Attention Network Changes of High-Altitude Migrants

Xin An; Getong Tao; Xinjuan Zhang; Hailin Ma; Yan Wang

INTRODUCTION: The present study aimed to explore whether there are changes in the alerting, orienting, and executive network efficiencies of attention function between high altitude immigrants and low altitude residents.

METHODS: Event-related potentials (ERP) were acquired during an attention network test (ANT). The high-altitude (HA) group comprised 22 college student immigrants who were born and raised at low altitudes and had lived at a HA (11,975 ft/3650 m) for 26 mo (tests were conducted when they returned to HA for 3 mo). The low-altitude (LA) group comprised 23 college students who had never visited HA areas before.

RESULTS: Compared with the LA group, the HA group had a higher pulse rate, lower oxygen saturation level, and decreased alerting and orienting effects in the behavioral results. The ERP results of the HA group showed a smaller P1 in the occipital area, a larger N1 both in the parietal and occipital areas of the alerting network, and a smaller P1 and larger N1 in the orienting network than the LA group. In the executive control network, the N2 amplitude of the HA group was more negative and the P3 amplitude of the HA group decreased in incongruent conditions.

DISCUSSION: Together, these findings suggest that high-altitude migrants are less effective at alerting and orienting than low-altitude residents. For executive control function, changes in the P3 amplitudes of incongruent conditions indicated a decrease in conflict inhibition underlying the executive-control network.

KEYWORDS: high altitude hypoxia, attention network, event-related potential, alerting, orienting, executive control.

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The Tibet Autonomous Region, located on the Qinghai-Tibet Plateau, or "the roof of the world," has an average altitude of more than 13,123 ft (4000 m).[4] The average partial pressure of oxygen in this region is only 60–65% that at sea level.[26] In recent years, studies using neuroimaging technology have found that long-term repeated exposure to hypoxia causes a decrease in gray matter volume in the bilateral prefrontal lobes, right cingulate gyrus and left precentral gyrus, etc.[32,33] This impairs mental functions such as perception, attention, memory, decision making, and emotions, as well as social adaptation.[3,24,34]

Attention is the orientation and concentration of psychological activities on certain objects. Posner suggested that attention involves voluntary (endogenous) and involuntary (exogenous) systems.[17] Voluntary attention is a volitionally controlled, top-down process that is usually related to central symbolic cues. In contrast, involuntary attention is an automatic reflexive, bottom-up process elicited by abrupt peripheral cues. Furthermore, the attention network is composed of three functionally distinct neural networks: alerting, orienting, and executive control.[18] Alerting is defined as physically increasing response preparation in reaction to an external warning stimulus. Orienting refers to the ability to prioritize sensory input by selecting a modality or location and shifting attention; for example, by distracting and refocusing attention. Finally, the executive control network involves conflict control and resolution during habitual response inhibition, decision making, and error detection.[18] Based on Posner's theory, Fan designed the attention network test (ANT), which can effectively measure the functions of the three attention networks.[6] The frontal and parietal lobes of the right hemisphere of the brain are involved in the alerting process.[6,22] In the orienting process, the dorsal and ventral attention systems are involved.[5] The former, responsible for top-down visuospatial orientation, consists of the frontal eye field (FEF), intraparietal

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sulcus, and superior parietal lobe. The latter, responsible for bottom-up reorientation, consists of the temporoparietal junction (TPJ) and the ventral frontal cortex (VFC).[17] In the executive control process, the anterior cingulate cortex (ACC) and dorsolateral prefrontal cortex play an important role in monitoring and resolving conflict.[27]

Event-related potentials (ERP) are special brain potentials evoked by stimuli, and ERP components reflecting specific cognitive functions can be extracted by using the fixed stimulus-response time-lock relationship and the computer's average superposition processing. These brainwave components are typically named using a combination of letters and numbers. P and N indicate the positive and negative trends of the waveform, respectively, whereas the numbers indicate the position of the peak in the waveform.[11] Studies examining ERP have found that P1 and N1 components in the parietal and occipital regions appear after 80–200 ms of stimulus presentation, which are related to alerting and orienting functions in the attention network.[35] The P1 is generally thought to be the earliest influence of spatial attention on visual processing.[15] The attended stimulus can also elicit a larger N1 amplitude. The increased amplitudes of P1 and N1 reflect a sensory-gain control mechanism that results in the enhanced perceptual processing of the attended stimulus.[35] The N2 component, which is associated with conflict monitoring in executive control function, occurs between 200–350 ms after stimulus presentation. The ACC is an anatomical region of the brain that affects the N2, which recruits top-down resources to improve stimulus evaluation when conflict is detected.[10] Many studies with flanker tasks have indicated that incongruent flanker conditions elicit a more negative N2 than congruent conditions.[19,20]

P3 is another component that is frequently measured in studies of executive control.[29] Its subcomponents, P3a and P3b, are often elicited about 300–600 ms after the stimulus.[29] The frontally generated P3a reflects involuntary and transient allocation of attention to distractors or novel stimuli. Parietal-generated P3b is a task-related activity regarded as related to the control of cognitive attention and the stimulus evaluation process.[29] In the present study, we focus on P3b, the traditional P3, in the ANT. However, there is controversy over in which condition P3 amplitude was larger.[15] Some of the authors have concluded that there was a larger P3 amplitude in the incongruent target and suggested that P3 amplitude was enhanced by response inhibition,[9] while others argue that reduction in amplitude may be related to greater response inhibition.[20]

