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Chapter 3

ELUCIDATION OF NEUROPSYCHOLOGICAL MECHANISMS OF EYE MOVEMENTS ACCOMPANYING COGNITIVE ACTIVITY

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ABSTRACT

Gaze-shifting during complex cognitive activities, what is sometimes referred to as gaze-shifting, is commonly reported; however, the neuropsychological mechanisms giving rise to gaze-shifting remain unclear and a number of conflicting theories have been reported. One prevailing view is that the gaze-shifting, alternatively referred to as gaze aversion (GA), makes it easier to disengage from distracting environmental stimuli and to facilitate the cognitive processing at hand. Gaze aversion has also been investigated from neurological and

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developmental viewpoints. Although children can also be considered as being able to use GA in managing cognitive loads, this view fails to account for continuous eye movements after initial gaze-shifting from the distracting stimulus. Nor does it account for the occurrence of this behavior even when stimuli are reduced to a minimum, such as by having the subjects close their eyes, and/or when the observation was conducted in a completely dark room. A series of studies, in which the relationship between the kind of memory and the eye movements, referred to as nonvisual eye movements (NEM), was examined by Ehrlichman et al., have proposed a hypothesis that searching for information in long-term memory generates eye movements, because the same neural circuits are involved in both long-term memory search and eye movements. In this hypothesis, NEM is considered a nonfunctional byproduct of task-related neural activation; however, this has not been confirmed. In most studies related to eye movements, the relationship between cognitive processes and the rate of eye movements has been determined subjectively by experimenters, and no effort has been made to further characterize the experimenter observed eye movements. This paper attempts to address this issue, and as a first attempt investigates the direction of eye movements, as casual observations suggest that the eyes of humans move in various directions when engaged in cognitive activities. Recently, eye-tracking technology allowing a dynamic examination of the patterns of eye movements accompanying cognitive activity (EMaCA) more precisely have become available. To elucidate the nature of EMaCA, we employed an eye-tracking recording system to examine the patterns of EMaCA in 19 adults aged 22 to 29 years and in 13 children aged 5 to13 years while they were performing cognitive tasks. The findings lead us to propose a novel hypothesis. In this chapter, following a historical introduction, we first review the studies on the EMaCA, then describe our studies with an eye-tracking recording system, and finally discuss our hypothesis.

INTRODUCTION

When engaged in moderately difficult cognitive activities, such as memory retrieval or in figuring out the answer to a question, humans often unconsciously close their eyes or shift their gaze. These eye movements relating to cognitive activity were first reported by Day [1], who described the phenomenon as consisting of lateral eye movements (LEM), which occur when a person is asked a question (not a very simple question) while gazing at the face of the person asking the question. The Day findings lead to the conclusion that the direction of the movement relates to basic personality differences and to differences in the subjective experience of anxiety. It was also suggested that the direction of the eye movements is associated with an attentional shift from a passive to an active mode [1, 2].

The LEM was subsequently studied further [3, 4, 5]. Bakan proposed the hypothesis that LEM is related to the functional asymmetry of the brain (hemispheric asymmetry) and may be considered a byproduct of the activation of the cerebral hemisphere contralateral to the direction of the gaze [5]. This hypothesis was substantiated by other research groups [6, 7] and the idea that the LEM can be used as an index of hemispheric asymmetry has been proposed [7] and a large number of studies were conducted based on this. However, many problems with the "laterality hypothesis" have been pointed out. For example, several studies reported no significant hemispheric asymmetry pattern for LEM [8, 9]. Procedural variations, such as the location of the questioner have also been shown to influence the phenomenon [10]. Vertical and an absence of eye movements (staring) have also been observed [11]. Because of these issues, Ehrlichman and Weinberger tested the hypothesis in a review of the literature on LEM and concluded that there is little justification for linking LEM patterns with hemisphericity, although they accepted that LEM is in some way related to brain activity [12]. After the Ehrlichman and Weinberger review, LEM has continued to be used in investigations of laterality by some researchers [13], but generally less attention is paid to these eye movements.

Some later investigations of eye movements accompanying cognitive activity focused on one of the characteristics already observed and reported by Day [1]: the more difficult the task, the higher the frequency of eye movements [14, 15]. More recently, renaming these task-related eye movements as "gaze aversion (GA)," Glenberg et al. [14] showed that GA improved subject memory retrieval and that in adult subjects its occurrence was related to the difficulty of a task. These relationships between frequency and task difficulty were similarly observed in both younger and older adults [16]. Doherty-Sneddon et al. [15, 17], who investigated the development of GA in children, found that the adult-like patterns of GA in response to difficult tasks (high cognitive loads) were acquired by eight years of age, and that task difficulty had a stronger influence on the frequency of the occurrence of GA than other social factors, such as face-to-face questions. Presently, after the appearance of these findings, a commonly adopted view is that GA arises when there is a need (wish) to avoid environmental distractions and to increase the efficiency of cognitive processing.

