and other cognitive functions.

**Keywords:** emotion, attention, reading comprehension, eye tracking, EMHMM

## Introduction

Traditionally, research in cognitive science examines cognitive systems independently from emotions. However, recent studies have called for more active consideration of emotions and for integrating affective processes into cognitive science (Dukes et al., 2021). Such calls have also been made in the fields of psycholinguistics and neurolinguistics (Bohn-Gettler, 2019; Hinojosa, Moreno, & Ferré, 2020). Indeed, a wide body of research has demonstrated the existence of interaction effects between one's emotional state with language functions, including common language ERP signals like N400 and P600 (Edigi et al., 2012; Verhees et al 2015; Lai et al., 2022), and language production (Braun, et al., 2019; Out et al., 2020). However, the role that emotion plays in reading has not been consistently reported in literature. Some studies claim that positive emotional valence facilitates reading comprehension (Bohn-Gettler & Rapp, 2011; Megalakaki et al., 2019; Scrimin & Mason, 2015), while other studies claim that negative emotional valence facilitates reading comprehension (Arfé, Delatorre, & Mason 2023; Mills, Wu, & D'Mello 2017; Mills, Southwell, & D'Mello 2023).

The seemingly contradictory findings reported in previous literature could be understood through the lens of attention. On the one hand, a significant body of literature indicates that attention is modulated by emotion (Taylor & Fragopanagos, 2005; Mohanty & Sussman, 2013; Schindler & Bublatzky, 2020). One popular theme is that positive emotional valence tends to broaden and expand attention (Fredrickson 1998, 2001), while negative emotional valence tends to elicit more localized and focused attention (Gasper and Clore, 2002). On the other hand, research also indicates that attention strongly regulates reading behavior (Franceschini et al., 2012; Valdois et al., 2019). Since the amount of information that can be processed is limited by the human visual system, readers must shift their eyes' fixation to sample new information about the passage. It is therefore argued by recent research that successful reading comprehension involves optimization of attention distributed on the reading passage (Zou et al., 2023; Hahn & Keller, 2023). Moreover, it has also been argued that the optimal distribution of attention depends on the goal of the task. For example, searching for a specific detail in a passage requires more focused attention than summarizing the main idea of a passage, and vice versa. Thus, we hypothesized that different reading goals impose distinct attentional demands, which are facilitated or hindered by different emotional valence. Specifically, we propose that positive valence promotes global attention strategies, which enhance reading performance, when the task goal requires evenly distributed attention across the passage, such as when summarizing the main idea. Conversely, negative valence induces more focused attention, which enhances reading performance when the task goal requires localized attention to extract specific information. Moreover, when the attentional strategy is incongruent with the goal requirements, we hypothesize that reading comprehension will be impaired.

While previous studies have explored similar hypotheses regarding emotion, attention and text processing, they are limited by two constraints. First, the measurement of attention in these studies has predominantly relied on traditional summative eye-tracking metrics, which may be insufficient for capturing individual differences in attention (Le Meur & Baccino, 2013). Secondly, these studies focused only on analyzing different post-reading question types that assessed different aspects of comprehension abilities, but not on goal-driven attention during the reading process. Therefore, this may have failed to elicit differential attention



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processes during reading, limiting their ability to explore the dynamic interplay between attention and task demands, and how these processes are regulated by emotional state.

To address this gap, this study adopts the novel paradigm from Zou et al. (2023) that manipulates participants' higher-level goal-driven attention to examine its interaction with emotion. Specifically, we present participants with different reading questions (i.e., to summarize or to extract local details in the article) prior to the reading. By applying an advanced, machine learning model based method, Eye Movement analysis with Hidden Markov Models (EMHMM) with co-clustering, which is shown to effectively quantify individual differences in eye movement patterns, we moved beyond mere summative eye tracking metrics and identified two representative eye fixation patterns during reading (Hsiao, An, Zheng, & Chan, 2021; An & Hsiao, 2021; Liao & Hsiao, 2024). In the current study, the aims were to: (1) test whether EMHMM could effectively distinguish distinct attentional processes during reading, and (2) explore whether the attentional patterns identified by EMHMM had a distinct impact on reading performance, and (3) evaluate whether emotional state could regulate such cognitive processes.