Various studies have investigated the effects of high altitude on attention. Studies using visual search tasks and the digit symbol substitution test have found that people exposed to high altitude environments for 8 h had reduced attention capacity and decreased scores in visual search tasks.[21] Additionally, a neuroimaging study has shown that high altitude influences brain areas related to attention processing (frontoparietal network), with a decreased volume of gray matter in the bilateral prefrontal area, right cingulate gyrus, and precentral gyrus among members of the Han ethnic group who were born and grew up (more than 20 yr) in high-altitude environments.[32] Previous research has also indicated that high-altitude subjects [individuals who were born and grew up in low-altitude areas but migrated to 11,975 ft (3650 m) in adulthood and have lived at high altitude for at least 3 yr] had longer reaction times and lower accuracy in spatial attention tasks compared to low-altitude subjects (individuals who have only lived in low-altitude areas). In high perceptual load conditions, the high-altitude subjects had a smaller N1 and P3 compared to the low-altitude subjects.[28] Furthermore, their bilateral occipital regions were activated and the lateralization effects of the attention process disappeared.[28] It has been suggested that long-term exposure to high altitude may influence spatial attention and the brain adapts to compensate for high-altitude environments.[28]

High altitude affects attention network functions. Our 2-yr longitudinal study using the ANT explored the temporal effects of high-altitude environments and showed that Han students who entered the 11,975-ft (3650-m) high-altitude area for the first time after adulthood experienced a significant decline in executive control network function after staying at high altitude for a week. Recovery occurred after 1 mo but declined again after 2 yr of living at high altitude.[1] This result suggested that high-altitude environments affect attention and the extent of the effect varies with the duration of residence.[1] However, the neural mechanisms of the effect of high altitude on attention network functions are still unclear. Previous studies have found that long-term high-altitude exposure influences executive control function.[12,13] Using the flanker task and go/no-go task, studies showed decreases in the conflict monitoring and conflict control abilities of Han students who migrated to high altitudes and stayed there for more than 3 yr.[12,14] However, evidence for the influence of high altitudes on alerting and orienting is still inconclusive. In addition, our previous work examined the neural mechanisms of high altitudes on Tibetans' attention network functions.[35] We found that young Tibetans who grew up at an altitude of 13,780 ft (4200 m) had decreased orienting function but increased executive control function.[35] Due to long-term adaptation to high-altitude environments, the genetic and physiological structures of indigenous residents are different from those of immigrants.[1] Therefore, results in indigenous residents cannot be extended to immigrants. In recent years, an increasing number of immigrants have visited high-altitude areas for work or travel. Thus, it is important to study the influence of exposure to high altitudes on attention function in immigrants from low-altitude areas.

In the current study, ANT was used and ERP was recorded to systematically explore the changes in attentional function of high-altitude migrants. Based on existing studies, due to high-altitude, exposure can damage the brain areas related to attention such as the bilateral prefrontal area, right cingulate gyrus, and precentral gyrus;[3,31,32] it also causes changes in ERP, such as the larger N1, N2, and smaller P1, P3.[12,14,28] We hypothesized that high altitude would affect attention networks, indicated by decreased scores on behavioral tests measuring alerting, orienting, and executive control. In the ERP results, we hypothesized that there would be a decreased P1 and increased N1 amplitude in both alerting and orienting networks, and increased N2 amplitude and decreased P3 amplitude of incongruent conditions in the executive control network.

METHODS

Subjects

A total of 49 healthy Han college students (age range:19–26 yr old; 25 men) participated in our experiment. We used G*Power 3.1[7] to calculate the required sample size (F = 0.25, α = 0.05, 1 - β = 0.80). The results showed that a total of 24 subjects were adequate for detecting an effect of altitude on N1 and P1 amplitude in the alerting and orienting networks, and 34 subjects were adequate for detecting an effect of altitude on N2 and P3 amplitude in the executive control network. Here, we sought to collect data from 49 participants in total. They were all right-handed and had normal or corrected-to-normal vision without psychiatric or neurological disorders. They had no stress-inducing activities, such as college examinations, for a month before taking the test. In addition, they were required to get adequate sleep the day before the test and to not take drugs, drink coffee, or engage in other behaviors that might interfere with the test. All participants were born and raised in low-altitude areas (<3281 ft or 1000 m). The 25 students in the high-altitude (HA) group were from Tibet University and had lived in Lhasa (11,975 ft/3650 m) for 26 mo. They were third-year college students who studied at high altitudes from March to July and September to December (9 mo in total), all returning to low altitudes (<1000 m) during the rest of the year. The 24 students in the low-altitude (LA) group had never been in a high-altitude environment before. Because of excessive eye movements and artifacts, two subjects from the HA group and two subjects from the LA group were excluded. Finally, 22 subjects in the HA group (21.88 ± 1.33 yr; 11 men) and 23 subjects in the LA group (21.36 ± 1.60 yr; 11 men) were included in the final analysis of behavioral and EEG data. The two groups were matched in terms of age, sex, education, and scores on national college admission examinations. This study followed the Declaration of Helsinki and was approved by the Health Science Research Ethics Board of the Institute of Psychology, Chinese Academy of Sciences (No. H16037). Written informed consent was obtained from all participants, who received compensation for their participation. The HA group was tested at an altitude of 11,975 ft (3650 m) when they returned to high altitude for 3 mo. The LA group was tested at an altitude of 131 ft (40 m). To avoid test differences caused by changes in equipment, we brought the equipment from the LA lab to the HA lab. Therefore, the same laboratory equipment was used for both tests. S_pO_2 and pulse rate were measured with a warmed hand in a resting condition using a pulse oximeter (DEDAKJ-CMS50D, Shenzhen City, China) before completing the ANT to obtain information regarding the degree of hypoxia in the two groups. S_pO_2 was significantly lower in the HA group than in the LA group (P < 0.01), while pulse rate was significantly higher in the HA group (P < 0.001) (**Table I**).

Table I. Age, Education, Pulse Rate, and S_pO_2 of Each Group [Mean (SD)].