However, the accuracy and applicability of this view has been questioned by Ehrlichman et al., who pointed out a number of observations that could not be explained by any effect of disengagement from distractions [18]. For example, the persistence of eye movements after averting the eyes from the face of the questioner by looking away [19] and the occurrence of eye movements in various experimental conditions in which environmental stimuli were reduced to the minimum possible [20-22]. Further, eye movements similar to GA are reported to be observed in patients with blindness [23]. Ehrlichman et al. focused on differences in the rate of occurrence of these eye movements, this time referred to as “nonvisual eye movements (NEM),” between verbal-linguistic and visual-image-based questions. Typically, the former requires extensive memory search. They examined the role of memory in such eye movements and proposed the hypothesis that searching for information in long-term memory generates these eye movements which are not related to task performance [24]. They also hypothesized that maintenance of working memory inhibits eye movements [24]. However, many questions remain to be answered: especially, the argument that the eye movements are a non-functional byproduct of long-term memory processes has not been confirmed [18].

Gaze is an important component in social interactions, and gaze shifts are caused by a variety of factors depending on the social context, indifference or attraction [25, 26]. In general, however, gaze shifts indicate changes in the focus of attention, an idea which can be supported by the current commonly accepted view that attention and eye movement functions are closely interrelated: based on the fact that there is a large anatomical overlap between neural systems involved in directing attention and in eye movement [27]. Therefore, although there is no direct evidence at present, it is possible to hypothesize that the eye movements accompanying cognitive activity, referred to as “EMaCA” (eye movements accompanying cognitive activity) in the following reflect ongoing cognitive processes, and are not restricted to memory retrieval.

As described here, despite a number of studies, the neuropsychological mechanisms involved in EMaCA remain unsubstantiated. Previous studies mainly focused on the type of stimuli used to produce EMaCA, such as verbal vs. visuospatial tasks and the experimental environment, and the effects on eye movement rates were mostly evaluated by the experimenters, and so subjectively determined. Differently, the direction of the EMaCA has been much less examined after the rejection of the “laterality hypothesis.” However, the direction of the EMaCA must still be considered important, as casual observations suggest that the eyes move in a variety of directions, when we perform cognitive activities. Recent highly sophisticated eye-tracking recording systems enable a precise and dynamic examination of the patterns of EMaCA. Here, to elucidate the nature of EMaCA, we have employed an eye-tracking recording system that examines eye movements of adults and children performing mental tasks.

This chapter summarizes investigations of EMaCA more recent than the Ehrlichman and Weinberger report [12], and details recent studies by the authors as well as it discusses a novel hypothesis on EMaCA based on these studies.

GAZE AVERSION (GA)

Glenberg approached memory theory guided by the question of “what is memory for?” and analyzing memory, he predicted the phenomenon of averting the gaze when people are engaged in a difficult memory task [28]. Glenberg suggested that “memory evolved in the service of perception and action in an environment, and that memory is embodied to facilitate interaction with the environment.” He argued that actions must respect the constraints of the environment, resulting in the cognitive system being commonly “clamped” to the environment, while various other cognitive activities, such as planning and language comprehension, require a disengagement from the environment [28]. It was also suggested that GA requires much less effort than cognitively suppressing environmental control over conceptualization.

To examine whether people avert the gaze in order to facilitate cognitive processing, Glenberg et al. [14] conducted five experiments, demonstrating that (1) the frequency of GA increased with the difficulty of cognitive tasks (autobiographical memory questions and general knowledge questions), (2) that GA was not simply due to either embarrassment or demand characteristics, because this phenomenon occurred in the experimental room where only a participant was present and as the relationship between the frequency of eye movements and task difficulty was observed for a wider range of questions, (3) task performance with both general knowledge and mathematics questions was higher in a closed eye condition than in “a looking at the experimenter’s nose” condition, and (4) task performance for free recall of random word lists was higher in a simple condition (a slide depicting a sunset was projected onto the screen) than in a complex condition (a 30-sec segment from a Chaplin movie projected without sound). The basic idea of

Glenberg et al. was that remembering (or problem solving) is sometimes a dual-task situation: while engaging in remembering we monitor environmental events. If the task to be remembered is difficult, cognitive resources devoted to monitoring the environment are diverted to the task. It was speculated that people avert the gaze to disengage from environmental stimulation and to facilitate memory retrieval [14].

