Early Attentional Control is Associated with Later Executive Function Skills : A Longitudinal Examination of the Relationship Between Eye-Tracking Measurements and Behavioural Responses

Early Attentional Control is Associated with Later Executive Function Skills: A Longitudinal Examination of the Relationship Between Eye-Tracking Measurements and Behavioural Responses

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Abstract：The present study used an eye-tracking technique to measure attentional control. It examined whether early executive attention had a longitudinal relationship with a child's performance on executive function tasks. 60 four-year-old children participated in this longitudinal study of executive functions (EFs). At time 1, attentional controls were measured with a modified flanker task in which eye-tracking was used in identifying correct anticipatory eye-movements. For the developmental outcomes, EFs (working memory, inhibition, shifting) were measured by eliciting verbal or touch responses at time 1, time 2 and time 3, with an interval between times of 12 months, including a flanker task with touch responses at time 3. The eye-tracking flanker task was associated with working memory and with the conventional flanker task 12 and 24 months later. This result demonstrated the validity of a new measuring technique using the eye-tracking method for studying attentional control for young children.

Keywords：Flanker task, eye tracking, attentional control, executive functions

Introduction

Attention development is one of the important human characteristics, that enables us to shape our interactions with both the physical and social world. Early development of attentional control is likely to form a building block for our executive processing of information, which is known as Executive Functions (EFs, thereafter). In the meta-analysis, Kavšek (2004) reported that infant visual habituation and dishabituation was a good predictor for later IQ. This suggests that early attention development is crucial for executing a wide range of tasks that reflect the construct of IQ.

Infants' visual looking time measurements have been playing a major role in studying children without relying on the use of language. Despite many successful infant studies to date, care is needed in the interpretation of looking time measures to ensure correspondence with what is actually observed in other experiments (Paulus, 2022). Although visual attention is available at an early phase in human development and it provides some indications of infants' interest in an object or a scene, it is still primitive in nature, and its development in relation to other executive skills has not yet been examined in full. It is likely that the development of attention and its control serves as a precursor to a more sophisticated level of information processing in terms of efficiency and accuracy.

Although infants as young as 6 months are able to show signs of EFs (Holmboe, Bonneville - Roussy, Csibra, & Johnson, 2018), relatively little investigation has been carried-out into these early emergent capacities and the subsequent development of executive functions during early childhood. Holmboe et al. (2018) argue that whether the nature of infant EF marker tasks maps onto EFs later in childhood and in adulthood needs to be investigated. To fill this gap, the present study explored a way of measuring EFs in different formats which still tap the same capacities. Use of human gazing is one of the widely used means in studying human capacities at any phase of development. The present study aims to address whether eye-tracking measures in a flanker task framework relate to the measurements derived from a conventional flanker task, which normally requires overt actions such as a touch or a key press. If the eye-tracking measure can also measure similar competencies, then it is possible to extend this method of measuring to much younger children.

In cognitive psychology, the flanker task originally refers to the Eriksen Flanker task (Eriksen & Eriksen, 1974), where the target stimuli are flanked by non-target stimuli which were aligned either horizontally congruent or incongruent with the direction of the target. The respondents were then asked to select the direction of the target stimuli. This task requires the respondents to use selective attention and to discard unrelated information. Thus, this task has been used as one of the EF tasks that tap attentional selection and inhibitory control abilities. More recent studies used a modified version of the original flanker task, to also measure children's EFs (Rueda et al., 2004). Further extensions were made available for the administration using computers as a part of the executive function toolbox (Zelazo et al., 2013). Although these computer administrations can accommodate younger children, they still require young children to use overt actions such as touching a designated area or pressing an assigned key. This physical maneuver could lead to possible measurement errors. On the other hand, eye gazing has been available from infancy to assess a child's response to a certain condition, such as an anticipatory look before the event actually happens.

To utilize young children's eye-gazing, an eye-tracking version of the flanker task was devised. Several modifications were made to induce a child's spontaneous eye-gazing behaviours. The target (an image of a shark) in the centre of the screen was about to move forward to get food (an image of a shoal of fish). After familiarization with this animation, the test phase included the flanker stimuli of sharks that were congruent or incongruent with the target. Children's eye-gaze in the context of the flanker task was measure desisned to see if the children were able to make a correct anticipatory look at the area to which the target was expected to move.