	LA (N = 23)	HA (N = 22)	t	P
Age (yr)	21.4 (1.6)	21.9 (1.3)	−1.3	0.22
Education (yr)	15.3 (1.5)	15.8 (1.2)	−1.4	0.16
Pulse rate (bpm)	74.0 (11.3)	82.0 (9.7)	−2.7*	0.01
S_pO_2 (%)	97.4 (1.1)	90.7 (2.8)	10.7**	0.001

HA = high altitude group; LA = low altitude group. *P < 0.05, ** P < 0.01.

Procedure

All the stimulus presentation for the ANT and behavioral response collection were conducted using software package E-prime 2.0 (Psychology Software Tools, Inc., Pittsburgh, PA). The procedure is illustrated in **Fig. 1**.

Subjects were seated in a comfortable chair at a viewing distance of 50–60 cm in front of the computer monitor in a quiet room. A fixation cross (+) 0.5 cm × 0.5 cm displayed on the center of the screen was maintained for a variable duration between 400 and 1600 ms, followed by a cue that lasted 100 ms. Subsequently, the target array appeared 500 ms after cue onset. There were four types of cue conditions: no cue, center cue, double cue, and spatial cue. Of note, the no cue was the condition without any cue after the fixation cross. The center cue was the condition when a "*" symbol of 0.5 cm × 0.5 cm briefly replaced the center fixation cross. The double cue condition referred to simultaneous "*" symbols of 0.5 cm × 0.5 cm appearing both above and below the fixation cross, and the spatial cue was the condition when an "*" appeared either above or below the fixation cross and thereby cued the location where the target array would appear. The target array consisted of five horizontally arranged arrows 1.0 cm in length, including one central target arrow and four flankers, and displayed 1.06° above or below the fixation cross. The target conditions could be congruent (flanker arrows had the same direction as the center arrow), incongruent (flanker arrows pointed to the opposite direction), or neutral (a central arrow with four horizontal lines). The congruent targets and incongruent targets were equal in number and presented randomly.

For each trial, responses were recorded by pressing the left mouse button with the right hand when the target arrow pointed to the left and the right mouse button when the arrow pointed to the right. Subjects were instructed to respond rapidly and accurately. Target stimulus were presented 400 ms after the cue interval and maintained on the screen until a response was made by the participant, or until a maximum of 1700 ms had elapsed. The task began with a complete practice block of 20 trials, followed by three experimental blocks of 96 trials, lasting about 20 min. The reaction time (RT), accuracy rate, and ERP were recorded during the task.

According to previous research, based on both congruent and incongruent correct response trials RT, the three attention networks were defined as follows: alerting effect = $RT_{\text{no cue}} - RT_{\text{center cue}}$—the larger difference indicated a greater alerting effect because attention will focus on the cue where the target stimulus will appear, thereby reducing the RT; orienting effect = $RT_{\text{center cue}} - RT_{\text{spatial cue}}$—the location of the spatial cue was the position where the target would later occur, so a greater difference meant a better orienting effect; and conflict effect = $RT_{\text{incongruent}} - RT_{\text{congruent}}$—in the incongruent condition, the executive control network plays an important role in suppressing the interference stimulus to effectively process the target

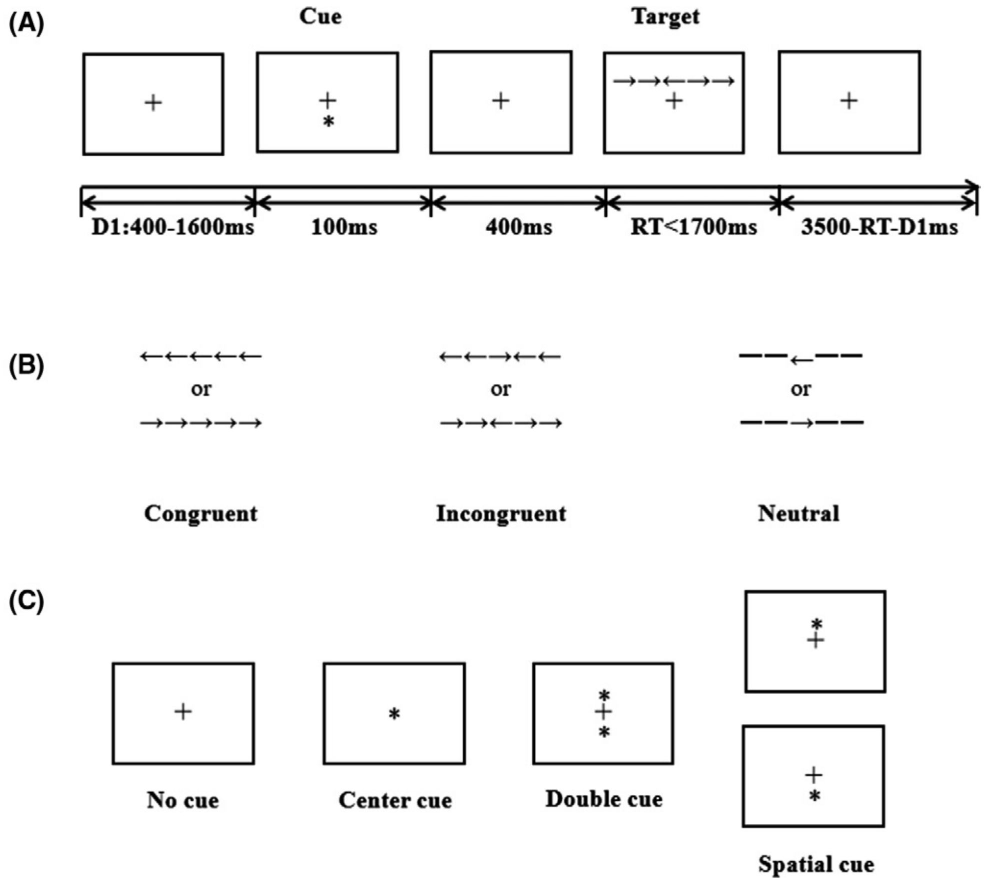

Fig. 1. Materials and procedure. A) The sequence of events for the ANT used in the present study; B) the three target conditions; and C) the four cue conditions.