GAZE AVERSION (GA) IN CHILDREN

Casual observations of children by Day [1] reported that the LEM did not occur until approximately age three and seemed to be related to acquiring an ability of delayed recall. This is consistent with the findings obtained from the later study by Reynolds and Kaufman [29], who examined 52 children aged 2-8 and 9-11 using spatial and verbal-analytic questions to elicit the LEM. Here the LEM appeared well-established by 3.5 years of age, which was accounted for by a possible relation to a cognitive variable such as entering Piaget's formal operational stage [30] or the development of Kagan's basic cognitive competencies [31].

Doherty-Sneddon et al. found that young children relied on visual communication to compensate for their relatively poor language skills, which could be expressed in less often averting the gaze from the interlocutor, a strategy for shifting attention [32]. The subsequent investigation of child communication abilities in face-to-face and audio-only interactions suggested that children aged six- and ten-years old were not "switching off" effectively from the interlocutor visual signals, which interfered with the performance of the task [33]. Since, however, it was found that older children perform tasks that require disengagement from irrelevant information better than younger children [34], and that attention shifting is improved with increasing age [35], it was expected that the rate of appearance of GA would increase with development. Here, Doherty-Sneddon et al. investigated the development of GA in children, eight- and five-year-olds, while the children were answering verbal reasoning and arithmetic questions of varying difficulty, and found that adult-like patterns of gaze aversion in response to difficult tasks were acquired by eight years of age [15]. They also investigated GA in eight-year-olds who were asked questions of various types and degrees of difficulty either face to face or across a live video link, and confirmed that task difficulty has a stronger influence on the frequency of gaze aversion than other social factors [17]. Doherty-Sneddon et al. argued that GA functions to control the level of cognitive load in a manner similar to what Glenberg proposed for adults and therefore it was considered an indicator that a child was thinking [15].

They expanded the investigations from typically developing children (TDC) to children with two neuro-development disorders: autism spectrum disorder (ASD) and Williams syndrome (WS). Both children diagnosed with ASD and WS show atypical face gazing, here the former (ASD) is associated with reduced sociability and the latter (WS) with hypersociability. Although there were some disorder-related differences, children with ASD and WS showed increased rates of GA as question difficulty increased, a typical pattern of GA observed in both adults and TDC [36, 37].

"Nonvisual" Eye Movements (NEM)

Ehrlichman et al. called the eye movements that we are dealing with here saccades, "random" or "spontaneous" saccadic eye movements, and referred to them as "nonvisual eye movements" (NEM) [18, 38]. In contrast to the earlier prevailing opinion that saccades reflect mental scanning of visual imagery [39], Ehrlichman et al. found that image-based questions elicit fewer saccades than verbal questions [12, 38]. They predicted that the differences in rates of eye movement of image-based and verbal questions would reflect differences in internal "sampling" rates, termed "cognitive change" by Antrobus [40]. Similarly, Bergstrom and Hiscock observed that visuospatial questions elicited a lower rate of eye movements than verbal questions, and that imagery questions that require a constrained memory search ("focusing attention on relatively circumscribed data base") elicited a lower rate of eye movements than unconstrained questions [41]. Antrobus [40] and Bergstrom and Hiscock [41] noted that lower cognitive change or constraint is associated with reduced search in the long-term memory.

Recently, Ehrlichman et al. tested the possibility that search through long-term memory may be the primary factor accounting for variations in the rate of eye movements during cognitive tasks by using several tasks that differ in the requirements for long-term memory retrieval [22]. Here it was found that the rates of eye movements were higher during high retrieval tasks than the low retrieval tasks, while either visual imagery or task difficulty was not related to the rates of eye movements, although a minor effect of task difficulty was observed. Subsequently, the role of both long-term and working memory in NEM was reported, and here it was shown that tasks requiring minimal long-term memory searching and tasks requiring focusing on material in the working memory elicited the lowest rates of eye movements, while tasks with high requirements for long-term-memory searching resulted in the highest rates of eye movements [24]. Further, since voluntary suppression of saccadic movements did not influence task performance, it was concluded that the NEM have little functional value. The close relationship between NEM and long-term-memory searching were explained as there are several brain areas of overlap, including the basal ganglia, and that there would be interaction between the neural circuits involved in both processes. The discussion here concluded that NEM are triggered by searching the long-term memory and the eye movements are a byproduct of the brain activation involved in memory retrieval [24]. It has also been hypothesized that maintenance of information in the working memory inhibits eye movements [18].