# Method

## Participants

We recruited 42 university students from Hong Kong. 2 participants were removed from further analysis due to unexpected program error, leaving 40 participants in total (29 Females, 11 males). Their age range was from 18 to 21 ($M_{age}$= 18.8, $SD_{age}$= 1.06). All of the participants spoke English as a second language. Their English ability was assessed using the Quick Placement Test. Result showed that their average English ability was equivalent to the B1 standard in the Common European Framework of Reference.

## Materials and Apparatus

**Reading materials.** The reading materials were adapted from the RACE dataset (Lai et al., 2017). RACE dataset is a large reading comprehension dataset consisting of English reading passages designed for Chinese high school students who learn English as a second language. We extracted 52 passages from the RACE dataset, which fell under 2 categories: global questions or local questions. Each passage was paired with only one corresponding question. Global question means that the answer was evenly distributed in the article, so a global understanding of the passage was required to answer successfully. For instance, asking a participant to summarize the main idea of the passage belongs to a global question. On the contrary, local question means that the answer was concentrated in a specific location of the article. Therefore, a more localized and focused understanding of the passage was required to answer successfully. There were 26 global questions and 26 local questions in total. The reading material was presented with triple line spacing to ensure sufficient eye tracking data quality.

**Eye tracker recording.** The stimuli were presented on the 20" (1680 by 1050 pixels) display monitor. Each letter extended 0.3 degrees of horizontal visual angle at a viewing distance of 75 cm. Participants' eye movement patterns were recorded using EyeLink 1000 Plus (SR research) with a 2000 Hz sampling rate. A nine-point calibration procedure was performed before the experiment and whenever the drift check error exceeded 1 degrees of visual angle.

**Music for Emotion-Induction Procedure** A standard emotion-induction procedure involving music and guided rumination was used for evoking positive and negative emotions. 10 pieces of classical music (5 positive and 5 negative) were selected based on previous studies which have demonstrated the effectiveness of the selected music (Ribeiro et al., 2019; Etzel et al., 2006; Marcusson-Clavertz et al., 2019). All music involved no lyrics and was re-edited using Adobe Audition to 2 versions, a longer version that lasted precisely 2 minutes, and a shorter version that lasted precisely 1 minute. "Fade in" and "Fade out" were also applied to remove any disruption caused by abrupt starts or stops. In addition, since the perception of emotion might vary among individuals (Carter et al., 1995), and to ensure the music indeed induced the intended emotions, we asked participants to rate the valence for all the music pieces before the formal experiment. The top two pieces with highest valence and lowest valence were used for positive emotion induction and negative emotion induction respectively.

## Design

Adapted from Zou et al's paradigm (Zou et al.,2023), all participants went through the reading task as shown in **Figure 1.**

**Reading trial.** **Figure 1A** illustrates one sample trial in the reading phase. Before starting to read the passage, the participants first read the question (without any answer options). After this, they entered the passage reading phase. Lastly, they engaged in answering the multiple-choice questions, where they chose one from four options. This procedure allowed us to study how attention was allocated to the passages based on the different requirements of the questions. Indeed, since studies have already shown that question requirements influence the allocation of attention during reading (Reynolds & Anderson, 1982), presenting the question in advance enabled us to separate distinct attention strategies associated with different reading goals. As mentioned in the previous section about reading materials, there were two types of reading questions, namely local and global questions. To answer these questions, the corresponding attention pattern should be reflected during passage reading. So that along with the emotional manipulation, we could investigate how emotional state differentially affected these distinct reading attention processes.

For each passage, participants were given a time limit of 60 seconds to complete their reading. However, they had the option to terminate the reading phase at any time if they felt prepared to answer the question. To motivate careful answering, in addition to the original rewards participants received, they were also told a bonus lottery would be given based on their rankings among all participants in terms of accuracy and reading time.