stimulus, resulting in a longer RT than the congruent condition. Hence, the smaller the difference, the better the executive control effect.[5]

Electroencephalogram (EEG) data were recorded during the ANT task with a 64-channel amplifier (SynAmps2, NeuroScan Inc., Herndon, VA, USA) and data acquisition software (Scan4.5, Neuroscan). The 64 Ag-AgCl electrodes were placed on the scalp by means of a head cap (NeuroScan Inc.), according to the 10-20 International System. Electrodes were online referenced to a reference site in the middle of the Cz and CPz locations, and an electrode placed between Fpz and Fz was used as the ground. Electrode impedance were maintained at 5 kΩ or less. Horizontal and vertical eye movements were recorded from tin electrodes placed at the outer canthi of both eyes, and above and below the left eye, respectively. EEG and electrooculogram (EOG) signals were continuously acquired and sampled at a rate of 500 Hz, applying a 0.05–100 Hz band-pass.

Statistical Analysis

All statistical analyses were conducted with SPSS (SPSS, Inc., Chicago, IL, USA) for Windows, with a significance level set at 0.05. The Student's t-test was conducted to analyze the score of the three network effects, with the altitude group as the independent variable.

EEG data were re-referenced to the average of bilateral mastoid electrodes. The EEG and EOG data were digitally filtered with a 0.1–30 Hz bandpass filter. Trials with eye blink/eye movements or muscle activity were excluded from further analysis. A regression procedure implemented in Neuroscan software (Neuroscan Inc.) was used to identify vertical and horizontal ocular artifacts and this study further removed them from the signal; trials with various artifacts were rejected with a criterion of ±75 μV. Epochs were computed for the 1000 ms after the onset of the target stimulus relative to a 200-ms prestimulus baseline. Each participant's average waveform of each of the four conditions was calculated and the incorrect response trials were excluded in the average ERP calculations.

The time frames of posterior target P1 were defined as the most positive peak at 80 to 150 ms and N1 were defined as the most negative peak at 150 to 250 ms after the onset of target stimulus. On the basis of previous studies, the posterior target P1 and N1 component was determined over three sites at the parietal area (P3, Pz, and P4) and three sites at the occipital area (O1, Oz, and O2), respectively.[15,35] A mixed factors ANOVA was adopted to the different network effects. A group (HA and LA) × cue condition (no cue and double cue) × brain area (the parietal area and the occipital area) ANOVA was carried out for the P1 and N1 mean components to analyze the alerting network effect. Three-way mixed design repeated measures analysis of variance was conducted with two within-subject factors, cue condition (center cue and spatial cue) and brain area (the parietal area and the occipital area), and one between-subject

Table II. Mean Reaction Times (ms) Based on Both Congruent and Incongruent Correct Response Trials of Each Experimental Condition for the Two Groups [Mean (SD)].

	NO CUE		DOUBLE CUE		SPATIAL CUE		CENTER CUE	
GROUP	CO	IC	CO	IC	CO	IC	CO	IC
LA	559 (52)	658 (74)	508 (55)	608 (66)	476 (54)	563 (68)	529 (61)	630 (71)
HA	591 (63)	681 (78)	537 (60)	647 (74)	518 (75)	602 (81)	550 (77)	670 (86)

CO: congruent; IC: incongruent; LA: low altitude; HA: high altitude.

factor, group (HA and LA), on mean amplitude of the P1 and N1 components to evaluate the orienting network effect.

In previous studies, the amplitudes of N2 and P3 were always largest at the midline electrode sites along the anterior to posterior axis, including FCz, Cz, CPz, and Pz.[8,16] Thus, in the current study, we analyzed N2 and P3 components from these electrode sites. The N2 and P3 components were analyzed for the time frame from 280 to 500 ms and 450 to 700 ms, respectively, following the presentation of target stimulus. We examined the mean amplitude of these two components for statistical analysis. We conducted a target condition (congruent and incongruent) × group (HA and LA) mixed-model ANOVA to analyze the N2 and P3 components. Simple effect analyses were adopted to further investigate interaction effects.

RESULTS

Table II summarizes the mean RT based on both congruent and incongruent correct response trials of each experimental condition between groups. Furthermore, **Table III** displays the calculation of the network scores. Since the average accuracy rate of both groups was over 99% and there was no significant difference, the accuracy results are no longer presented.

With respect to the alerting network, *t*-testing indicates a significant effect of group [$t(43) = 2.65$, $P < 0.01$]. The alerting scores of the HA group were lower than those of the LA group. As for the orienting network, there was a significant effect of group, with a larger orienting score in the LA group than in the HA group [$t(43) = 2.90$, $P < 0.01$]. However, there were no differences between the executive control score in either group [$t(43) = -1.04$, $P > 0.05$], but there was also a downward trend in executive control efficiency (90.9 vs. 98.4). The scores of the attention network are shown in **Fig. 2** and Table III.

Posterior Target P1 Amplitude

We observed a significant main effect of the cue condition [$F(1,43) = 49.84$, $P < 0.001$, $\eta^2 = 0.54$], showing that the P1 amplitude of the no cue condition was increased compared with that of the double cue condition. The interaction between the cue condition, brain area, and group were significant [$F(5, 39) = 3.65$, $P < 0.01$, $\eta^2 = 0.32$], with increased P1 amplitude in the occipital area of the LA group compared with the HA group in the no cue condition ($P < 0.05$) (see alerting in **Fig. 3**). There were no other main effects or interactions.