The aim of this study is to validate an eye-tracking version of the flanker task that is performed by means of eye-gaze rather than by overt responses so that we can measure attentional control as part of the EFs for younger children whose physical maneuvers may be more limited. An unique aspect of the present study is that the attentional control was measured using eye-gazing. If the eye-tracking flanker task measures corresponded to a conventional flanker task, performance then we could observe a positive correlation between the measurements. This attentional control measurement would also be expected to correlate with other executive function measurements because the previous study with 4 year-old children (Plebanek & Sloutsky, 2018) established the relationship between the flanker task and working memory.

A concurrent relationship has been established between eye-tracking measurements using the flanker task and working memory (Tsuji, 2021). However, whether or not this measurement has a longitudinal relationship with EFs is not clear. To extend this validation, the present study focuses on two questions: the first is to address if this flanker task using eye-tracking measurements has a longitudinal relationship with working memory; the second is to address if this eye-tracking measurement has a longitudinal relationship with the conventional flanker task that is measured by a conventional responses, in this case with touch responses.

Method

Participants

60 children who enrolled in the age 3 classes of a nursery school participated in this study (M_{age} = 48.1ms SD= 3.2ms 32 girls). They had three testing sessions with a one year interval between sessions over a two year period. Data for two children were unavailable after the first session due to family relocations. Written informed consents were obtained from their parents prior to the testing sessions.

Tasks and procedures

Flanker task using eye-tracking

To measure attentional control, a flanker stimuli video was created based on the child version of the flanker task (Rueda et al., 2004). The video included a fixation point for 1000ms followed by the presentation of an array of 5 sharks (one pink shark as the centre stimuli and four grey sharks as flanker stimuli) with a simultaneous presentation of a shoal of small fish just outside the array of sharks for 3000ms. After this testing period, the centre shark moves straight to catch the fish (figure 1). Viewers' eye-movements were recorded by an eye-tracker (Tobii ProX-120) to identify if a correct initial anticipation look occurred during the 3000ms period.

Prior to these testing sessions, each child was presented with two practice trials in which the child watched the pink shark (shown in a centre) without flankers, move straight to the right/left to catch the shoal of small fish so that the child could learn to anticipate the movement of the pink shark. The logic of test sessions is that if a child anticipates the movement of centre stimuli correctly, their eye-gaze will shift towards the direction of the correct fish shoal. There were four test sessions in which the direction of centre shark was either congruent or incongruent with the flanker stimuli (i.e. grey sharks). This measurement was only taken for time 1. All the eye-tracking data were analysed using Tobii Studio Pro (Tobii pro ®).

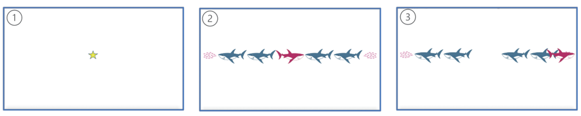

Figure 1. An example of an incongruent test session

Executive function tasks

Three components of executive functions (EFs) were measured using the following three tasks: digit span task for working memory; stroop task for inhibitory control; and Dimensional Category Card Sort (DCCS) task for shifting of attention. Additionally, a traditional flanker task where the child pointed at the target on a screen was administered at time 2 and 3. Please note that for time 2, due to time constraints for the administration of this task, some children's data were not available for the analyses.

Digit span task

Working memory (WM) was measured using the digit span task following the instructions in the K-ABC (Kaufman & Kaufman, 2004). The total number of trials with correct responses was used as the scores.

Stroop task

Inhibitory control was measured by a modification of the task used by Berger, Jones, Rothbart, and Posner (2000). The task required participants to touch either of the two images that were laid out horizontally to match (= congruent block) or mismatch (=incongruent block) an animal with the sound an animal. There were two blocks of tasks, where the incongruent block was followed by the congruent block. A total number of the correct responses to the incongruent block was used as the scores.

DCCS task

Shifting of attention was measured using the DCCS task (Zelazo, 2006). Participants were shown two images that include two different dimensional categories at two levels (colour: blue and red; and shape: hat and bag). They were asked to choose the one of the images that matched the first rule (match the colour). This block of 6 trials were followed by a block of 6 trials where the rule was switched (match the shape). A total number of correct responses to the sessions after the rule was switched was used as the scores.

Flanker task with conventional responses

This task was devised following Rueda et al. (2004) in such a way that it was analogous to the eye tracking flanker task, the difference was that the participants were asked to touch the shoal of fish image that the centre shark was about to catch. There were equal numbers of congruent and incongruent trails in the direction of flanker combinations, totaling 16 trials without feedback. Prior to this test block, there were two practice trials where only the centre shark moves to catch one of the fish shoals. The number of correct responses were used as scores. This task was administered at time 2 and time 3. For time 2, due to time constraints the number of children that were available for this task was limited.