EYE MOVEMENTS ACCOMPANYING COGNITIVE ACTIVITIES (EMACA)

In the following the eye movements discussed above will be termed as EMaCA (eye movements accompanying cognitive activities). Previous studies mainly focused on methods to produce EMaCA: (1) the type of tasks (visuospatial tasks, verbal tasks, or task difficulty), and (2) the experimental environment (face-to-face or closing of the eyes), and the effects on eye movement rates. In the present study, we investigated the characteristics of EMaCA dynamically irrespective of task types.

METHODS

Subjects

Nineteen healthy adults (eight females, 11 males, from 22-29 years old), undergraduate and postgraduate students at a Japanese university, 17 healthy younger (nine girls, and eight boys, from 5-8 years old) and 13 healthy older children (six girls, and seven boys, from 9-13 years old), who were or had been affiliated with a kindergarten at the university, participated in the measurements of eye movements by an eye-tracking recording system. All subjects had normal visual acuity, without or with correction, and visual fields. Prior to enrollment in the study, written informed consent was obtained from each of the participants and also from the parents of the child participants. Approval of the study was obtained from the ethics committees of the Tokyo Metropolitan Institute of Medical Science and Hokkaido University (the previous affiliations of the authors).

Tasks

For the adults, 11 mental tasks in the form of riddles (three mental arithmetic (task 1-3), two verbal fluency (task 4 & 5), two memory retrieval (task 6 & 7), and four visuo-spatial imagery tasks (task 8-11) were used to elicit the EMaCA. A maximum of 60 seconds was allotted to each task. Tasks for the younger children (5-8 years), with wordings adjusted to suit the ages of the subjects, included 5 riddles, a verbal fluency task, and 7 memory retrieval tasks. For the older children (9-13 years), the tasks were the same as for the younger children with an additional 2 mental arithmetic tasks. It would be difficult for children to concentrate on a task for 60 seconds and a maximum time of 30 s was allotted to perform each task for both the younger and older children. The allotted time for the tasks for children was different from that for the adults, but a sufficient number of eye movements were produced by both groups. All questions were asked by an experimenter sitting behind the subjects.

Although the questions asked of the subjects were varied according to the age of the subjects, every effort was made to create moderately difficult questions for all groups of subjects to ensure that the subjects would have to spend at least a few seconds in figuring out an answer, and this was to ensure that an adequate number of EMaCA would take place. The questions were created based on the results of our pilot studies. Task performance was evaluated by the percentage of correct answers for the total number of questions except for narrowly personal questions. There were no statistically significant differences in this percentage among the three groups.

Recording of Eye Movements and Data Analysis

The eye movements of the left eye of the subjects were monitored by a contact-free eye-tracking system with a sampling rate of 60 Hz (EMR-AT Voxer, nac, Japan). The Voxer is a video-based eye tracker, in which LED light at 850 nm is irradiated and light reflected from the eye is sensed by a video camera. It employs the pupil/cornea reflection method: the cornea reflection and the center of the pupil are used as features in the tracking. The Voxer cannot measure extremely fast and extremely small amplitude saccades, and such short duration, minute saccades were not an object of the present study. Instead, we focused on the relatively slow and large amplitude eye movements that could be detected visually. Subjects were seated on a chair and were instructed to fixate on a point produced by a laser pointer on a screen 4 m ahead while listening to the question. The fixation point was shown only during the question presentation, and was individually adjusted so that the subjects would be able to view it comfortably (without any change of head position), and it was switched off when a question had been asked. The Voxer measurements started about 5 min before the first task and were continued at least 30 s after the end of all tasks. A built-in video camera, which was connected to the Voxer through the multi viewer system (MV-40F, FOR-A Ltd, Japan), recorded the face and head of the subject, and an area around the left eye so that eye blinks and head motions were displayed simultaneously with the eye tracking on a monitor. The recordings were used to establish the occurrence of unexpected movements of the subjects such as eye blinking.

A field camera (CCD camera, ICD-808, Ikegami, USA) was placed close to the left side of the head of the subject at eye level to record the visual field of the subject. The center of this field camera image was adjusted to correspond to the point the eye of the subject fixated on, creating a camera coordinate system (referred to as CCS in the following) of 640 by 480 pixels, and an angle of view of 37 by 28° (Figure 1). A real-time image of the eye positions of subjects generated by the Voxer (eye marks) was superimposed on the CCS and the combined images throughout the performance were videotaped. In the data analysis, the gaze point was defined as a group of eye marks staying within a 50-pixel diameter circular area (0.46 by 0.35°) for more than 0.1 s. By taking the initial fixation point as the center, the CCS was divided into eight isosceles triangle-shaped sectors (height 240 pixels, sectors 1~8) with a central angle of 45 degrees (Figure 1). Comparisons of the task performance between the directions of the EMaCA were performed by using one-way ANOVA. $P < 0.01$ was chosen as the level of significance.

