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WHY DO THE EYES MOVE DURING COGNITIVE ACTIVITY?

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ABSTRACT

Shifting gaze during difficult cognitive activities is a very common phenomenon in our daily life, whereas its underlying neuropsychological mechanisms remain controversial. Preceding studies on adults have indicated that by shifting the gaze people disengage from environmental stimulation in order to concentrate on cognitive tasks. Further studies on children have suggested that approaching this eye movement phenomenon from the developmental viewpoint opens a window on its mechanisms. Here, we used an eye-tracking system to examine eye movements in adults and children while they were performing cognitive tasks, and also employed near-infrared spectroscopy to examine the neural basis of the gaze shift. Adults moved their eyes toward individual specific directions regardless of the task type. In contrast, younger children looked around more extensively with no directionality. Transition to adult-like patterns of eye movements was observed at 10 years of age, which corresponded to the time period of achieving adult levels of performance on a standard measure of executive functions. The eye movements were accompanied by activation of the premotor cortex and/or the lateral prefrontal cortex. These data suggest that the eye movements represent a more positive function than mere disengagement from the environment; probably access to cognitive space. It is also implicated that 10 years of age is a crucial period for cognitive development.

Key Words: eye movement, gaze shift, cognitive space, development

INTRODUCTION

When engaged in moderately difficult cognitive activity, people often close their eyes or shift their gaze unconsciously. Glenberg et al. (1998) showed that averting the gaze had benefits for memory retrieval and its appearance was related to the difficulty of a task in adults. The benefits of gaze aversion were similarly observed in younger and older adults (Einstein et al., 2003). Doherty-Sneddon et al., who investigated development of gaze aversion in children, found that adult-like patterns of gaze aversion in response to cognitive difficulty were acquired by eight years of age, and that cognitive difficulty had a stronger influence on the gaze aversion than social factors (Doherty-Sneddon et al., 2002, 2005). From these results, it is now thought that the eye movement accompanying cognitive activity, which is hereafter referred to as "EMCA", is

an action to suppress environmental distractions in order to manage cognitive load. However, EMCA occurs even when people are faced with a blank wall in a calm room, where environmental stimuli are considerably suppressed. Furthermore, EMCA are also observed in patients with blindness (Griffiths and Woodman, 1985). These findings raise doubts about the recent idea that the primary function of EMCA is disengagement from the environment.

Characterizing eye movements during mental tasks, a classic approach to EMCA, is essential for elucidating the basic mechanisms of EMCA. Recent sophisticated eye-tracking systems show greater promise toward this aim than the conventional approaches used in a number of the preceding studies, in which eye movements were examined either by an experimenter situated across from a participant or eye movements recorded by a video camera were analyzed. In addition, elucidating the neural basis of EMCA is crucial for interpretation of this phenomenon. Moreover, the findings obtained from two research groups have indicated that EMCA should be treated as a developmental issue: one is above-mentioned (Doherty-Sneddon, 2002) and the other reported that the LEMs appeared well-established by 3.5 years of age (Reynolds and Kaufman, 1980). Therefore, to elucidate the neuropsychological mechanisms behind EMCA, by using an eye-tracking system we analyzed eye movements while adults and children were performing mental tasks. We also investigated which regions of the brain were engaged in EMCA with event-related near-infrared spectroscopy (NIRS).

MATERIALS & METHODS

Subjects

Nineteen healthy adults (eight women, 11 men, ranging in age from 22-29 years) and 30 healthy children (nine girls, eight boys, ranging in age from 5-7 years; six girls, seven boys, ranging age in 10-13 years) participated in measurements of eye movements by an eye-tracking system. Thirteen healthy adults (seven women, six men, ranging in age from 21-29 years) participated in NIRS measurements. Prior to each study, written informed consent was obtained from all of the participants and also parents of the child participants. The ethics committees of the Tokyo Institute of Psychiatry and Hokkaido University approved the study.

Tasks

For adults, 11 mental tasks (3 arithmetic, 2 verbal, 2 memory retrieval, and 4 visuospatial imagery tasks) were used to elicit EMCA. The maximum time of one min was allotted to perform each task. Tasks for younger children (5-7 years) were 23 riddles and 1 verbal fluency task, and those for elder children (10-13 years) were 20 riddles, 4 arithmetic and a verbal fluency tasks. The questions were asked by an experimenter from behind the subjects.

