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RESEARCH ARTICLE

Clean air captures attention whereas pollution distracts: evidence from brain activities

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HIGHLIGHTS

- We find air pollution distracts attention and reveal the neurocognitive mechanisms.
- Clean air captures more attention and evokes larger N300 amplitudes in all trials.
- Pollution causes lower accuracy and larger P300 wave in attention-holding trials.
- Pollution causes higher accuracy and lower P300 wave in attention-shifting trials.

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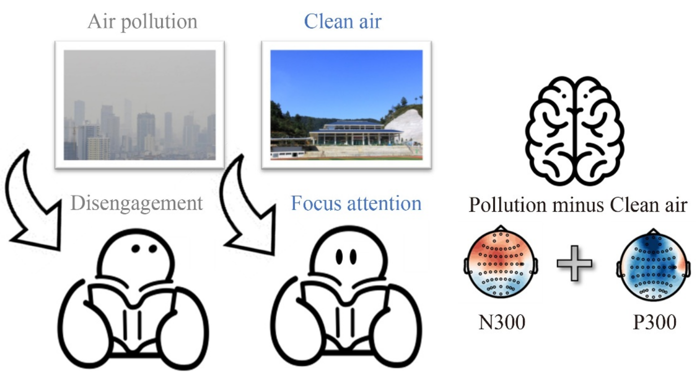
GRAPHIC ABSTRACT



ABSTRACT

Awareness of the adverse impact of air pollution on attention-related performance such as learning and driving is rapidly growing. However, there is still little known about the underlying neurocognitive mechanisms. Using an adapted dot-probe task paradigm and event-related potential (ERP) technique, we investigated how visual stimuli of air pollution influence the attentional allocation process. Participants were required to make responses to the onset of a target presented at the left or right visual field. The probable location of the target was forewarned by a cue (pollution or clean air images), appearing at either the target location (attention-holding trials) or the opposite location (attention-shifting trials). Behavioral measures showed that when cued by pollution images, subjects had higher response accuracy in attention-shifting trials. ERP analysis results revealed that after the cue onset, pollution images evoked lower N300 amplitudes, indicating less attention-capturing effects of dirty air. After the target onset, pollution cues were correlated with the higher P300 amplitudes in attention-holding trials but lower amplitudes in attention-shifting trials. It indicates that after visual exposure to air pollution, people need more neurocognitive resources to maintain attention but less effort to shift attention away. The findings provide the first neuroscientific evidence for the distracting effect of air pollution. We conclude with several practical implications and suggest the ERP technique as a promising tool to understand human responses to environmental stressors.

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1 Introduction

Air pollution is a major health risk factor for citizens around the world (Xie et al., 2023). Sources of air pollution also produce pollutants such as CO_2, and thus mitigating air pollution is essential to reaching the UN Sustainability Development Goals. It is well documented that air pollution causes adverse physical health effects, including respiratory and cardiovascular diseases (Li et al., 2018) . New evidence shows that both short-term and long-term exposure to air pollution influences people's cognitive function, behavior, and productivity. For example, by merging longitudinal survey and air quality data in China, Zhang et al. (2018) found that cumulative exposure to air pollution impedes cognitive performance in verbal and math tests. Similarly, Sunyer et al. (2015) found that traffic-related air pollution can reduce cognitive development in primary school children. Further, Graff Zivin and Neidell (2012) analyzed individual-level daily harvest rates among agricultural workers to show that elevated air pollution negatively affects labor productivity. These empirical findings demonstrate that overlooked cognitive impacts of air pollution may cause substantial social costs.

Current knowledge about how air pollution impairs cognitive performance is relatively limited. A range of pathological studies provide hypothesized biological pathways to explain the phenomenon. Potential contributory mechanisms include oxidative stress and neuro-inflammation, which often occur when ambient pollutants reach the brain areas (Allen et al., 2017). Another group of studies observe that short-term visual exposure to air pollution such as smoggy and dirty landscape can directly influence emotions and human wellbeing through psychophysiological pathways. For instance, Yang et al. (2021) presented participants with low-visibility cityscape photos caused by particulate matter (PM) pollution and found that their stress recovery process got largely impaired. Similarly, by showing observers simulated images with different levels of PM pollution, Li et al. (2019) suggested that higher air pollution levels predicted stronger negative emotions. Despite these research efforts, little attention until now has been paid to the neuroscientific mechanisms through which air pollution affects human cognitive performance.

According to the biophilic hypothesis, humans have an innate desire to approach nature, such as vegetation, green spaces, and water bodies in urban areas. There are huge amounts of evidence showing that nature helps relieve stress and restore attention. Conversely, pollution caused by anthropogenic activities is often viewed as threatening and can induce defensive reactions (Bradley et al., 2001). Air pollutants, especially PM pollution, is often associated with remarkable visibility degradation and is thus easy to perceive (Hyslop, 2009). In many heavily polluted developing countries, the public have high perceptions of air pollutants and are concerned about its health risks (Huang et al., 2017). This high risk perception toward threatening pollution stimuli in the environment may result in attentional avoidance during visual exposure, which further makes people disengage their attention and lead to more saccades to surrounding visual space.

Attention is the cognitive process that enables humans to position their cognitive resources toward relevant stimuli and respond to it (Compton, 2003). Cognitive performance is closely related to a person's ability of focusing and sustaining attention in the presence of other distracting stimuli. Since the capacity of human cognition is always limited, attentional disengagement may impair human cognitive performance by fostering forgetfulness, memory loss, and careless errors (Sunyer et al., 2017). Abundant studies have demonstrated that attention distraction has negative impacts on cognitive performance in almost every area of life such as academic achievement, driving, and work productivity (Lee et al., 2014). Therefore, it would be informative to test if the threatening information that individuals perceive from air pollution will affect attentional resource allocation process and subsequently decrease cognitive performance.