The frequency of eyes moving outside of the CCS sectors was calculated to assess the range of the visual space for each individual (RVS in the following). A large RVS means that subjects oriented the gaze to a visual space far from the initial position. The RVS was calculated as the percentage of the total time for eye positions to fall outside the sectors to the duration of performing a task. Data during eye blinks were excluded. The RVS of a subject was expressed as the average RVS value for all the tasks. Variation in the directions of eye positions outside the boundaries of the sectors (VDEO in the following) were also assessed by calculating the number of sectors which eye marks passed through the boundaries during performance of each task, and the average number of sectors for all the tasks. The VDEO reflects the degree of variation of the individual in eye movement directions. Comparisons of the RVS and VDEO between children and adults were performed by the Kruskal-Wallis and Mann-Whitney U tests. $P < 0.01$ was chosen as the level of significance.

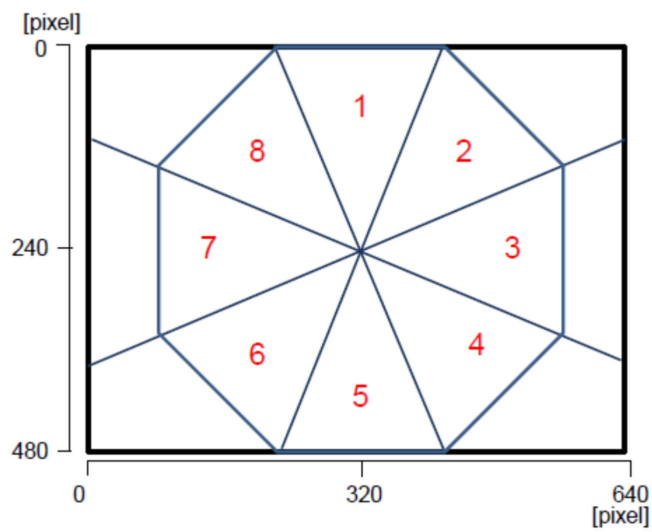

Figure 1. The camera coordinate system (CCS) with eight sectors. The angle of view was 37 by 28° in the present experimental setup.

RESULTS

Eye Movements in the Adults

Three out of the 19 subjects fixated on the initial fixation point during the performance of all the tasks. There is no good explanation for this, and the data for these three subjects were excluded from further analyses. Typically, an initial relatively large saccadic eye movement was observed after a question (the first phase). The directions of the first EMaCA varied from individual to individual, but were consistent and to a specific sector for an individual irrespective of the type of question in 9 of the 16 subjects analyzed. In the remaining 7 subjects, the directions of the first EMaCA were to two specific sectors and for one subject to five sectors. Table 1 summarizes the directions of the first EMaCA for all the subjects, expressed by the sectors visited by the first EMaCA (present study data).

The initial saccadic eye movement was often followed by smaller saccadic and/or smooth pursuit-like eye movements (the second phase) within a limited sector of the CCS. In the 9 subjects where the directions of the first EMaCA were consistent for all the tasks (subjects 1-9 in Tables 1 & 2), these sectors, which included the sector visited by the first EMaCA, were also consistent and were unique to the particular subject (type A in Table 2).