**Music Phase.** To study the effects of emotion on reading comprehension, music was used in combination with guided rumination (Jiang et al., 2024). Specifically, **p**articipants were instructed to immerse themselves in the music and to develop matching thoughts corresponding to the music. For example, in positive conditions, the participant should generate positive events while listening to the positive music, vice versa for negative conditions. We did not include neutral conditions, because previous research has shown that it is difficult to find music with a neutral emotional tone, as different listeners may perceive it as either positive or negative (Ribeiro et al., 2019). Therefore, we decided to only include two emotional conditions. A block design was used here, with a positive emotional group and a negative emotional group. As indicated by **Figure 1B,** during the music phase, participants received a 9 x 9 affective grid to measure their baseline valence (Russel et al., 1989). Then, they entered either a positive emotional block or a negative emotional block. The order of the blocks was counterbalanced. Then, the participants received an emotional induction procedure that lasted 2 minutes, and a second affective grid was used to measure their changes in valence. Given that prior studies indicated that the effectiveness of emotional induction diminished after 4 minutes and physiological changes reverted to baseline after approximately 2 minutes (Gillies & Dozois, 2021; Ribeiro et al., 2019), we also designed shorter, 1-minute “booster” induction sessions interspersed between trials. We switched to a new music piece after every 13 passages to maintain the novelty of music for emotional induction.

**Reading Phase.** After the emotional induction, the participant was then asked to complete the reading task as described in the section of reading trial. A total of 52 questions were used. After each trial, the participant moved back to the music phase to receive a 1-minute emotional booster. A 5-to-10-minute break was given after every 13 trials. The behavioral measures, including accuracy in question answering and reading time, were recorded during this phase. In addition, their eye movement was recorded as measure of attention. In the current study, the independent variable was the emotion condition induced in the music phase, while dependent variable was the reading behavior and attention measures in the reading phase.

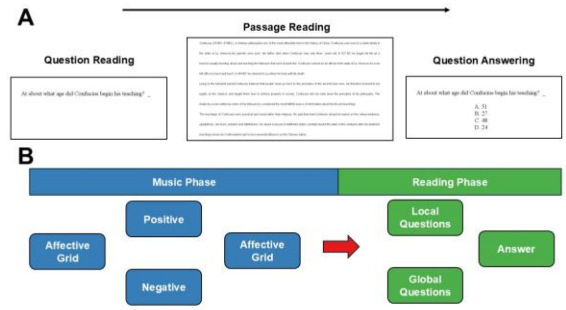


Figure 1: 1A displaying one sample trial that consists of question reading, passage reading, and question answering. 1B illustrates the general flow of the experimental flow.

## Eye Movement Analysis

EMHMM with co-clustering was used to summarize participants’ eye movement behavior during reading (Hsiao et al., 2021). This analysis involved two steps. In the first step, an individual’s eye movement pattern in each passage was summarized using a Hidden Markov Model (HMM) with personalized regions of interest (ROI) and transitions among these ROIs. Building on previous studies (Liao & Hsiao, 2024; Liao, Li, & Hsiao, 2022), we modeled the emission probability for each hidden state to follow a 2D Gaussian distribution, and the transition between each hidden state as a Markov process, which means that the current hidden state depended on the previous hidden state. Therefore, the individual differences in both spatial and temporal dimensions of eye movements (gaze locations and transitions) were captured. Here, we selected the range of the number of hidden states in each individual model to be from 1 to 8 and used variational hierarchical expectation maximization (VHEM) algorithm to estimate the optimal number of hidden states for each model (Coviello, Chan, & Lanckriet, 2014).

In the second step, a co-clustering method was applied to discover representative pattern groups such that participants clustered to each pattern group had similar eye movement patterns to one another across passages Following previous studies using EMHMM with co-clustering, we clustered participants into two representative pattern group, and within each pattern group each passage had a representative HMM summarizing eye movement patterns from the participants being clustered into the pattern group. (Liao & Hsiao, 2024; Zheng et al., 2022; Cho et al., 2022). For each representavie passage model, the number of hidden states was set to be the median number of the hidden states of individual HMMs. All models (including the individual HMMs) mentioned above were trained 300 times with different initial Gaussian ROIs, and models with the highest log-likelihood of the data were selected.