To fill this research gap, we designed a neuroscientific experiment aimed to reveal the neuroscientific basis of which air pollution affects attentional resource allocation and cognitive performance. More specifically, we investigated the impacts of air pollution picture stimuli on human's selective attention. In an adapted visual detection task, participants need to first capture attention toward salient stimuli and then decide to hold or shift attention (Biggs et al., 2012). We hypothesized that images with the polluted landscape would lead people to shift attention, whearas images with good air quality will facilitate the attention-holding process. The disengaging effect of air pollution can be reflected by using more cognitive resources to respond to targets appearing at the same place of pollution images but fewer to detect visual targets in other locations. It may help explain the cognitive mechanisms underlying why people find it more difficult to concentrate and have poorer performance and productivity on polluted days (He et al., 2019). We used two behavioral measurements, including response accuracy and reaction time, to evaluate participants' task performances.

To investigate the neurocognitive process of visual attention allocation, we used the high-temporal resolution technique of event-related potentials (ERPs). ERPs are derived from electroencephalography (EEG), a procedure that continuously records brain activity at the millisecond scale using electrodes placed on the scalp. To clearly observe the brain's response to the stimuli, experimenters conduct many trials and average corresponding EEG signals together at time-locked or event-locked moments, averaging out random brain activity and keeping only the relevant waves, namely the ERP (Luck and Kappenman, 2012). ERP measures also provide additional knowledge about unique component waves that infer typical cognitive processes. For example, the famous P300 component elicited in the decision-making process can reflect resources necessary for visual attention in our experiment (Woodman, 2010). Furthermore, the amplitude of the ERP component is associated with the cognitive resources allocated for specific cognitive processes. By comparing ERP waves in “bad air” and “good air” conditions, we can identify the impacts of air quality on attention engaging and disengaging neurocognitive processes.

To our knowledge, this is the first study that examines the neurocognitive processes underlying attentional responses to air pollution. The results provide novel insights into how air pollution as visual stimuli affects attention allocation and task performance. Our study to some extent bridges the gap between environmental science and social cognitive neuroscience. We also conclude with several practical implications for minimizing the hidden social costs due to the neurocognitive influence of air pollution.

2 Materials and methods

2.1 Subjects

We conducted the experiment in the Environmental Psychology Laboratory at Nanjing University, China, in June 2020. The laboratory has an electrically shielded and sound-attenuating cabin where participants complete their tasks alone on the computer using keyboards. The experiment was approved by the university’s Ethical Evaluation Committee. Inclusion criteria for participation in our project were: healthy and non-smoking young college students since they are one of the most widely used sources of research subjects in neuroscience experiments. These subjects should not suffer from any medical conditions that could affect test performance, such as anxiety, fatigue, and attention deficit disorder. All participants had normal or corrected-to-normal visual acuity and intact color-vision. The study calculates a minimum sample size of at least 28, ensuring a power of 90%, a significance level of 5% (two-sided), and an effect size of 0.5 between pairs. Finally, a total of 32 undergraduate students (17 females, 15 males, 19.4 ± 0.97 years old) participated in our project for course credit with written informed consent obtained.

2.2 Experimental task and procedure

We used a variant of Posner’s dot-probe task paradigm to investigate the visual attention allocation process in response to air pollution stimuli. Posner’s paradigm has been widely adopted to study the attentional orientation patterns for threatening information (Mogg and Bradley, 2016). In such tasks, participants reacted to the onset of a target presented at the left or right visual field. Here we set two horizontal or two vertical dots as the target and ask participants to respond accordingly. The probable location of the target is forewarned by a visual cue (i.e., polluted landscape images or clean air images in our study) appearing at either the target location (attention-holding trials) or the opposite location (attention-shifting trials) (Fig. 1). For example, an attention-holding trial may show a visual cue (the image) on the right, followed by the presentation of the target (two dots), also on the right. An attention-shifting trial may show the visual cue on the right, but then present the target on the left. Theoretically, for attention-holding trials, behavioral responses are usually rapid and accurate because the visual cue already directs attention to the target location. Responses are typically slower and less accurate for attention-shifting trials because attention must be disengaged from the incorrect cue location and reallocated toward the target position.

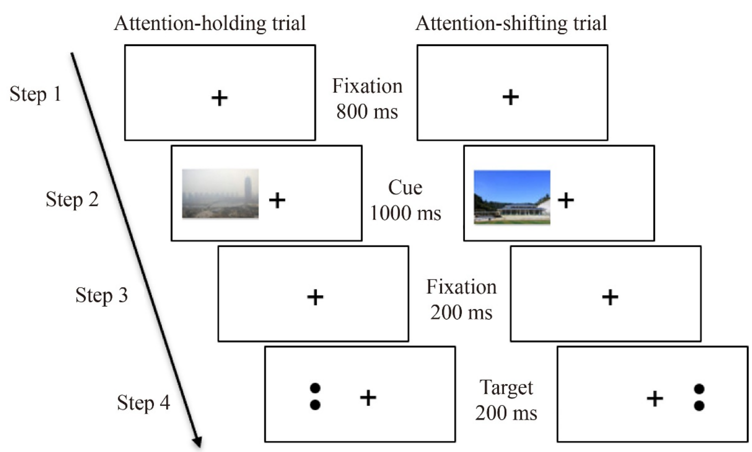

Fig. 1 Example trial sequences in the experiment. The attention-holding trial on the left side shows an example of using PM pollution pictures as the cue, and the attention-shifting trial on the right side shows an example of using good air pictures as the cue.