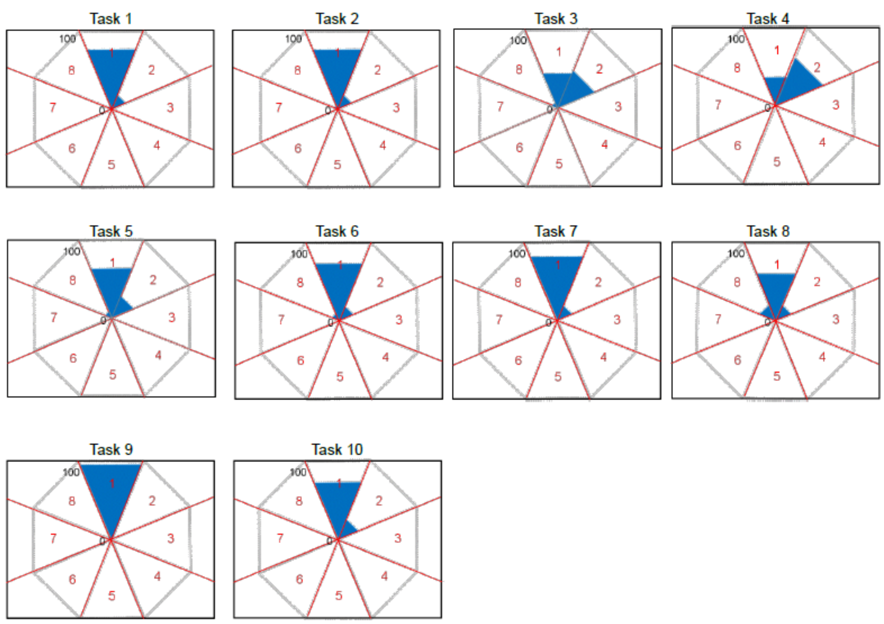

Figure 2. Numbers of gaze points in each sector (sectors 1-8) for the type A EMaCA subject 2 as detailed in Tables 1 & 2. The numbers of gaze points are expressed as the percentage of the total number, and the maximum number on the axis is 100 %. The graph is superimposed on the sectors in the CCS as shown in Figure 1. Red Arabic numerals denote the sectors. task 1-3, mental arithmetic; task 4 & 5, verbal fluency task; task 6 & 7, memory retrieval task; task 8-10, visuo-spatial imagery task.

Table 1. Sectors visited by the first EMaCA

Subject	**Present study**	**Previous study**
1	2	2
2	1	1
3	3	3
4	7	7
5	2	#
6	1	--
7	1	--
8	1	--
9	1	--
10	3 or 7	--
11	2 or 8	--
12	1 or 5	--
13	1, 2, 3, 5 or 8	1, 2, 3, 5 or 8
14	1 or 5	1 or 5
15	1 or 7	1 or 7
16	1 or 7	1 or 7

Arabic numerals, sector number of Figure 1; --, not measured; #, fixation on the center.

Figure 2 is an example of the data, subject 2 in Tables 1 & 2, showing the numbers of gaze points in each sector of the CCS. The gaze points of this subject were exclusively in the upward direction (sector 1 or sectors 1 and 2) during the performance of all the tasks except one task which was immediately answered without any eye movement. The seven subjects where the directions of the first EMaCA were to two or more sectors (subjects 10-16 in Tables 1 & 2) also turned their gaze on a limited number of sectors (one or two sectors). The sector visited by the first EMaCA was included among this limited number of sectors (type B in Table 2). Directions of the eye movements from one gaze point to the next in the second phase were not necessarily the same as either the directions of EMaCA in the first phase or the opposite directions (the return to the initial fixation point). For instance, subject 2 performing task 2, first moved the eyes into sector 1; and most of the subsequent eye movements from one gaze point to the next were horizontal within that sector.

Nine out of the 16 subjects had also participated in an 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 posed. As is shown in Tables 1 and 2 (previous study data), the patterns of EMaCA for individual subjects were reproducible after an interval of six months. In addition, except for subject 5, who fixated on the initial fixation point during the performance of all the tasks in the previous study, the initial directions of EMaCA in each subject were the same as those six months ago.

Eye Movements in the Children

Different from the adult subjects, the younger children (under 10 years of age) moved the eyes far less within the sectors, and since their eye movements tended towards the outside of the CCS, fewer gaze points were recorded and counted. Except for tasks where the answers were produced immediately, the eye movement directions were more varied. All of the 10-year-old children (n = 5) showed EMaCA with a focus-direction within a narrow range, similar to that of the adults, and both type A and type B of EMaCA were observed. Three of these five children moved the eyes outside the boundaries of the sectors in multiple directions similar to the eye movement of the younger children (below), when the answers did not come easily. Six of the children over 10 years of age showed the adult-like pattern, EMaCA with the focus-direction within a narrow range even when performing difficult tasks.

Figures 3 and 4 details the results of the analysis for the participating children. Figure 3 shows the RVS (range of visual space, percentage outside the sectors) for each age group. There were statistically significant differences in the RVS of the three age groups (5-9 years, 10-13 years, and adults, $p < 0.0001$). The Mann-Whitney U test showed that there were differences in the RVS between the younger and older children (younger children, 85.6 ± 15.9% (mean ± SD), n = 19; older children, 30.6 ± 25.4%, n = 11, $p < 0.0001$) and between the older children and adults (adults, 1.5 ± 1.4%, n=19, $p < 0.0001$). Figure 4 shows the VDEO (number of sectors, in which eye marks passed beyond the boundaries during the performance of each task) in each age group, except for the five-year-old children where the directions could not be assessed accurately. There were also statistically significant differences in the number of sectors between the three age groups ($p < 0.0001$) and between the younger and older children (younger children, 5.6 ± 1.0, n = 12; older children, 3.4 ± 1.9, n = 11, $p < 0.005$) and between the older children and adults (adults, 1.0 ± 0.7, $p < 0.001$).