Posterior Target N1 Amplitude

The main effect of cue condition was significant [$F(1,43) = 119.63$, $P < 0.001$, $\eta^2=0.74$], indicating that the N1 amplitude of the double cue condition was more negative than that of the no cue condition. The main effect of group was significant [$F(1,43) = 5.14$, $P < 0.05$, $\eta^2 = 0.11$]. The N1 amplitude of the HA group was more negative than that of the LA group. The interaction between the cue condition, brain area, and group were significant [$F(5, 39) = 5.42$, $P < 0.01$, $\eta^2 = 0.41$]. In the double cue condition, the N1 amplitude in the occipital area of the HA was more negative than that of the LA group ($P < 0.05$). In the no cue condition, the N1 amplitude in both the parietal and occipital area of the HA were more negative than that of LA group ($P < 0.05$). There were no other main effects or interactions.

Posterior Target P1 Amplitude

We found a significant main effect of cue condition [$F(1,43) = 21.37$, $P < 0.001$, $\eta^2 = 0.33$], indicating that the P1 amplitude of the center cue condition was increased compared with that of the spatial cue condition. The main effect of group was significant [$F(1,43) = 11.44$, $P < 0.01$, $\eta^2 = 0.21$]. The P1 amplitude of the LA group was more positive than that of the HA group (see orienting in Fig. 3). There were no other main effects or interactions.

Table III. Attention Network Scores Based on the RTs of the Two Groups [Mean (SD)].

	LA (*N* = 23)	HA (*N* = 22)	*t*	*P*
Alerting	55.79 (19.67)	42.36 (13.65)	2.7	0.011
Orienting	59.42 (17.54)	44.85 (16.12)	2.9	0.006
Executive control	90.88 (24.96)	98.43 (23.61)	−1	0.304

RT: reaction time; LA: low-altitude group; HA: high-altitude group.

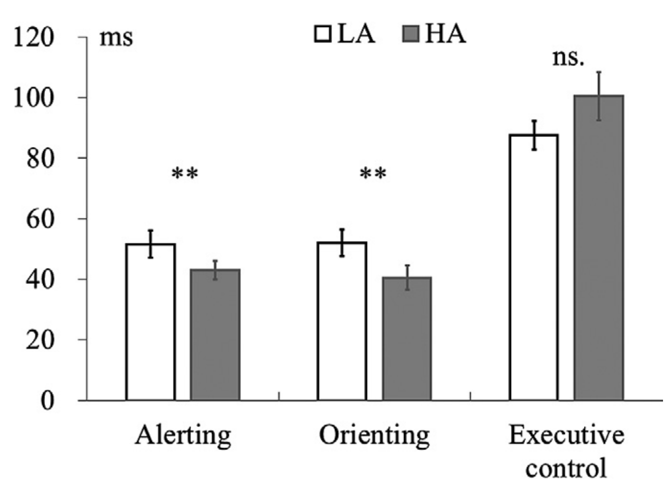

Fig. 2. Attention network scores based on the RTs of the two groups (Mean ± SEs). $^{**}P < 0.01$.