Figure 1 depicts the example sequence for each trial. First, a fixation cross is presented for 800 ms to help concentrate attention. This was followed by a clean or polluted cue image for 1000 ms on either the left or right side of the screen. Although the cues are irrelevant to the task, we hypothesize it may affect responses to the stimuli because of its attentional engaging/disengaging effect. After a second fixation period of 200 ms, two horizontal or two vertical dots are presented as the target for another 200 ms. The target could be either on the same side as the cue (attention-holding trials, 60% of total trials) or on the opposite side of the screen (attention-shifting trials, 40% of total trials). Participants were instructed to keep their gaze fixated on the central cross and respond to the targets' orientation (either vertical or horizontal) by pressing corresponding buttons (either left or up arrows) as quickly as possible.

When participants arrived, they were greeted by an experimenter and given general task instructions. The whole session for each subject contained 640 trials with 384 attention-holding and 256 attention-shifting trials, which lasted about 2 h, including the mounting and removal of the EEG electrode cap. Through the experimental session, attention-holding and attention-shifting trials occurred in random order. Cue-target combinations and the location of the target dots were also counterbalanced. Reaction time, response accuracy, and EEG signals are recorded for each trial. Each participant took a practice block of 3 min and 50 trials before the start of the formal experiment to ensure they understood the task. Participants were debriefed after the experiment about the nature of the study. They sat in a chair approximately 90 cm from the 24-in. monitor with fingers poised on the response buttons.

2.3 Materials and apparatus

We used 16 polluted landscape images and 16 clean air images as cues in the formal experiment. The images were obtained online and have a diversity of sources, including open-access real photo databases for research purposes (e.g., Archive of Many Outdoor Scenes, AMOS) (Jacobs et al., 2007), personal snapshots shared on social media, and other public photo-sharing data sets without copyright restriction for research (Yang et al., 2021). The polluted landscape images show distant views from urban buildings with severe PM pollution backgrounds, gray skyline, and low visibility. The clean air images should contain blue sky and a clear landscape. These images are from different geographic areas and do not contain any local landmarks. All photos were provided with specific location and time information, so that we were able to match real-time $PM_{2.5}$ concentrations for each photo sourced from the closest air monitoring center. See example images in Fig. S1.

To ensure that image characters are consistent and will not influence experimental results, we set a few inclusion criteria and did the following preprocessing steps. First, for pollution group, we included only images with $PM_{2.5}$ concentration higher than 150 μg/m^3, a level that has enabled to induce negative emotions. For clean air group, we only kept images with $PM_{2.5}$ concentrations lower than 30 μg/m^3, a level that is able to trigger positive responses (Yang et al., 2018). Second, we used Photoshop software to crop the images and make sure the sky area covers more than 70% of the image. The cue images were scaled to 12-cm in width and 10-cm in height. The target stimuli (two horizontal or vertical dots) were adjusted to a comparable size of 3-cm diameter for each. The resolution, luminance, chrominance and contrast of all photos were set as automatic referring to previous studies (Bradley and Lang, 2007). Finally, before the experiment, we invited 20 volunteers to rate their perceived air quality, annoyance, valence and arousal on each group of images using a 9-point Likert scale. Mean scores and standard deviations are given in Fig. S2. The self-ratings suggest that people perceived significant lower air quality, higher annoyance and lower valence toward images in the pollution group. It shows that participants are able to clearly distinguish the threatening information from pollution images.

2.4 Data analysis and hypotheses

We expected that exposure to visual impact of air pollution leads to attentional disengagement. More specifically, in attention-holding trials, we assumed that people would need more cognitive resources to focus on the target at the same location when cued by air pollution images compared to the clean air images. In attention-shifting trials, fewer cognitive resources are needed to shift attention *away* from the pollution cues than the clean air cues, and *toward* the target on the opposite side of the screen. Accordingly, four hypotheses were tested (Table 1), considering two behavioral measures and two neurocognitive indicators.

Regarding behavioral measures, we recorded response accuracy and reaction time as the measures of task performances. Response accuracy is a dichotomous variable that measures if the participants make correct button-press in response to the target in each trial. Reaction time is the time taken to press button correctly since the onset of targets in each trial. Trials that had a response time faster than 150 ms were considered outliers and excluded from the analysis. We expected that pollution cues lead to lower accuracy than clean air cues for attention-holding trials but higher accuracy for attention-shifting trials (Hypothesis 1). Then, pollution cues lead to longer reaction time than clean air cues for attention-holding trials but shorter reaction time for attention-shifting trials (Hypothesis 2). We employed ANOVA analysis to examine the influence of trial types

Table 1 Four research hypotheses and related behavioral and EEG indicators

No.	Indicators	Hypothesis
#1	Response accuracy (Accuracy of making correct button-press in response to the target)	Pollution cues lead to lower accuracy than clean air cues in attention-holding trials but higher accuracy in attention-shifting trials
#2	Reaction time (Time taken to press button correctly since the onset of targets)	Pollution cues lead to longer reaction time than clean air cues in attention-holding trials but shorter reaction time in attention-shifting trials
#3	N300 amplitudes (ERP component in response to picture stimuli. Larger amplitudes indicate more greater attention captures)	Clean air cues can capture more attention and are associated with higher N300 peak amplitudes than pollution images, both for attention-holding and attention-shifting trials
#4	P300 amplitudes (ERP component elicited in the process of decision making. Larger amplitudes indicate more cognitive resource use)	Pollution cues lead to higher P300 amplitudes than clean air cues for attention-holding trials but lower P300 amplitudes for attention-shifting trials

(attention-holding or attention-shifting), cue types (pollution or clean air), and the interaction between the two variables on response accuracy and reaction time respectively.