Then, the similarity between individual HMMs and the representative group-level HMMs was quantified using data log-likelihoods (the likelihood that the given fixation data of one participant was generated from either group-level HMM A or B). We defined an A–B scale as $(L_A – L_B) / (|L_A| +|L_B|)$, where $L_A$ and $L_B$ are the log-likelihood of the participant's data being generated by cluster group A or cluster group B. Thus, along the A-B scale, a more positive score indicates higher eye movement similarity to group A HMM pattern, and a more negative score indicates higher eye movement similarity to group B HMM pattern. In addition, eye movement consistency of participants was assessed using the overall entropy of the HMM: a higher entropy of the model indicates lower consistency in the distribution of the fixations and sequences of the ROIs summarized in the model (Hsiao, An, & Chan, 2020; Hsiao et al., 2022; Liao, Li, & Hsiao, 2022).

## Result

### Emotion manipulation

To validate emotional manipulation, we performed paired sample t-tests on the valence ratings before and after the music for all trials. The results revealed a significant difference in valence ratings during the positive emotional induction, with post-test ratings (M = 6.56, SD = 1.07) being significantly higher than pre-test ratings (M = 5.89, SD = 1.23), $t(1039) = 22.61$, $p < 0.001$). Similarly, a significant difference was observed during the negative emotional induction, with post-test ratings (M = 3.72, SD = 1.01) being significantly lower than pre-test ratings (M = 4.40, SD = 1.09), $t(1039) = -21.54$, $p < 0.001$). Therefore, manipulation effectively induced the target emotional states.

### Behavioral Results

**Figure 2** displays the behavioral results for accuracy and reading time. A repeated-measures ANOVA was used to analyze these behavioral results. To control for English proficiency, the QPT score was included as a covariate.

For accuracy, the result revealed a significant main effect of question type ($F(1, 38) = 5.64$, $p = 0.023$); however, there was no significant main effect of emotion condition ($F(1, 38) = 2.36$, $p = 0.132$). A significant interaction between Question Type and Emotion condition was also observed ($F(1, 25) = 21.24$, $p < 0.001$), indicating that the effect of question type varied depending on the emotional condition. A post hoc test was performed on the interaction term. As shown in **Figure 2A**, for local questions, the performance was higher in the negative emotional conditions than the positive condition, and this effect was significant after correcting for multiple comparisons ($p_{tukey}= 0.003$). But it was not statistically significant for global questions ($p_{tukey}= 0.092$). Importantly, the QPT score did not show any significant between-subjects effect ($F(1, 38) = 1.78$, $p = 0.19$). This suggests that English proficiency did not influence the observed behavioral results.

For reading time, a significant main effect was found for Question Type ($F(1, 38) = 113.85$, $p < .001$) and Emotion Condition ($F(1, 38) = 36.46$, $p < .001$). Similarly, no significant between-subjects effect in QPT score was observed ($F(1, 38) = 0.03$, $p = 0.863$). The interaction term also shows a significant effect ($F(1, 38) = 88.1$, $p < .001$). Therefore, a post hoc test was performed on the interaction term. As shown in **Figure 2B**, for global questions, the positive emotional group had similar reading time as the negative emotional group ($p_{tukey}=0.734$). This is likely because global questions, being more summative in nature and requiring participants to integrate information from the entire text, generally took longer to process. This could have led to a ceiling effect, where the emotional condition did not further influence reading time. But for local questions, participants read faster in the negative conditions, and longer in the positive condition ($p_{tukey}<0.001$).