Eye movement recording and analysis

Binocular eye movements were monitored by using an eye-tracking system (Voxer, Nac, Japan). Subjects sat on a chair and were instructed to look at the fixation point on

the wall 4 m in front of them while listening to a question. The fixation point was individually determined so that the eye position within the orbit was normal when a subject looked at the point. Measurements with the Voxer were started about 5 min before the first task and were continued until the end of the last task.

The view image (the camera coordinate system of 480 by 640 pixels), which was recorded by a field camera and eye marks (eye positions) were superimposed on in real-time, was firstly divided into 256 square areas (30 by 40 pixels). The number of gaze points, of which one was defined as a group of eye marks staying within 50-pixel circle for more than 0.1 s, was determined for each square area. And then, the camera coordinate system was divided into 8 directions every 45 degrees by taking the initial fixation point as a center. Excluding gaze points within 9 square areas surrounding the fixation point (90 by 120 pixels), areas with more than 50% of the maximum number of gaze points were defined as directions of EMCA.

NIRS data acquisition and processing

A multichannel NIRS imaging system (OMM-2000, Shimadzu Co., Japan) was employed for measurements. Four pairs of illuminating and detecting light guides were symmetrically placed on the lateral frontal region of both sides with an illuminating and detecting light guide separation of 3 cm. This alignment of light guides measured 24 regions (channels), which covered the lateral PFC and premotor cortex. The subjects' eye movements were simultaneously measured by a video camera, of which data were transferred to the OMM-2000 in real-time. Upon completion of the study, subjects underwent MRI measurement to confirm the brain region beneath each light guide.

In the present study, changes in oxygenated hemoglobin (oxy-Hb), which is the most sensitive indicator of changes in regional cerebral blood flow (rCBF) (Hoshi et al., 2001), were analyzed. One of the 13 subjects was excluded from the analysis, because this subject stared at the fixation point during performance of all the tasks. From the videotape, the beginning point of each EMCA was detected. The value of oxy-Hb at the beginning point of EMCA was taken as 0, and then changes in oxy-Hb were recalculated for 2 s from 0.5 s before and 1.5 s after this beginning point. EMCA was observed more than 30 times in the 12 individual subjects. Oxy-Hb changes related to each EMCA were independent of each other, and changes in oxy-Hb also occurred during a period without EMCA; the baseline was different from event to event. Thus, comparison of mean values of oxy-Hb changes 0.5 s before and 1.5 s after the beginning point of EMCA at each channel was performed by a two-way ANOVA with an α of 0.05 for factors of time (two levels: before and after the beginning point of EMCA) and event (EMCA). $P < 0.01$ was chosen as the level of significance.

RESULTS

Eye movements in adults

Directions for EMCA differed across individuals, but were consistent within an individual irrespective of the type of questions in 16 of the 19 subjects, including three subjects who stared at the initial fixation point during performance of all the tasks.

Figure 1 shows an example data set of numbers of gaze points in each area of the camera coordinate system for subject 2, who showed EMCA with task-type-independent directionality. This subject moved the eyes exclusively upward (area 1 or areas 1 and 2) during performance of all the tasks except for one that was immediately answered without eye movement. The remaining 3 subjects also showed EMCA, of which directions varied with the question type. Table 1 summarizes the directions of EMCA for all the subjects.

When subjects did not easily give answers, frequency in EMCA was increased within the individual, unique areas of the camera coordinate system, but directions of the eye movements from one gaze point to another were not necessarily the same as either the directions of EMCA or its opposite directions (i.e., returning to the initial fixation point). For instance, while subject 2 was performing task B1, she moved her eyes into area 1; however, most of her eye movements from one gaze point to another were horizontal within area 1.

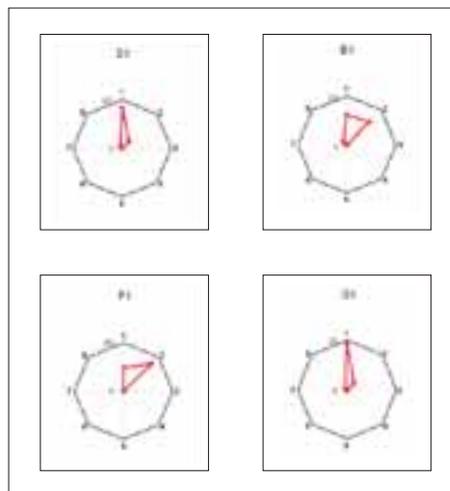


Figure 1 Numbers of gaze points at each area (1-8 areas) while subject 2 in Table 1, who showed EMCA with task-type-independent directionality, performed 4 tasks. Letters denote tasks. Numbers lower left of area 1 denote the maximum number of the radar chart axis.