EEG activities were acquired and synchronized using the 64-channel NeuroScan SynAmps amplifier. A 64-channel cap fitted with sintered Ag-AgCl electrodes was positioned in accordance with the standard 10–20 system, see the topographical distribution of channels in Fig. S3. EEG signals were referenced to the mastoid electrodes and recorded at a sampling rate of 1000 Hz. All electrode impedances were kept below 5 kΩ to ensure good data quality. Preprocessing steps were performed first. We filtered continuous raw EEG data offline with a bandpass filter of 0.05 to 30 Hz. We visually detected corrupted electrode channels for each participant and removed them. Epochs of 2,200 ms were then extracted from the continuous EEG signal, starting 200 ms before the onset of the cue (i.e., pollution or clean air images) and ending 600 ms after target (i.e., horizontal or vertical dots) offset. We removed the mean baseline value from each epoch using the 200-ms pre-cue interval as the window. Artifacts caused by eye blinks and eye movements in each epoch were corrected using the independent components analysis (ICA) algorithm. Epochs were rejected if they contained scalp muscle artifacts beyond ± 120 μV. After these data preprocessing steps, ERPs were derived by averaging epochs from all the subjects for each cue type, trial type, and electrode site. Epoch rejection rates across trial types and cue conditions are given in Table S1. About 11%–14% of epochs were removed and the number of epochs remained are comparable in different conditions.

For the analysis of the neural data, we were especially interested in two ERP components. The first one is the fronto-centrally distributed N300 component followed by the onset of cue images (pollution/clean air), which is a negative-going wave that peaks 250–350 ms post-stimulus. The N300 is closely related to emotional processing of complex visual stimuli. Studies have reported that the N300 shows greater amplitudes in response to more attractive and activating stimuli (Carretié et al., 1997). We specified electrodes FCz, FC1, FC2, FC3, FC4, Fz, F1, F2, F3, and F4 as the regions of interest. For time-windows of interest, we extracted the mean amplitude between 250 ms to 350 ms in accordance with previous literature (Kumar et al., 2021). Lanscapes with good air quality meet with the innate of human instinct to connect with healthy natural environment and also have greater value of aesthetic appreciation (Hyslop, 2009). In our study, we expected that clean air cues can capture more attention and are associated with higher N300 peak amplitudes than pollution images, both for attention-holding and attention-shifting trials (Hypothesis 3).

The second component we were interested in is the P300 after the onset of targets (vertical or horizontal dots). The P300 is a relatively late component that peaks around 300 ms post-stimulus. P300 is a good indicator to reflect the amount of cognitive resources necessary for the disengagement of attention. P300 amplitude is sensitive to the amount of attentional resources engaged during tasks. ERP studies using Posner's cueing paradigm have reported that P300 amplitude increases in the centro-parietal regions of the brain as disengagement from previously cued stimuli becomes more difficult (Kessels et al., 2010). We chose channels CPz, CP1, CP2, CP3, CP4, Pz, P1, P2, P3, and P4 as the regions of interest in line with previous studies. Mean P300 amplitudes within a window of 300 ms to 500 ms following the onset of the target were compared between different cue types. Given that our study aimed to investigate if pollution distracts attention, we expected that pollution cues lead to higher P300 amplitudes than clean air cues for attention-holding trials but lower P300 amplitudes for attention-shifting trials (Hypothesis 4).

3 Results

3.1 Response accuracy and reaction time

ANOVA analysis of behavioral data reveals that trial type ($F = 0.097$, $p = 0.768$, Cohen'd = 0.017) and air pollution cue ($F = 0.038$, $p = 0.846$, Cohen'd = 0.025) do not significantly affect response accuracy. However, there is an interaction effect between air pollution cue and trial type ($F = 8.262$, $p = 0.025$, Cohen'd = 0.084). Figure 2(a) illustrates this interaction effect. Specifically, in attention-holding trials, when cues are polluted landscape images, participants had lower averaged response accuracy than when cues are clean air images (~0.90%). It indicates due to the disengaging effect of pollution stimuli, participants' attention is shifted to other places and hence has lower accuracy in detecting targets occurring at the same location of the cue. In attention-shifting trials, when cues are polluted landscape images, participants had relatively higher response accuracy than clean air images (~1.17%). It suggests that participants' attentional resources are disengaged from the pollution images, and thus are easier to detect targets at the opposite location of the cue. While it should be noted that these effects are small, this may be behavioral evidence to support our Hypothesis 1 that air pollution distracts attention and affects task performance.

Regarding reaction time, we identified the main effect of trial type showing that participants tended to have a longer response time in the attention-shifting trials than in the attention-holding trials (~14 ms) (F = 92.622, p < 0.001, Cohen'd = 0.280) (Fig. 2(b)). This result is as expected since participants need to distract attention to detect visual targets in attention-shifting trials, which may take more time. However, there is no significant main effect or interactive effect of cue type. It indicates that air pollution images do not significantly affect speeds of behavioral performance, which does not support Hypothesis 2.

3.2 Effects of pollution cues in attention-holding trials

We then examined the effects of pollution/clean air cues on the neurocognitive process in the attention-holding trials by comparing ERPs with different cues. Visual inspection of topographic maps suggests similar brain activity distribution for both pollution and clean air trials (the first and second panels in Fig. 3(a)). When cues are onset, there are positive components in the occipital lobe indicating the process of visual perception (200–400 ms). Then, negative components are detected surrounding the central sulcus before and after the target appears, representing the cognitive process of spatial searching (1000–1400 ms). Finally, when subjects are making responses, there are remarkable positive components in the parietal and prefrontal cortex (1600–1800 ms).