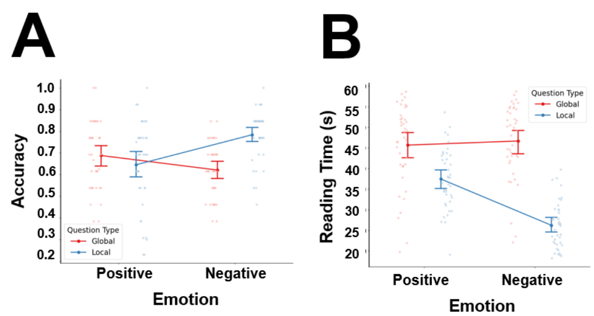


Figure 2: 2A displaying Emotion and accuracy. 2B displaying Emotion and reading time.

### Eye Movement Results

Through EMHMM with co-clustering, we discovered two representative pattern groups during passage reading among all participants. Since there were two types of questions (i.e., local and global), we plotted the representative patterns for a sample passage of each Question Type in **Figure 3 and Figure 4** respectively.

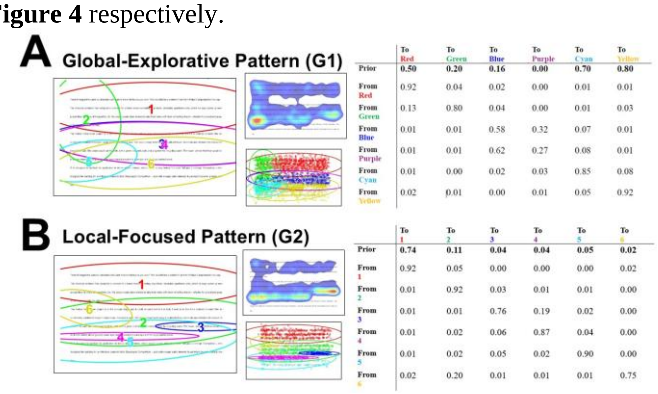


Figure 3: Local-focused and Global-explorative patterns for one sample passage for a local question. Ellipses show ROIs as 2-D Gaussian emissions. The small image shows the corresponding heatmap and fixations assigned to each ROIs. Transition probabilities among ROIs and the prior are shown on the right.

For the sample local question displayed in **Figure 3**, the question prompt was "The building's first floor would be built high above ground because…?". The location the participant needed to focus on is "first floor would be built nine meters above ground…to save space in thickly populated areas". In group 1, ROIs were evenly distributed across the whole articles and involved some vertically wider, horizontally narrower ROIs like ROI 2 (in green) (**Figure 3A**). Previous study discovered that an eye movement pattern with vertical ROIs involves a larger proportion of vertical saccades, (Zheng et al., 2022). Therefore, this suggests that participants were not only fixating narrowly within local areas but were instead scanning larger portions of the text vertically. On the other hand, group 2 have some vertically narrower, horizontally wider ROIs, such as ROI 3 (in blue) and ROI 4 (in purple) (Figure 3B). Importantly, these regions align with the locations targeted by the question prompt. Thus, group 1 was more explorative, and group 2 was more focused.

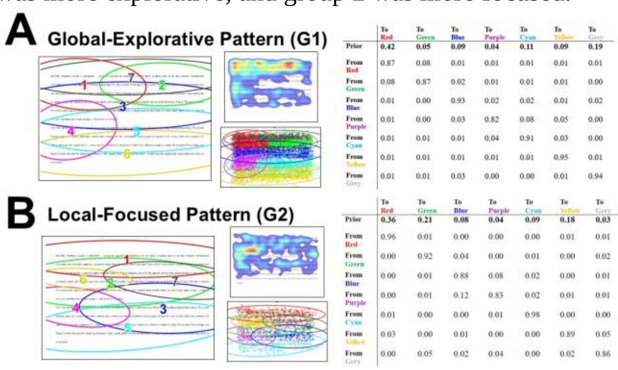


Figure 4: Local-focused and Global-explorative patterns for one sample passage for a global question.