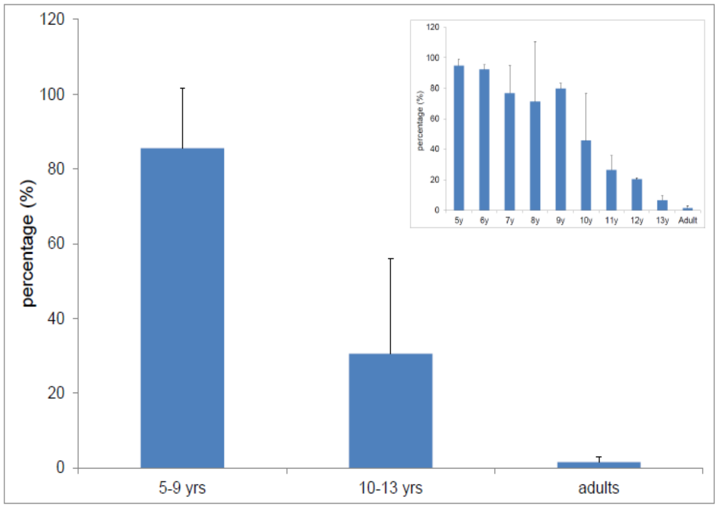

Figure 3. Range of visual space (RVS) in the three age groups. The RVS was calculated as the percentage of the total time for eye positions falling outside the sectors vs. the duration of performing the tasks. Thin vertical bars represent the standard deviation. Insert figure: RVS in all age groups.

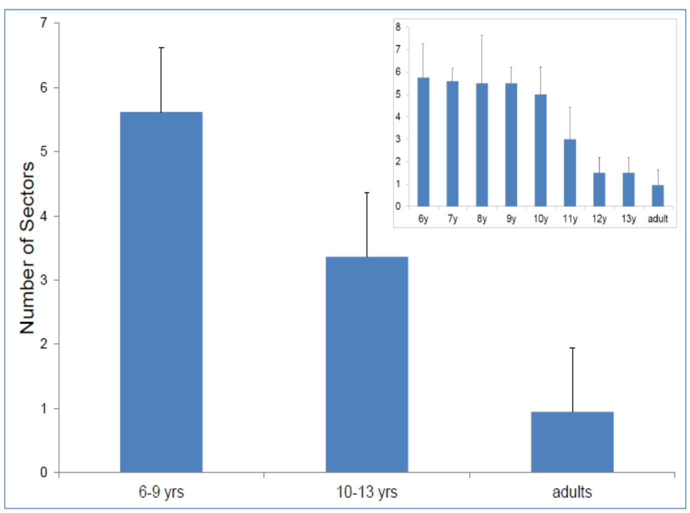

Figure 4. Variation of directions of eye positions outside the boundaries of the sectors (VDEO) in the three age groups. The vertical axis denotes the average number of sectors, in which eye markers passed beyond the boundaries, for all subjects in each of the age groups. Thin vertical bars represent the standard deviation. Insert figure: VDEO of all age groups.

Task Performance

The mean percentage of correct answers for the total number of questions in the adults, older children, and younger children were 50.0%, 48.14%, and 43.32%, respectively. There were no significant differences in these percentages among the three age groups ($F = 3.39$, $p = 0.89$) similar to the results of the pilot study. There were no differences in the accuracy between type A and type B subjects. Subject 13 (Tables 1 & 2), where the directions of the first EMaCA were more numerous (five sectors) than other subjects, showed the poorest performance (12.5%).

Table 2. Patterns of EMaCAs in the second phase

Subject	Present study	Previous study
1	A	A
2	A	A
3	A	A
4	A	A
5	A	#
6	A	--
7	A	--
8	A	--
9	A	--
10	B	--
11	B	--
12	B	--
13	B	B
14	B	B
15	B	B
16	B	B

A, type A; B, type B; --, not measured; #, fixation on the center.

DISCUSSION

Hypothesized Mechanisms of the EMaCA

The present results have shown that EMaCA in adults typically consist of two phases: an initial relatively large saccadic eye movement followed by smaller saccadic and/or smooth pursuit-like eye movements. It is also shown that the pattern of EMaCA in children is different from that in adults. In the adult subjects, the EMaCA were oriented to individual-specific directions within a narrow range, which showed good reproducibility within individuals. By contrast, in younger children, the orientation of the EMaCA was irregular going in various directions within a wide range. The first large saccadic eye movement in adults would correspond to the GA hypothesis mentioned in the previous section. However, overall, the results indicate that EMaCA are none of either just a sign of disengagement from the environment or of a nonfunctional byproduct of neural activation related to a memory search.