Eleven out of the 19 subjects had also participated in the investigation similar to the present study six months ago, in which the types of questions were the same as those of the present study but different questions were used. As is shown in Table 1, the patterns of EMCA for individual subjects, that is, EMCA with task-type-independent directionality and EMCA with task-type-dependent directionality and staring, were reproducible in an interval of six months. In addition, the directions of EMCA in each subject with task-type-independent directionality were the same as those six months ago.

Eye movements in children

Unlike adults, younger children (5-7 years of age) fixed their eyes far less in the camera coordinate system. Figure 2 shows an example data set of eye positions while a

Table 1 Directions (areas of the view image) of EMCA

Subject	Present study	Previous study
1	2	2
2	1, 1~2	1, 1~2
4	3, 7	3, 7
5	3, 7	3, 7
6	2	Staring
7	1~2	—
8	3, 7	—
9	2, 8	—
10	1	—
11	1, 5	—
12	1, 7	—
13	8, 2	—
14	Staring	Staring
15	Staring	Staring
16	Staring	Staring
17	∞	∞
18	∞	∞
19	∞	∞

—, not measured

∞, task- type-dependent directionality

6-year-old girl was performing four tasks. She turned her eyes outside the boundaries of the camera coordinating system with no directionality during performance of all the tasks except for those which were answered immediately. In contrast, four of six 10-year-old children tended to move their eyes within the camera coordinate system but with less directionality compared with adults, and the directions of EMCA varied with individual questions. When they did not find an answer easily, they turned their eyes outside the boundaries of the camera coordinate system like the younger children. The remaining two 10-year-old children showed fairly adult-like patterns of EMCA: EMCA with task-type-independent directionality was observed. Four 11-year-old children and a 13-year-old girl also showed the adult pattern.

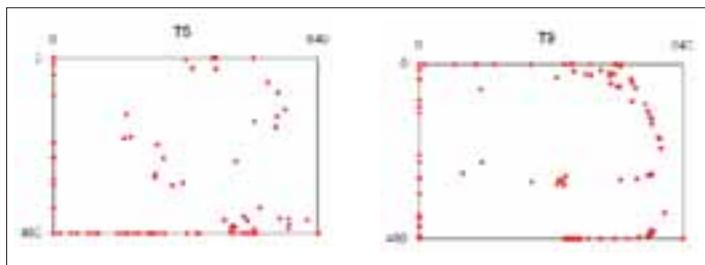


Figure 2 Example distributions of eye marks (eye positions) for a 6-year-old girl during performance of two tasks (T2 and T5).

Cerebral blood flow changes related to EMCA

EMCA was accompanied by increases in oxy-Hb in the premotor cortex and/or the lateral prefrontal cortex unilaterally or bilaterally in all the 12 subjects, although localization of activated brain areas varied with each subject. Table 2 summarizes the activated brain areas related to EMCA. Figure 3 shows examples of oxy-Hb changes related to EMCA for subject 8 in Table 2. Subject 8 showed activations in the bilateral inferior premotor areas and the bilateral dorsolateral prefrontal cortices (DLPFCs).

Table 2 Activated brain areas related to the appearance of EMCA

Subject	Brain areas
1	L dorsolateral prefrontal cortex (BA 9/46)
2	R inferior premotor area (BA 6)
3	L inferior premotor area (BA6)
4	R inferior premotor area (BA6)
5	L inferior premotor area (BA 6) R inferior premotor area (BA 6)
6	L dorsolateral prefrontal cortex (BA 46)
7	L inferior premotor area (BA 6)
8	L dorsolateral prefrontal cortex (BA 46) L inferior premotor area (BA6) R dorsolateral prefrontal cortex (BA9/46) R inferior premotor area (BA 6)
9	R superior premotor area (BA 6)
10	L ventrolateral prefrontal cortex (BA45)
11	L inferior premotor area (BA6)
12	L dorsolateral prefrontal cortex (BA46) R dorsolateral prefrontal cortex (BA 9/46) R ventrolateral prefrontal cortex (BA 45/47)