For the sample global question displayed in **Figure 4**, the question prompt is "Which of the following expresses the main idea of the text?". Unlike the local questions, there was no single location that the participant should focus on. Instead, participants should try to integrate the entire passage. As shown in **Figure 4A**, similar to local questions, the ROIs of group 1 were generally vertically wider, horizontally narrower ROIs like ROI 1 (in red) and 4 (in purple). On the other hand, the ROIs of group 2 had more vertically narrower, horizontally wider ROIs, such as ROI 6 (in yellow) and 7 (in grey). Therefore, group 1 was more explorative, while group 2 was more focused. Taking the clustering results in both local and global question passages into account, here we refer to group 1 as the Global-Explorative pattern, and group 2 as the Local-Focused pattern. A-B scale is referred to as G-L scale. A more positive G-L scale indicates a higher similarity to the Global-Explorative pattern.

The representative HMMs of the two pattern groups were significantly different from each other according to Kullback-Leibler divergence approximation using data log-likelihoods: data from participants being clustered into the Global-Explorative pattern group were more likely to be generated by the representative HMMs in the Global-Explorative pattern group than the Local-Focused pattern group (t(51)=7.551, p <0.001), and vice versa (t(51)=6.6, p <0.001).

## Eye Movement and Behavior

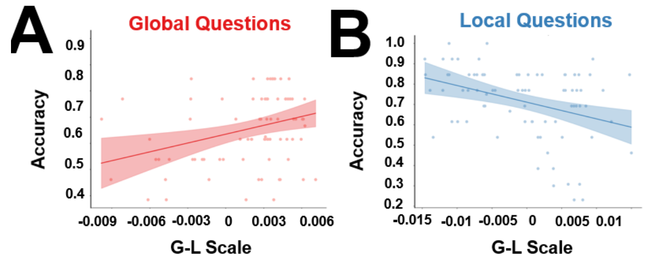


Figure 5: Correlation between accuracy under different question types and G-L Scale

A paired-sample t-test to examine whether participants' HMMs under global questions and local questions differed significantly in entropy. The results showed a significant difference (t(39) = 4.83, p < 0.001), with models for the global questions (M = 11.39, SD = 0.45) having a higher entropy than those for the local questions (M = 11.23, SD = 0.29). As entropy is a measure of eye movement consistency, this suggests that eye movements were more consistent when participants were reading to answer local questions compared to global questions. Indeed, since there were keywords present in local questions, there should be higher consistency to look at these keywords compared to global questions, where there were no keywords. Correlations between the G-L scale (higher G-L scale indicates higher similarity to the Global-Explorative pattern) and performance measures (accuracy) were then analyzed for local and global questions separately. As shown in **Figures 5A and 5B**, the G-L scale was positively correlated with accuracy in global questions (*r* = 0.31, p = 0.005), suggesting that a more global-explorative pattern was associated with better passage reading performance for global questions. Critically, a reverse trend was observed in local questions, where the G-L scale was negatively correlated with accuracy (*r* = -0.36, p = 0.001), suggesting that a more local-focused pattern was associated with better performance for local questions. These results indicated the importance of adopting the eye movement strategy that matches the task requirements.

We then conducted a repeated–measures ANOVA on G-L scale to examine the effect of emotion and question type on eye movement patterns. The result showed that the interaction effect was significant (F(1, 38) = 6.94 p = 0.012; **Figure 6**): there was no significant difference between positive and negative emotion in G-L scale for global question type ($p_{tukey}$=0.992), but there was a significant effect of emotion condition for local question type ($p_{tukey}$ = 0.005). Specifically, negative emotions induced a more Local-Focused eye movement pattern, while positive emotion induced a more Global-Explorative pattern. Similarly, no effect was found for English proficiency as the QPT score showed no between subject effect (F(1, 38) = 0.14 p =0.712).