Topographical distribution of ERP difference waves (the third panel in Fig. 3(a)) shows prominent divergence in the ROI (Region of interest) of the N300 and P300. Here the ROI of ERP components can be understood as the scalp region where certain brain activity is mostly likely to be observed. First, 200–400 ms after the onset of the cue, we find different amplitudes of N300 (pollution minus clean air) in the centro-frontal cortex, as shown by the large areas of deep red color. N300 indicates the process of perceptions of complex visual stimuli. It suggests that participants are sensitive to the visual information contained in the pollution and clean air images. We then draw the mean ERP waves for the channels of N300 ROI to examine the differences at higher temporal resolution (Fig. 3(b)). Starting from about 250 ms, the evoked N300 by good air cues show larger negative amplitudes than pollution cues. Statistical comparison further demonstrates that on average amplitudes elicited in the N300 interval (250–350 ms) for clean air trials were ~0.86 mV greater than pollution trials (t = −3.23, p = 0.003, Cohen'd = 0.590). The results support Hypothesis 3, showing that clean air images, which are emotionally pleasing and arousing, can capture

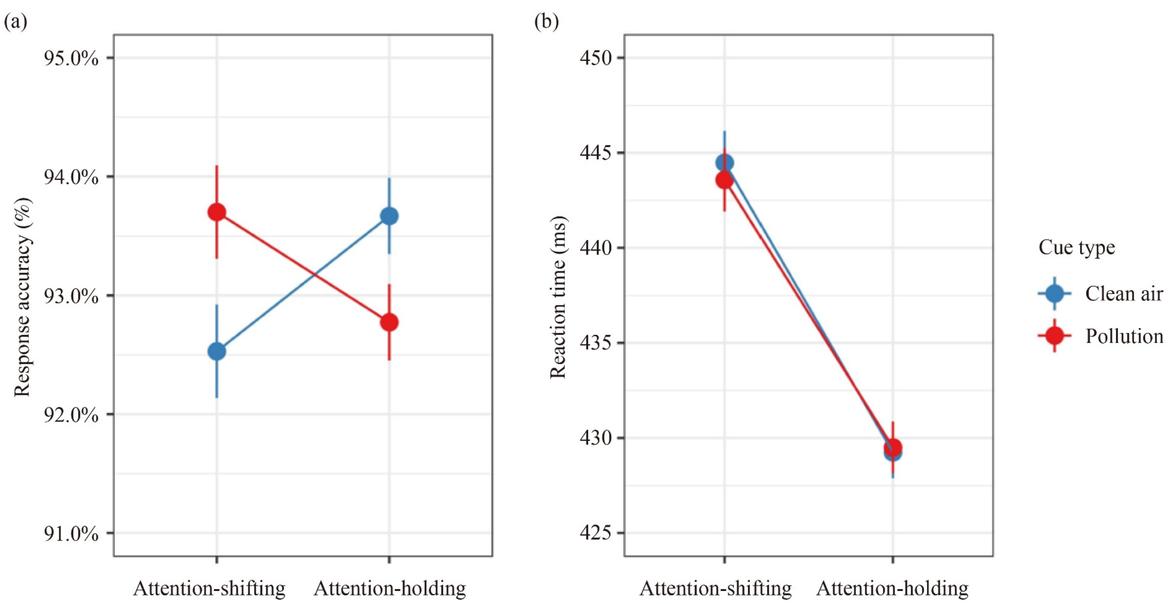

Fig. 2 Behavioral performance per cue type and trial type. Red and blue dots represent the least-squares means of pollution cues and clean air cues of (a) response accuracy and (b) reaction time, respectively. Error bars reflect standard errors of the mean (SEM).

more visual attention than pollution images.

Next, after the target onset, topographical maps show differences in ERP wave amplitudes (pollution minus clean air) around centro-parietal lobes (the third panel in Fig. 3(a)). It indicates that different cues affect the distribution of attentional resources when performing the tasks. Mean ERP waves for the P300 ROI (Fig. 3(c) show that pollution trials have ~0.56 mV higher P300 amplitudes than clean air trials at 1500–1700 ms when people make responses ($t = -1.70$, $p = 0.039$, Cohen'd = 0.311). It shows that when target and cue are presented on the same side of the screen, pollution cues tend to distract people's attention, and subjects will need more cognitive resources to focus on the task. On the contrary, in clean air trials, subjects are easier to give behavioral responses. Our results support Hypothesis 4 and demonstrate the disengaging effect of visual exposure to air pollution. It may explain why subjects are lower in response accuracy in attention-holding trials when cues are pollution images.

3.3 Effects of pollution cues in attention-shifting trials

We finally investigate the effects of pollution cues in attention-shifting conditions. Through the visual inspection of topographic maps (the first and second panel of Fig. 4(a)), we find the ERP in attention-shifting trials follows a similar pattern as we have elaborated in the attention-holding trials. However, the differences in ERP waves (pollution minus clean air) in attention-shifting trials are not fully consistent with that in attention-holding trials (the third panel of Fig. 4(a)). Shortly after the onset of the cue (200–400 ms), the differences in brain activities between pollution and clean air trials are prominent in the prefrontal and parietal cortex. Again, it indicates that subjects have allocated different attention in processing visual information of pollution and clean air images. However, in attention-shifting trials, pollution cue elicits a smaller amplitude of ERP component than clean air cue when subjects are making responses (1400–2000 ms), as shown by the deep blue color over a vast brain area. This is contrary to what we have found in the attention-holding trials.