Results

Flanker task using eye-tracking.

The correct responses were coded and scored using the following rules for measuring eye-tracking responses. The first fixation (using the Tobii I-VT fixation filter) to the AOI (Area of Interest) during the test phase of 3000 ms was identified and if this was located in the correct AOI then one point was given; if the initial fixation fell into the area where the direction of the gaze was correct but did not fixate exactly on the AOI then a half point was given (Figure 2). The distribution of the scores is given in Figure 3. The scores for incongruent trials were significantly less than for the congruent trials: t (59) = 4.54, p < .001, indicating that incongruent trials were more difficult than the congruent trials, as they required inhibitory control to not attend to the flanking sharks.

Figure 2. The schematic image of the coding area of the AOI.

Example of the incongruent trial. The left facing shark in a middle is expected to move to left. An anticipatory look that first fixates to the left fish shoal is a correct response (1 point); if the first fixation was made in the correct direction but to fell short of the correct AOI then 0.5 point was given.

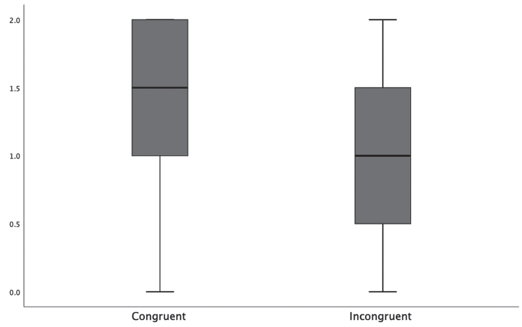

Figure 3. The distribution of scores for the congruent and incongruent trials.

Prior to the present study, we found that the flanker eye-tracking measures were correlated significantly with working memory (r = .029, p < .05), but not with inhibitory control or shifting of attention (Tsuji, 2021). The present study aimed to examine longitudinal relationships between the early attentional control using flanker eye-tracking

Table 1 . Descriptive statistics of EF performances at time 2 and 3 and their correlations with the Flanker task using the eye-tracking measurement at time 1.

Waves	FF variables	n	Min	Max	M	(SD)	Pearson correlation eye-tracking flanker (time 1) and EFs		partical correlation (age1)	
time 2										
	t2 WM	57	3	12	8.72	2.25	.32	*	.33	*
	t2 Stroop	57	0	8	6.86	2.07	.30	*	.30	*
	t2 DCCS	57	0	6	4.44	2.12	.22		.21	
	t2 Flanker	45	6	16	12.44	3.51	-.12		-.14	
time 3										
	t3 WM	55	4	14	9.86	2.14	.41	**	.40	**
	t3 Stroop	55	0	8	7.47	1.66	.20		.20	
	t3 DCCS	55	0	6	5.05	1.73	-.01		-.03	
	t3 Flanker	55	8	16	15.07	2.09	.32	*	.32	*

Note: [1] Age was used as a control variable. * < .05; ** < .01

measures and the later performances on the EF tasks, including the flanker task using conventional responses. Table 1 summarises the descriptive statistics and Pearson product-moment correlations between these variables.

Developmental changes in the four EFs were examined. Paired t-tests suggest that the performance on all EF tasks increased from time 2 to time 3: $t(55) = 5.92$, $p < .001$ for WM; $t(55) = 2.71$, $p < .01$ for the Stroop task; $t(55) = 2.17$, $p < .05$ for DCCS; and $t(44) = 4.74$, $p < .001$ for the flanker task with conventional responses. The correlational analyses were conducted to examine how attentional control using the flanker eye-tracking at time 1 associates with later development of EFs at time 2 and time 3. Correct attentional control at time 1 correlated significantly with WM at time 2 and 3. Also, correct attentional control correlated significantly with the Stroop task at time 2 but not at time 3. The same measure correlated significantly with the conventional flanker task at time 3, but not at time 2. No significant correlations were found between attentional control at time 1 and the DCCS task at time 2 and 3. These significant correlations were held when the partial correlations were conducted with the age variable being controlled for.