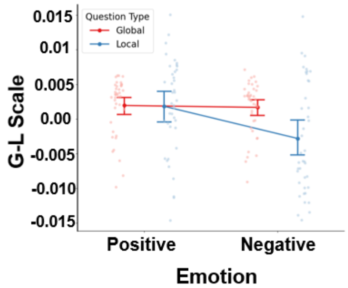


Figure 6: The interaction between Emotion and question type on G-L scale

## Discussion

In the current study, we utilized EMHMM to identify two representative eye movement patterns during reading: the Local-Focused pattern and the Global-Explorative pattern. As expected, these patterns reflected distinct attention allocation strategies driven by task goals. The Local-Focused pattern enabled participants to concentrate their attention on critical areas of the text. In contrast, the Global-Explorative pattern promoted distributed attention across the entire passage. Then, we found for local questions, a more localized attention pattern led to higher accuracy, as it helps guide participants' attention to sample information from the most relevant areas of the passage with regard to the question. Conversely, for global questions, a more Global-Explorative attentional pattern improved accuracy by promoting distributed attention across the passage, aiding in overall comprehension. Moreover, our findings on entropy differences between these patterns suggest that Local-Focused strategies exhibited greater consistency in eye movements, possibly due to the presence of keywords in localized text sections that enhanced attention planning efficiency.

Our findings also contributed to the understanding of how emotion may interact with the processes mentioned above. At the behavioral level, our results suggest that negative emotions were associated with higher accuracy and faster reading speed for local questions, while the positive emotional state was associated with lower accuracy and slower reading time. This difference in performance aligns with the hypothesis that negative emotions elicit more analytical and detail-focused cognitive processing, which enhances performance on tasks requiring localized attention. In contrast, positive emotions broaden attentional scope, which might hinder performance when precision and focus on specific details are needed. Furthermore, the results also demonstrated a significant effect of emotional conditions on attention allocation for local questions. In particular, positive valence led to a more Global-Explorative strategy, whereas negative valence resulted in a more Local-Focused strategy. This difference in attentional strategies based on emotional valence provides evidence for the hypothesis. Indeed, previous studies using aggregated eye movement data have shown that negative emotional valence enhances localized attention, making text processing more analytical (Arfé, Delatorre, & Mason 2023), while other studies on visual attention have found that positive emotional valence broadens attentional breadth and facilitates access to a greater diversity of information (Rowe, Hirsh, & Anderson, 2007; Fredrickson & Branigan, 2005). To put the evidence together, we found that for local questions, emotional valence differentially influenced attention allocation, which in turn affected comprehension accuracy. In other words, this supports the hypothesis that emotional valence influences text comprehension and the corresponding attention process.

However, it is worth noting that emotional conditions did not have a significant impact on global questions. One possible explanation is that the current emotional manipulations were insufficient to influence attention during more complex reading processes. Considering that the global question condition here may not only require attention to specific locations, but also comprehensive understanding of the entire passage. Therefore, there might be more complex attention mechanisms that are beyond the scope of the current emotional induction procedure.

Another possible concern is whether language proficiency may have influenced the results of this study. However, we argue that language proficiency is unlikely to substantially undermine our findings for two reasons. First, the stimuli used in this study has been carefully selected. As mentioned, all question from the RACE datasets is based on standardized test of the Chinese college entrance examination. In other words, these questions are specifically designed for testing the English reading skills of L2 speakers of English. Second, all participants have reached at least the B1 level of the European language standard. This indicate all the subjects in this study are proficient L2 English speakers. In addition, our analysis included English proficiency as covariates, and the results did not find any significant effect, suggesting that English proficiency does not affect our analysis. Nevertheless, it is important to acknowledge that prior research has found that non-native speakers do spend more time reading question-related information than native speakers (Zou et al., 2019). This may be because more proficient readers dealing with relatively easy texts process information so efficiently. Therefore, it is unclear whether the differences in attention allocation caused by different emotions will be the same in L1 and L2 readers. This will be an interesting topic to bring into the discussion and application in reading education and should be continued in future research.

In conclusion, this study provides empirical evidence that distinct attentional processes can be discovered through the EMHMM approaches, and that they have a distinct impact on different goal-oriented reading processes. We also show that emotional state can elicit different attentional strategies and influence reading behaviors including accuracy and reading time. These findings offer insights into how emotional states and attentional strategies interact to support goal-oriented reading processes.

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