From the present findings, we hypothesize that the first EMaCA represents the orienting of attention to the cognitive space of the individual, and that the following EMaCA signals the shifting of attention from one target item to others within this space. A cognitive space has been variously defined by a number of investigators [42-45]. What we here term a cognitive space is in many respects similar to the mental representations described for example by Nobre et al. [46], but the term "cognitive space" could also be seen to suggest a more substantial entity. Here, we propose to define "cognitive space" as an imaginary space or location where mental operations such as imagining, recalling, and thinking are assumed to take place.

Adults may be expected to have an individually unique cognitive space established through memory retrieval in everyday life. As individuals repeatedly perform such internal operations in their own ways, they establish individually distinct habits of mind that suit the mental activity of the individual. The subjects here showed individually specific directions of the first EMaCA, and further EMaCA appeared to be consistent over extended time periods in the adults. This consistency of EMaCA across time supports the hypothesized mechanism of EMaCA.

Different from adults, children may be assumed as less likely to be skillful in the performance of searching/exploring activities in a still developing mental space. Other developmental neuroimaging studies have shown that children recruit larger, more diffuse cerebral regions during the performance of cognitive tasks than young adults [47-49]. The pattern of activity within brain regions correlated with task performance becoming more focused with development and age-related increases in activity are primarily in newly recruited regions, whereas brain regions not correlated with task performance decrease in activity with age. Thus, one plausible explanation for the observation in younger children that the orientation of the EMaCA is irregular and extends in various directions within a wide range is because of the more limited experience in manipulating the cognitive space using eye movements, the younger children were not as skilled as adults in orienting attention while performing mental tasks.

In another series of studies, we carried out by a 3D motion analysis system (MAC3D System, MotionAnalysis, USA) we examined the head motion in adults and children while they were performing mental tasks. The results showed that children tended to move their heads in close correlation with the EMaCA, while adults were more likely to maintain their heads stationary while moving the eyes (unpublished data). Murray et al., who examined the head movement frequency of 4 to 15-year-old children in response to visual step stimuli, have reported that the frequency and variability of the head movements decreased with age, and speculated that this monotonic change could be due to pre-programmed factors related to neurological development [50]. From these studies, it would seem acceptable to conclude that children will show more frequent head movements while processing information, and that this would account for the higher RVS as we have reported above (Figure 3).

Future Work

It is not feasible to provide direct evidences for the hypothesis proposed here because cognitive space is an imaginary space. Therefore, instead of directly testing the hypothesis, we will collect further supporting evidence in future work. For this, the following two approaches will initially be explored. One is to analyze eye-tracking data more objectively and quantitatively to distinguish the first phase from the second phase, which was based on a visual inspection of the data in the present study. The speed and trajectories of eye movements and the trajectory length should be examined to distinguish the two phases. Since the current software that was built into and installed in the Voxer does not make it possible to perform these analyses at present, and further development and updating of the software will be required.

The second is to examine the connection between the development of EMaCA and the development of child cognitive ability. The sample size in this study was small and no clear conclusions could be drawn about the precise timing of the transition from the child to the adult patterns in EMaCA. However, the results here (see especially Figures 3 and 4) suggest the possibility that this may occur between 10 and 13 years of age. This would correspond to the age of the earliest development of conceptual thought as it is commonly accepted [30, 51]. However, the tasks employed in the current study varied with the ages of the subjects and this may have biased the findings. Appropriate cognitive tasks will need to be elaborated in the future work.

Summary

The present results suggest that EMaCA occurs in a two-phase operation rather than as a single indivisible gaze-aversion function. While this does not reject the existence of the gaze-aversion function, we propose the hypothesis that EMaCA reflect a two-phase operation: (1) the act of orienting the attention to an imaginary space where information processing occurs and (2) the act of shifting attention from one target item to others, once the attention is established in this space (searching for the answer to a posed question). To substantiate this hypothesis, we need to investigate both the cognitive development of children and the spatiotemporal dynamics of eye movement.

CONCLUSION

During the more than 50 years since the report of LEM by Day [1], a number of theories about EMaCA have been proposed. Among these, disengagement from distracting stimuli, long-term memory search, and orienting and shifting attention are all among the possible and likely theories. However, these theories remain incomplete and are little better than suppositions. There is however no doubt that EMaCA reflects neural activities associated with cognitive processes. Younger children show different patterns of EMaCA than adults, something which is thought to be attributable to brain development. Persons with neuropsychiatric disorders, such as dementia and schizophrenia, may also show different patterns of EMaCA. Thus, it is expected that elucidating the neuropsychological mechanisms of EMaCA, which is a very challenging object, will contribute to a further understanding of the neural bases of cognitive development and the pathophysiology of neuropsychiatric disorders.

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