To further delineate this discrepancy, we draw the mean ERP waves in ROI of N300 and P300. After the cue onset, we find clean air stimuli can induce greater amplitude of negative N300 component than pollution

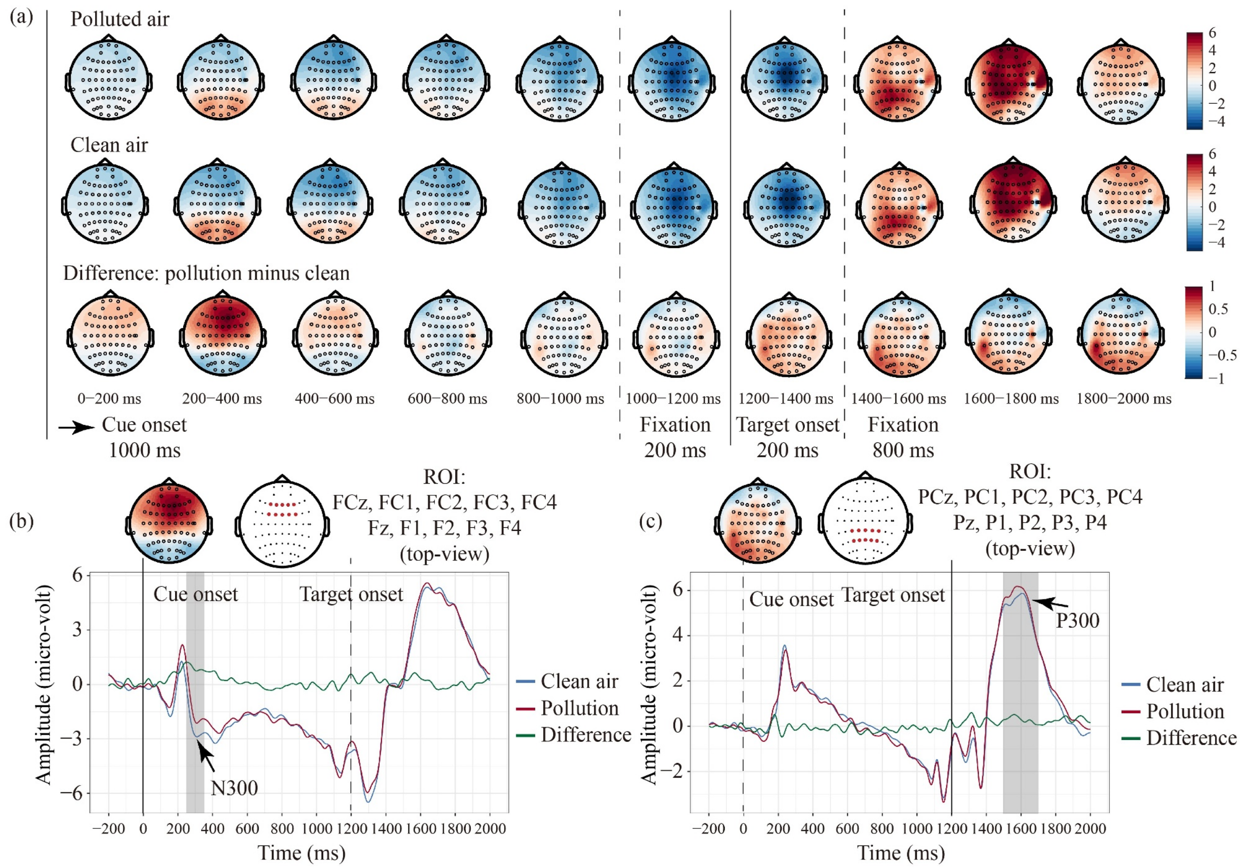

Fig. 3 ERP comparison between pollution and clean air cues in attention-holding trials. (a) Topographic plots of ERP waves show the brain activities in attention-holding trials per 200 ms with pollution images (the first panel) and clean air images (the second panel) as the cue. The third panel shows the ERP difference waves between pollution and clean air conditions. (b) Mean ERP waves for the channels of N300 ROI. (c) Mean ERP waves for the channels of P300 ROI. Gray rectangles indicate time windows of interest.