Discussion

The present study investigated whether early attentional control had longitudinal relationships with the development of EFs measured by conventional response tasks. To this end, we developed a new method of measuring young children's attentional control that reflects executive processing. This new measurement applied a child version of the flanker task (Rueda et al., 2004) and used eye-tracking measurements. If a child anticipated the movement of a centre stimuli correctly then their eye-gaze will shift towards the correct target during a testing period of 3000 ms. The coding was made in such a way that any attentional shifts towards a correct direction as indicated by the AOIs was incorporated to measure the degree of attentional control. The distribution of the coded scores indicated levels of difficulty between the congruent and the incongruent trials in that scores of incongruent trials were significantly lower than those of congruent trials.

To clarify that early quality of attentional control is related to EFs beyond a concurrent relationship (Tsuji, 2021), the prospective relationships with the EF tasks using conventional responses provides further support for the measurement's validity. The most important findings of this study were two-fold.

The first was that early attentional control as measured by the eye-tracking version of the flanker task at time 1 had a significant association with the flanker task using conventional responses at time 3 but not at time 2. The early attentional control measures should also be significantly related at time 2. Failing to find a significant relationship may have resulted from not being able to test all children at time 2 who tested at time 1, due to time constraints at time 2. However, a longitudinal association between the eye-tracking version of flanker task at time 1 and the flanker task using conventional responses at time 3 suggests that these measurements share some common ground in that attentional control is required by the flanker task.

It is possible that even though the underlying theoretical ground is the same, what is measured by each task may differ due to varying operational requirements such as gaze or hand movement. During the first 5 years of their lives, young children's motor development is changing dramatically and possible variability exists in different aspects of movements (Dourou, Komessariou, Riga, & Lavidas, 2017). When kinetic responses were required for younger children, the complexity of responses may lead to measurement errors due to the inability of making adequate movements. For this reason, a simpler measurement for younger children utilizing eye-gazing can be useful in the measurement of EFs. The results of the present study provided some support for the validity of these measures over two years during the preschool periods.

The second important finding is that the early attentional control measure was found to correlate with the concurrent and longitudinal measurement of WM. This provides positive support for the existing studies that report the relationship between working memory and the development of attentional control (Osaka et al., 2003; Plebanek & Sloutsky, 2018; Unsworth, Miller, & Robison, 2020; Vogel, McCollough, & Machizawa, 2005). However, this does not confirm the direction of relationships between attentional control and WM in that attentional control is a precursor to the development of WM. Although there have been some tentative explanations for the relationships between attention and WM (Oberauer, 2019), there are still unanswered questions, including direction of the relationship between attentional control and WM.

A limitation of the present study is in the scoring scheme for the eye-tracking measurements. The present study used the first visit to the AOIs to represent the participants' anticipatory look. However, this first look measure may have missed some of the attentional control in progress, which might have shown a correct look during the 3000ms. The previous study examined eye-gaze at the correct responses for the DCCS task. The children of 6 and 7 years of age who made correct conventional responses took longer to look at the correct target in the post-switch trials than in the pre-switch trials (Jincho & Mazuka, 2014) . In this respect, children do not necessarily make a spontaneous look toward correct AOI, but may take some time to control their attention to make a correct look. If this is the case, we should find some instances where there was a correct look during the 3000 ms but not represented in the current coding. More detailed analyses on how attentional control during the 3000 ms may have progressed could address the gap between the measures using eye-gazing and conventional responses.

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初期の注意コントロールは、後の実行機能スキルと関連する
―アイトラッキング測定と行動反応との関係の縦断的検討―

学芸学部　心理学科　辻　弘美

要　約

　本研究では、アイトラッキングの手法を用いて注意の制御を測定した。この研究では、初期の実行的注意が実行機能課題における子どもの成績と縦断的な関係を持つかどうかを検討した。60人の4歳児がこの実行機能（EF）の縦断的研究に参加した。 Time 1において、注意のコントロールは、アイトラッキングを援用したフランカー課題をデザインし、予期的な眼球運動を識別することで測定された。発達的アウトカムとして、EF（ワーキングメモリ、抑制、シフト）は、time 1、time 2、time 3で言語またはタッチ反応により測定された。Time 3ではタッチ反応を伴うフランカー課題を含めた。これらの測定は、それぞれ12ヶ月の間隔があけられた。視線追跡型フランカー課題は、ワーキングメモリと、12ヶ月後および24ヶ月後の従来のフランカー課題との関連性がみられた。この結果は、幼児を対象とした注意制御の研究に、アイトラッキング法を用いた新しい測定手法の有効性を示すものであった。

キーワード：フランカー課題、アイトラッキング、注意コントロール、実行機能