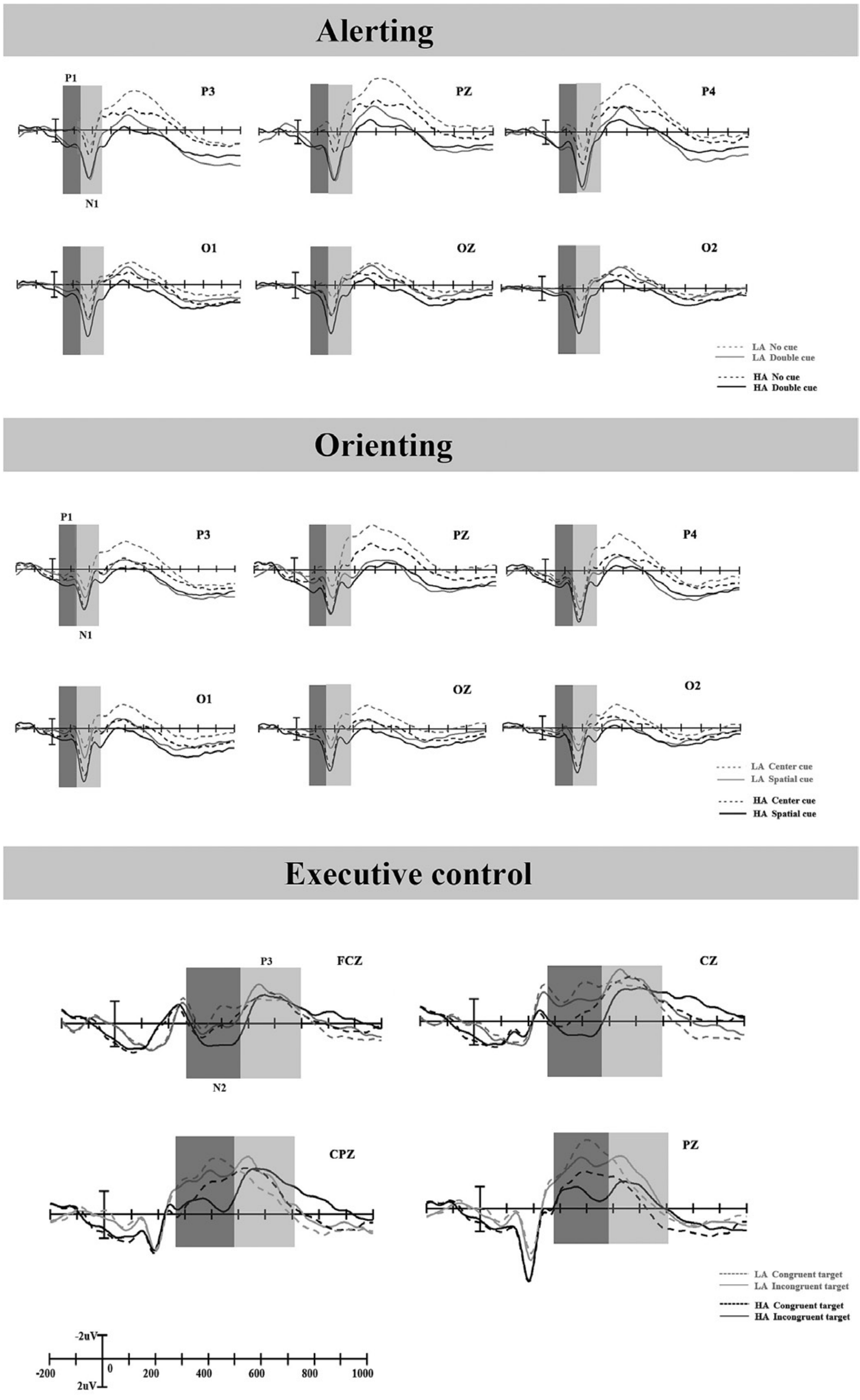

Fig. 3. ERP waveforms of alerting effect, orienting effect, and executive control in the two groups. The P1 and N1 waveforms were located in the parietal areas (P3, Pz, P4) and occipital areas (O1, Oz, O2) at 80 to 150 ms and 150 to 250 ms. The N2 and P3 waveforms were located in the anterior to posterior axis (FCz, Cz, CPz, Pz) at 280 to 500 ms and 450 to 700 ms.

Posterior Target N1 Amplitude

Regarding the target N1 amplitude, the main effect of cue condition was significant [$F(1,43) = 32.44$, $P < 0.001$, $\eta^2 = 0.43$], with more negative N1 amplitude in the spatial cue condition compared with that of the center cue condition. The main effect of group was significant [$F(1,43) = 14.90$, $P < 0.001$, $\eta^2 = 0.26$], demonstrating that the N1 amplitude of the HA group was more negative than that of the LA group (see orienting in Fig. 3). There were no other main effects or interactions.

Target N2 Amplitude

With respect to the target N2 amplitude, the main effect of target condition was significant [$F(1,43) = 24$, $P < 0.001$, $\eta^2 = 0.36$], with larger N2 amplitudes in incongruent conditions than in congruent conditions. The main effect of group was significant [$F(1,43) = 4.80$, $P = 0.040$, $\eta^2 = 0.10$] and the N2 amplitude of the HA group was more negative than that of the LA group (see executive control in Fig. 3). There were no other main effects or interactions.

Target P3 Amplitude

With respect to the target P3 amplitude, we observed a significant interaction between target condition and group [$F(1,43) = 3.60$, $P = 0.036$, $\eta^2 = 0.18$], with smaller P3 amplitude in the HA group than in the LA group under incongruent conditions [$F(1,43) = 3.12$, $P = 0.041$, $\eta^2 = 0.13$] (see executive control in Fig. 3). There were no other main effects or interactions.

DISCUSSION

This study was designed to explore whether there are changes in attention network between high altitude immigrants and low altitude residents. Behavioral data showed a decrease in alerting and orienting efficiency scores in the HA group. There was also a downward trend in executive control efficiency. The higher pulse rates and lower blood oxygen saturation of the HA group are responsible for these effects. Correspondingly, in the alerting network, the P1 amplitude of the HA group was smaller than the LA group in the occipital area in the no cue condition, and the N1 amplitude of the HA group was larger in the double cue condition in the occipital area and larger in the no cue condition in both the parietal and occipital areas. In the orienting network, the P1 amplitude of the HA group was smaller and the N1 amplitude of the HA group was larger. Compared with the LA group, the N2 amplitude of the HA group was larger in the incongruent condition, and the P3 amplitude of the HA group was smaller in the executive control function. These results suggest that the attention networks for alerting, orienting, and executive control of high-altitude migrants was more decreased than those of low-altitude residents, which may be caused by high altitude hypoxia exposure.

Behavioral performance revealed a high-altitude effect on alerting and orienting functions. The efficiency of alerting and orienting in the HA group was lower than that in the LA group. The decreased alerting efficiency in the HA group indicated that they needed more time to focus on cue location. The lower orienting network efficiency suggests that the HA group did not benefit as much as the LA group from physical or symbolic cues that direct attention to the likely location or identity of upcoming target information. We inferred that the decline in these two functions might result from changes in the neural systems that support these functions.

Of note, the ERP results greatly corresponded with behavioral performance in alerting and orienting efficiency. Specifically, concerning the post-target P1, the amplitude of the alerting-related post-target P1 of the HA group was smaller than that of the LA group in the no-cue condition. P1, an early component of the attention process, was enhanced by increasing attention load, reflecting the early processing of stimuli. The decreased P1 amplitude in the HA group indicated weak perceptual processing of target onset, reflecting poor alerting. In addition, the HA group had a smaller orienting related P1 amplitude, which is similar to the results of a previous aging study. This suggests that there may be a correlation between the effects of high altitude and aging through common neural mechanisms. Furthermore, in the orienting function, a center cue showed a greater positive P1 than those following a spatial cue in both the HA and LA groups. This is a common finding that invalid cues elicit a larger P1 than valid cues.[30] The decreased P1 amplitude in the HA group indicated that they were not as sensitive to less informative cues (invalid cues like center cues in our study) as the LA group.

The amplitude of post-target N1 was greater for the HA group than for the LA group both in the alerting and orienting functions, similar to the previous study.[26] The N1 amplitude reflects the difficulty of target discrimination.[25] The increased N1 amplitude of the HA group demonstrated that a high-altitude environment might affect the early perceptual processing of attended stimuli, resulting in the HA group showing a stronger engagement with the target properties and experiencing greater difficulty in target discrimination than the LA group. Compared with residents in lower-altitude areas, previous researchers using ANT also demonstrated that residents of higher altitude regions had more negative N1 amplitudes in their orienting network.[35] This indicated that mental resources were limited in HA residents for the alerting and orienting networks. In addition, consistent with previous research, the post-target N1 was more negative in the double-cue condition than in the no-cue condition in the alerting function and more negative following spatial cues compared to center cues in the orienting function.[30] This suggested that post-target N1 reflects the characteristics of the stimulus and may be related to top-down modulation of a visual discriminative process at attended locations.