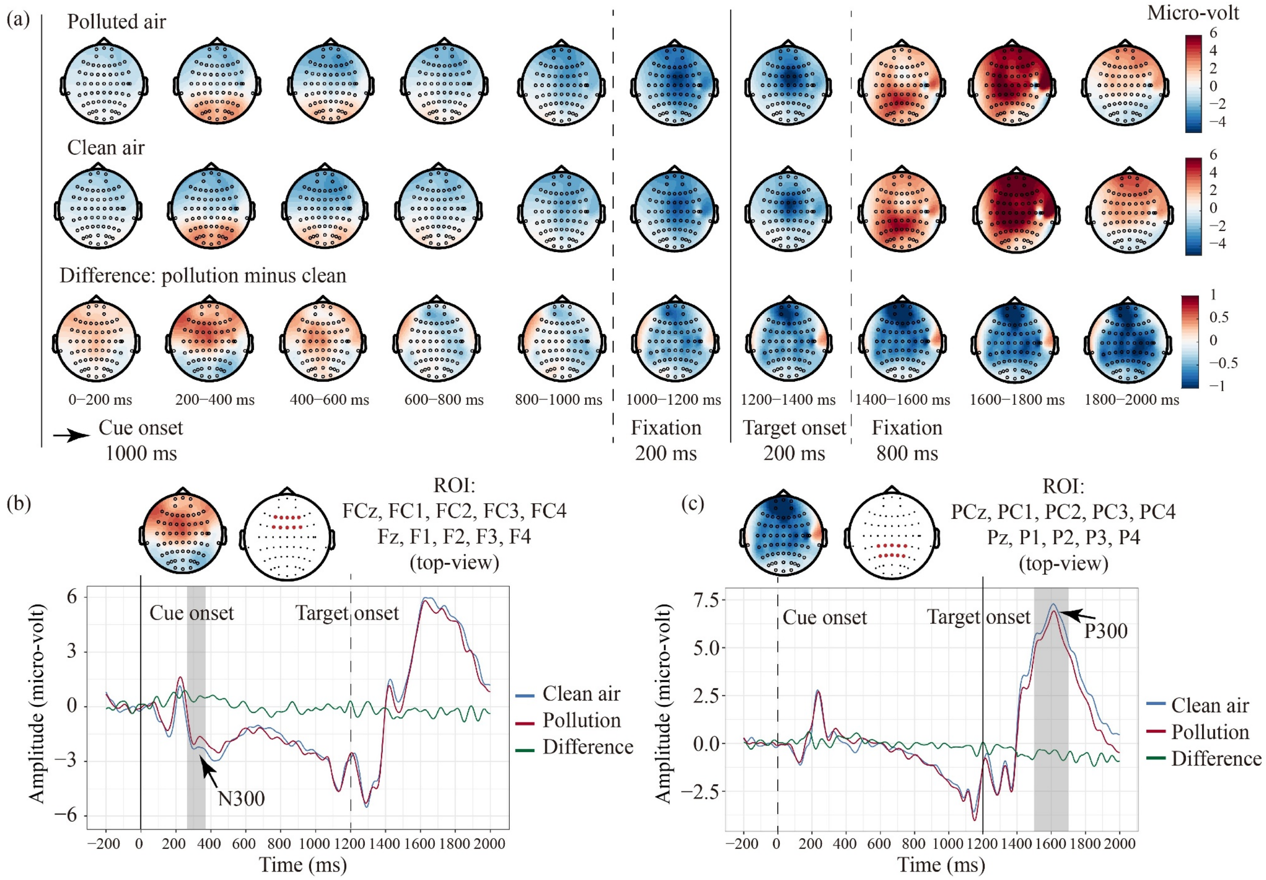

Fig. 4 ERP comparison between pollution and clean air cues in attention-shifting trials. (a) Topographic plots of ERP waves show the brain activities in attention-holding trials per 200 ms with pollution images (the first panel) and clean air images (the second panel) as the cue. The third panel shows the ERP difference waves between pollution and clean air conditions. (b) Mean ERP waves for the channels of N300 ROI. (c) Mean ERP waves for the channels of P300 ROI. Gray rectangles indicate time windows of interest.

stimuli (Fig. 4(b)). Statistical test demonstrates that mean amplitudes elicited in the N300 interval (250–350 ms) for clean air trials were ~0.61 mV greater than pollution trials (t = −1.88, p = 0.071, Cohen'd = 0.342). The result is consistent with the pattern in the attention-holding trials and supports Hypothesis 3, suggesting that clean air images are more attention-capturing because of their pleasing features.

Next, starting from 1400 ms after the target onset, we find that the amplitudes of the positive ERP waves in pollution trials are significantly lower than those in clean air trials (Fig. 4(c)). Statistical test reveals that mean ERP amplitudes for the P300 interval (1500–1700 ms) of pollution trials are ~0.66 mV lower than clean air trials when people make responses (t = 2.24, p = 0.033, Cohen'd = 0.409). It indicates when the cue is a pollution image, and the target is on the opposite side of the screen, it takes less cognitive resources for subjects to disengage attention away from the cue to the target. As such, these results confirm Hypothesis 4 and suggest that visual exposure to air pollution facilitates attentional disengagement. It also explains why subjects tend to have higher response accuracy when cued by pollution images in attention-shifting trials.

4 Discussion

In this study, we design an experiment paradigm provide both behavioral and neuroscientific support for the hypothesis that air pollution disengages people's attention and decreases cognitive performance. We find that there is a significant interaction effect between pollution stimuli and the trial type of the target regarding response accuracy for the dot-searching task. When cued by pollution images, subjects tend to have relatively lower accuracy if the target is still on the same side of the cue, demonstrating distracting effect of pollution. After the cue onset, clean air images evoke larger amplitudes of N300 than pollution images for both attention-holding and attention-shifting trials. It suggests that clean air is more likely to capture human's attention. However, when performing the task, pollution cues are associated with higher P300 amplitudes in attention-holding trials than clean air cues but smaller P300 amplitudes in attention-shifting trials. It indicates that people need more cognitive resources to concentrate their attention when cued by pollution images but needs fewer efforts to disengage attention away. While it should be noted that these effects are only moderate, the findings from both behavioral performance and neural data proivde support for our hypotheses in the direction anticipated.

Our findings align with several health psychological studies, suggesting that the major reason for attentional disengagement is because people respond defensively to unpleasant and health-threatening information. For example, Kessels et al. (2010) presented high-threat and low-threat health warning pictures to smokers and non-smokers simultaneously. Their results showed smokers who perceived high-threat stimuli self-relevant, are more efficient in disengaging attention. Using eye-movement tracking technique, Berdica et al. (2018) compared pairs of pictures with different emotional contents, such as fear-related animals and facial expressions. Results show that unpleasant pictures are more difficult to sustain attention compared to neutral pictures. As a prominent environmental risk, air pollution images with low visibility and gray cityscape make people feel health-threatening and promote avoidance motivation. Color characters of air images may also affect attention engagement. Studies have shown that colors of maximum saturation and brightness attract the most attention (Camgöz et al., 2004). Cool colors and high brightness levels could help people be orientated in a space and facilitate their memories (Hidayetoglu et al., 2012). An eye-tracking study examines the effect of landscape color and complexity on viewing behavior (Huang and Lin, 2020). It finds that landscapes with higher hue variation and chroma such as mountain, aquatic and forest landscapes can encourage visual fixation. Compared to pollution images, clean air landscapes with light colors are more complex and arousing, which may help capture and hold more attention. These together may explain why attention-holding of pollution stimuli is very short and attention disengagement is more efficient.