L, left; R, right; BA, Brodmann area

DISCUSSION

The present study has clearly shown that EMCA represents a more positive implication than simply enhancing cognitive operations by switching-off from environmental stimulation. In general, gaze shifts indicate changes in focus of attention, which is supported by the current view that attention and eye movement systems are tightly related: a large anatomical overlap exists between neural systems involved in directing attention and in eye movement (Corbetta, 1998). Here, we propose a novel hypothesis for the mechanism of EMCA: it represents orienting attention to cognitive space and shifting attention from the current information processing to a new mode of processing within the same space. Cognitive space, which is a virtual, two, three, or higher dimensional space to describe thoughts, memories and ideas, is defined as the set of concepts and relations among them held by a human (Newby, 2001). The

individual cognitive space, consisting of cognitive/emotional structures determined by the experiences, controls the perception and further processing of external input (Ingwersen, 1996). The cognitive space is similar in many respects to mental representations described by Nobre et al. (2004), but the cognitive space is a more comprehensive entity. Using event-related functional magnetic resonance imaging (fMRI), they found that orienting spatial attention to external perceptual and mental representations maintained in working memory showed a largely overlapped network involving the parietal, frontal and visual cortices, whereas several frontal lobe regions were selectively engaged in orienting attention to the components of working memory. These overlapped activation areas in the frontal and parietal cortices are included in the fronto-parietal cortical network, which has been thought to participate in orienting attention to visual locations (Corbetta, 1998; Kanwisher and Wojciulik, 2000).

In the present study, where we measured oxy-Hb exclusively in the frontal cortex but not in the parietal cortex, the brain activation related to EMCA was most consistently observed in the inferior premotor area, while activations of the ventrolateral prefrontal cortex (VLPFC) and the DLPFC were also observed in some subjects. Only one subject showed an activation of the superior premotor area, which presumably corresponded to the frontal eye field. Since head motion did not accompany EMCA in the adult subjects, the premotor activation was unlikely to reflect the preparation of head motion. Several neuroimaging studies have demonstrated that the inferior premotor area is engaged in non-motor cognitive roles, such as orienting/shifting attention (Vandenberghe et al., 1996; Beauchamp et al., 2001) and object information processing in serial prediction (Schubotz and von Cramon, 2003; Kansaku et al., 2007).

Several neuroimaging and electrophysiological studies have indicated that the lateral PFC is implicated in top-down control of attention (Buschman and Miller, 2007; Gazzaley et al., 2007). A recent review article has reported that the lateral PFC is critical in switching attentional control on the basis of changing task demands (Rossi et al., 2009). Taken together, the present findings that the appearance of EMCA was accompanied by activations of the premotor cortex and/or the lateral PFC support our hypothesis that EMCA reflects attentional orientation/shifting. It is supposed that the lateral PFC activations were related to shifting attention from one cognitive process to another within the cognitive space, because it required more top-down control of attention than directing attention to the cognitive space. In this study, we did not distinguish eye movements related to orienting from those related to shifting. This may partly account for individual variations of activated areas.

Adults are expected to have the individual cognitive space, of which the structure varies with individuals. It is therefore reasonable that the eye movement propensity of one individual during cognitive tasks was not necessarily the same as those of the others. In contrast to adults, younger children are unlikely to establish the individual space. Thus, one possible explanation for non-directionality of EMCA observed in younger children is that because of the lack of establishment of a cognitive space, they don't know where to orient their attention while performing mental tasks, and consequently move their eyes in various directions. In a series of our studies, by using the 3D motion analysis system (MAC3D System, MotionAnalysis, USA) we examined

head motion in adults and children while they were performing mental tasks. Younger children tended to move their heads associated with EMCA, while adults' heads tended to be stationary (unpublished data). The frequent head movements in children account for the finding that younger children looked around more extensively.

Transition to the adult pattern of EMCA was observed at 10 years of age, which corresponded to the achievement of adult levels of performance on a standard measure of executive functions at around 10 years of age (Chelune and Baer, 1986; Welsh et al., 1991). This coincidental development of EMCA and executive function also supports the contention that EMCA is a behavior to access cognitive space and shift one cognitive structure to another.

In summary, our results indicate that EMCA represents a more positive implication than disengagement from the environment. It is proposed that EMCA is a behavior to access cognitive space and an indicator that one is performing cognitive activities. It is also implicated that 10 years of age is a crucial period for cognitive development.

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