In incongruent trials, the HA group had a smaller P3 amplitude than the LA group, suggesting that high-altitude environments influence the conflict-resolving stage in the executive control process, meaning that the conflict-resolving ability of the HA group was decreased. The P3 amplitude is associated with attentional resources used to improve cognitive control.[29] The smaller the amplitude, the less attentional resources are available. A decrease in the P3 amplitude was observed in the HA group. A possible explanation is that, compared to the LA group, the HA group required more attentional resources to overcome conflict when performing the same task, which was regarded as a dysfunction of attentional resource allocation and inhibition control in patients with neurotrauma.[2] This means that, with their limited attentional resources, the HA group always has a high cognitive demand to overcome conflict control. Similarly, our previous study found that P3 amplitude was smaller in the HA group, indicating that long-term exposure to high altitudes consumes attentional resources.[26] In addition, we examined the effects of high altitude on executive control using the flanker task.[14] The results showed that the HA group had a smaller P3 amplitude than the LA group in incongruent conditions, and incongruent P3 components were localized in the parietal cortex. The parietal cortex, which plays a key role in conflict resolution, was affected by long-term high-altitude exposure.[3] This explains the decrease in the incongruent P3 amplitude in the HA group. Therefore, we conclude that executive control function is altered after exposure to high-altitude areas as a consequence of the affected cognitive process in the conflict-resolution stage.

For the behavioral results, the executive control function scores between the two groups were not significant; however, the results still showed a declining trend at high altitudes. The disappearance of behavioral effects may be due to the lower sensitivity of the behavioral tests. The ANT detects executive control mainly by judging the direction of an arrow. It is relatively simple for our test subjects, with an average correct rate of over 99%, though there may be a ceiling effect. Behavioral effects may be more obvious with a more difficult task. After the ANT task, we asked the subjects to complete a more difficult Stroop color word task, which specifically detects executive control function, and found that the behavioral RT of the HA and LA groups were significantly different, as reported in another paper.[23]

There were some limitations to the current study. First, although the subjects lived at high altitude for a total of 26 mo, they returned to low altitude several times to rest. Previous studies have shown that the adaptation period for living at or above 11,975 ft (3650 m) can be divided into three stages. The first stage is the acute adaptation period (3 d after entering the high-altitude environment), during which individuals are prone to acute mountain sickness. The second stage is subacute adaptation (within 6 mo after entering the high-altitude environment). Most people can compensate during this stage through compensatory mechanisms with the extension of exposure time and gradually adapt to the hypoxic environment. The third stage is chronic adaptation or complete hematocrit adaptation, in which chronic altitude sickness may occur and manifest as excess red blood cells and severe reversible tissue hypoxia.[36,37] These physiological conditions also affect mental functioning. The test used in this study was conducted when the subjects had just returned to high altitude after spending 3 mo in a low-altitude area. They may have been experiencing both acute and chronic hypoxia. To better illustrate the impact of high-altitude exposure on the attention network in future research, we will strictly control the duration of the subjects' stay at high altitude.

For the second limitation, the subjects were distributed across 13 provinces in China before they were admitted to Tibet University. We were unable to gather data for the baseline test before the participants entered high altitude. Therefore, it was not possible to conduct a longitudinal study, which is another limitation of this study. In future research, we will consider selecting army soldiers as test subjects for a longitudinal study, since they are assembled first at low altitude before entering Tibet.

For the third limitation, the advantage of ERP is its high temporal resolution; however, its spatial resolution is insufficient. In the future, various technical methods, such as fMRI, could be used to explore this effect collaboratively. In addition, we investigated the effects of high altitude on cognitive function by comprehensively considering the many factors that make up a high-altitude environment, including special natural and cultural environments such as hypobaric hypoxia, low temperatures, intensive ultraviolet radiation, and unique living customs. Future studies should independently examine these factors.

Finally, can these altered cognitive functions recover after returning to low altitude? How long does recovery take? Can cognitive training be used to maintain a good cognitive level in high-altitude environments? These issues should be explored further in future studies.

In conclusion, the current study indicates that the attentional network was decreased in high-altitude immigrants compared with low-altitude residents. The changes in attention function were due to the influence of high-altitude exposure on attention-related areas of the brain.

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REFERENCES

1. An X, Ma H, Han B, Liu B, Wang Y. Attention network varied along with the time of residence at high altitude. Chin J Clin Psychol. 2017; 25(3):502–506 [in Chinese].
2. Chen A, Zhang Z, Cao C, Lu J, Wu S. Altered attention network in paratroopers exposed to repetitive subconcussion: evidence based on behavioral and event-related potential results. J Neurotrauma. 2021; 38(23):3306–3314.