Disengaging effect of air pollution observed in our study could serve as the neurocognitive mechanism for many empirical studies that demonstrate the negative impact of pollution on attentional outcomes and work productivity. For example, by investigating the relation between air pollution and individual investors' trading performance, Huang et al. (2020) found that air pollution makes investors more susceptible to attention-driven buying behavior, highlighting the unexplored risks in stock markets. They speculate that the distraction effect of air pollution may reduce the amount of attention allocated for stock trading but cannot provide more detailed evidence. Also, Sager (2019) reports that air pollution impairs safe driving performance, and an additional 1 $\mu g/m^3$ $PM_{2.5}$ is associated with a 0.3%–0.6% increase in traffic accidents per day. The author explains that air pollution may cause impatience or distraction, further reducing driving performance. Still, the author admits that the interpretation is only speculative. Our study closes this gap and provides direct neuroscientific evidence for the distracting effect of air pollution.

We also demonstrate that the ERP technique as a high temporal resolution neuroscience tool can be used to answer questions in the field of environmental psychology in future academic research. Researchers can combine self-report, behavioral, and neuroscientific measures to help understand how people respond to environmental issues and reveal the cognitive mechanism underneath. N300, as a useful ERP component reflecting complex visual perception process, can be used to measure preferences or risk perceptions toward different environmental subjects (Kumar et al., 2021). Studies have used N300 as a useful attention-drawing indicator to investigate the effectiveness of different warning signs (e.g., traffic lights and dangerous goods labels) (Ma et al., 2018). Our study also shows that P300, which is related to the amount of cognitive resource used in the decision-making, is an informative indicator to reflect people's attitude toward environmental issues. Scholars have used P300 as a neurophysiological indicator to reveal the effect of social distance and social observation on explicit pro-environmental behaviors (Li et al., 2023). The P300 component was also efficient in explaining the neural mechanism of the effect of social norms on the willingness to use recycled water (Liu et al., 2022). Our study enriches relevant literature by employing P300 component to examine cognitive impacts of pollution exposure.

In practice, our results also have implications for policymakers to protect public mental health and improve work productivity. In addition to the pathological pathways such as inducing neuro-inflammation through which long-term chronic exposure to air pollution can affect behavioral performance, our study shows that even visual exposure to air pollution, which is often the case in daily life, can directly affect the cognitive process (Yang et al., 2023). This disengaging effect may be connected to people's avoidance motivation toward air pollution, which finally leads to defensive behaviors like wearing masks and reducing exposure. In hazy days, information campaigns could encourage people to pay more attention to this distracting effect of air pollution, such as seeking some nature-based therapeutic solutions to help relieve mental stress and increase the ability of attentional regulation.

There are also several limitations in our study that should be acknowledged. First, the dot-probe task is relatively easy for young adults. This leads to a very high percentage of response accuracy, which reduces the effect size of statistical tests on behavioral data. Meanwhile, we instructed the participants to respond as quickly as possible. Due to this reason, the expectation that pollution images cause faster response time in attention-shifting trials was also not supported. The insignificance of reaction time is also reported in previous studies. Nevertheless, our ERP analysis is more informative. It still reveals the effect of pollution on the cognitive process in fine-grained time windows, which is difficult to be measured by behavioral metrics. Second, the subjects in our study are young students in China. In the Chinese context, air pollution has been a social hot spot issue, and the public is aware of the adverse health outcomes of pollution exposure. It is unknown if the disengaging effect of air pollution still exists for residents in developed countries where air quality is better. Third, since visual attention is highly related to visual space and gazing point, analyzing saccade data using eye-tracking technique in future studies would provide extra evidence for the disengaging effect. Moreover, since both cue and target are static visual pictures with limited visual spaces, it is worth considering whether the observed effects can be attributed to other characteristics of these images, such as differences in color between the two types of images. To extend our research design and examine disengaging effect of air pollution on other types of attention allocations, scholars could consider adding control group experiment, using full-filed landscape images as cues, or using auditory discrimination task as probe tests in future studies.

5 Conclusions

Based on behavioral measures and ERP technique, we reveal that exposure to the visual impact of air pollution can distract attention and affect task performance. There is a strong interaction effect between cue type (pollution or clean air images) and trial type (whether cue and target are on the same side of the screen) regarding response accuracy. When cues are polluted landscape images, participants tend to have lower averaged response accuracy in the attention-holding trials but higher accuracy in attention-shifting trials. Similar patterns are also found in ERP analysis. After the cue onset, clean air images evoke higher N300 amplitudes than pollution images, indicating that clean air tends to capture more attention. When cued by pollution images, the P300 related to the target response process has higher amplitudes in the attention-holding trials but lower amplitudes in attention-shifting trials. The evidence suggests that people are more efficient in disengaging their attention due to exposure to air pollution and need more cognitive resources to focus on the task at a previously cued location. To our knowledge, this is the first study adopting the ERP technique to examine the attentional impact of air pollution at a high temporal resolution. The findings call for attention to this subtle phenomenon, especially in developing countries.

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