3. Chen X, Liu J, Wang J, Xin Z, Zhang Q, et al. Altered resting-state networks may explain the executive impairment in young health immigrants into high-altitude area. Brain Imaging Behav. 2021; 15(1):147–156.
4. Chu U, Da Z, Laba Z. Spatio-temporal distribution patterns of snow cover on the Tibet and orographic impacts. Journal of Geo-Information Science. 2017; 19(5):635–645.
5. Fan J, McCandliss BD, Fossela J, Flombaum JI, Posner MI. The activation of attentional networks. Neuroimage. 2005; 26(2):471–479.
6. Fan J, McCandliss BD, Sommer T, Raz A, Posner MI. Testing the efficiency and independence of attentional networks. J Cogn Neurosci. 2002; 14(3):340–347.
7. Faul F, Erdfelder E, Lang A-G, Buchner A. G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. Behav Res Methods. 2007; 39(2):175–191.
8. Fleck JI, Payne L, Halko C, Purcell M. Should we pay attention to eye movements? The impact of bilateral eye movements on behavioral and neural responses during the attention network test. Brain Cogn. 2019; 132:56–71.
9. Groom MJ, Cragg L. Differential modulation of the N2 and P3 event-related potentials by response conflict and inhibition. Brain Cogn. 2015; 97:1–9.
10. Larson MJ, Clayson PE, Clawson A. Making sense of all the conflict: a theoretical review and critique of conflict-related ERPs. Int J Psychophysiol. 2014; 93(3):283–297.
11. Luck SJ. Event-related potential basis. Shanghai (China): East China Normal University Press; 2009.
12. Ma H, Wang Y, Wu J, Liu H, Luo P, Han B. Overactive performance monitoring resulting from chronic exposure to high altitude. Aerosp Med Hum Perform. 2015; 86(10):860–864.
13. Ma H, Wang Y, Wu J, Luo P, Han B. Long-term exposure to high altitude affects response inhibition in the conflict-monitoring stage. Sci Rep. 2015; 5(1):13701.
14. Ma H, Wang Y, Wu J, Wang B, Guo S, et al. Long-term exposure to high altitude affects conflict control in the conflict-resolving stage. PLoS One. 2015; 10(12):e0145246.
15. Ma H, Zhang X, Wang Y, Ma H, Cheng Y, et al. Overactive alerting attention function in immigrants to high-altitude Tibet. Stress and Brain. 2021; 1(1):76–95.
16. Neuhaus AH, Urbanek C, Opgen-Rhein C, Hahn E, Ta T, Koehler S. Event-related potentials associated with attention network test. Int J Psychophysiol. 2010; 76(2):72–79.
17. Petersen SE, Posner MI. The attention system of the human brain: 20 years after. Annu Rev Neurosci. 2012; 35(1):73–89.
18. Posner MI, Petersen SE. The attention system of the human brain. Annu Rev Neurosci. 1990; 13(1):25–42.
19. Purmann S, Badde S, Luna-Rodriguez A, Wendt M. Adaptation to frequent conflict in the Eriksen Flanker Task: an ERP study. J Psychophysiol. 2011; 25(2):50–59.
20. Reuter EM, Vieluf S, Koutsandreou F, Hubner L, Budde H, et al. A non-linear relationship between selective attention and associated ERP markers across the lifespan. Front Psychol. 2019; 10:30.
21. Stivalet P, Leifflen D, Poquin D, Savourey G. Positive expiratory pressure as a method for preventing the impairment of attentional processes by hypoxia. Ergonomics. 2000; 43(4):474–485.
22. Sturm W, Willmes K. On the functional neuroanatomy of intrinsic and phasic alertness. Neuroimage. 2001; 14(1):S76–S84.
23. Tao G, An X, Jiang Y, Ma H, Han B, Wang Y. Long-term high altitude exposure influence the processing stage of conflict inhibition. Chinese Journal of Behavioral Medicine and Brain Science. 2020; 29(7):7.
24. Virués-Ortega J, Garrido E, Javierre C, Kloezeman KC. Human behaviour and development under high-altitude conditions. Dev Sci. 2010; 9(4): 400–410.
25. Vogel EK, Luck SJ. The visual N1 component as an index of a discrimination process. Psychophysiology. 2000; 37(2):190–203.
26. Wang X, Lu X, Zhang P, Li Y, Gao B. Research progress on the correlation between congenital heart disease and hypoxia environment in plateau areas. Journal of Clinical Medicine in Practice. 2021; 25(11):109–113.
27. Wang X, Zhao X, Xue G, Chen A. Alertness function of thalamus in conflict adaptation. Neuroimage. 2016; 132:274–282.
28. Wang Y, Ma H, Fu S, Guo S, Yang X, et al. Long-term exposure to high altitude affects voluntary spatial attention at early and late processing stages. Sci Rep. 2014; 4(3):4443.
29. Wei X, Ni X, Liu J, Lang H, Zhao R, et al. Simulation study on the spatiotemporal difference of complex neurodynamics between P3a and P3b. Complexity. 2020; 2020:2796809.
30. Williams RS, Biel AL, Wegier P, Lapp LK, Dyson BJ, Spaniol J. Age differences in the Attention Network Test: evidence from behavior and event-related potentials. Brain Cogn. 2016; 102:65–79.
31. Xin Z, Chen X, Zhang Q, Wang J, Xi Y, Liu J. Alteration in topological properties of brain functional network after 2-year high altitude exposure: a panel study. Brain Behav. 2020; 10(10):e01656.
32. Yan X, Zhang J, Gong Q, Weng X. Adaptive influence of long term high altitude residence on spatial working memory: an fMRI study. Brain Cogn. 2011; 77(1):53–59.
33. Yan X, Zhang J, Gong Q, Weng X. Prolonged high-altitude residence impacts verbal working memory: an fMRI study. Exp Brain Res. 2011; 208(3):437–445.
34. Yang G, Feng Z, Wang T. Influence and protection of high altitude hypoxia on psychological function. Chinese Journal of Behavioral Medicine. 2003; 12(4):471–473.
35. Zhang D, Zhang X, Ma H, Wang Y, Ma H, Liu M. Competition among the attentional networks due to resource reduction in Tibetan indigenous residents: evidence from event-related potentials. Sci Rep. 2018; 8(1):610.
36. Zubieta-Calleja G. Human adaptation to high altitude and to sea level: acid-base equilibrium, ventilation and circulation in chronic hypoxia. Riga (Latvia): Vdm Verlag Dr Müller; 2007.
37. Zubieta-Calleja GR, Paulev PE, Zubieta-Calleja L, Zubieta-Castillo G. Altitude adaptation through hematocrit changes. J Physiol Pharmacol. 2007; 58 Suppl. 5(Pt. 2):811–818.