

Development of Attentional and Oculomotor Control

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The present study was conducted to examine the development of attentional and oculomotor control. More specifically, the authors were interested in the development of the ability to inhibit an incorrect but prepotent response to a salient distractor. Participants, who ranged in age from 8 to 25 years, performed 3 different eye movement tasks: a prosaccade, an antisaccade, and an oculomotor capture task. The time required to initiate a saccade decreased with age across all 3 tasks. Consistent with previous reports, accuracy was relatively age invariant in the prosaccade task. Performance improved with age, asymptoting at 16 years in the antisaccade task. It is interesting to note that despite the superficial similarity of the antisaccade and oculomotor capture tasks, performance was relatively age invariant in the latter. These results are discussed in terms of developmental differences in the interaction of goal-directed and stimulus-driven processes in the control of attention and action.

Keywords: eye movements, visual attention, development

The development of attentional control and, more specifically, the ability to ignore or inhibit a prepotent response to a salient stimulus has been a topic of increasing interest in recent years (Cepeda, Kramer, & Gonzalez de Sather, 2001; Jones, Rothbart, & Posner, 2003; Kirkham & Diamond, 2003; Schul, Townsend, & Stiles, 2003). One context in which attentional control has been examined is eye movement tasks. Two specific eye movement tasks have been used: the prosaccade and the antisaccade tasks.

The *prosaccade task* requires an observer to fixate a stimulus in the center of a display and then move his or her eyes as rapidly as possible to a peripherally presented target. The task involves both a stimulus-driven influence from the onset of the peripheral stimulus and goal-directed control based on instructions to shift the eyes to the target as soon as it appears. Indeed, the prosaccade task provides a laboratory analogue of much of human exploratory eye movement behavior in response to changes in the visual environment. The *antisaccade task*, first introduced by Hallett (1978), requires an observer to fixate a stimulus in the center of a display and, on presentation of a peripheral stimulus, shift his or her eyes in the opposite direction. Thus, this task pits a stimulus-driven influence (i.e., the peripheral onset) against the individual's intention to move his or her eyes in the opposite direction. The antisaccade task might be thought of as a laboratory analogue of a situation in which one is searching for one's car in a busy parking lot while other automobiles and pedestrians are moving all around; reflexive eye movements to bustling but task-irrelevant stimuli must be suppressed in favor of goal-directed movements in search

of one's vehicle. A detailed discussion of the patterns of saccades observed in these paradigms is provided below.

The prosaccade and antisaccade tasks are useful both because (a) they contrast a situation in which stimulus-driven and goal-directed factors behave in a cooperative fashion (i.e., the prosaccade task) with a situation in which goal-directed factors (i.e., the intention to move the eyes away from the stimulus) and stimulus-driven factors (i.e., the sudden onset of the peripheral stimulus) compete (i.e., the antisaccade task) and (b) the neurophysiological circuits that support these two tasks have been relatively well studied. An extensive discussion of the research that has been conducted to explicate the neuronal circuits that underlie these types of eye movements is beyond the scope of the present article (for additional details, see reviews by Becker, 1991; Gaymard, Ploner, Rivaud, Vermersch, & Pierrot-Deselligny, 1998; Pierrot-Deselligny, Milea, & Müri, 2004; Pierrot-Deselligny, Rivaud, Gaymard, Müri, & Vermersch, 1995). However, below we briefly describe some of the findings that address the manner in which saccades are controlled in the brain.

A variety of different research techniques have been used to study the neural control of saccades in humans. In an effort to localize specific saccade control functions, early research on humans focused on the examination of patients with circumscribed lesions. For example, the research of Guitton, Buchtel, and Douglas (1985) examined the performance of prosaccade and antisaccade tasks by temporal- and frontal-lobe lesion patients as well as by unimpaired control participants. The research revealed selective deficits in performance on the antisaccade task by the frontal-lobe lesion patients. These patients displayed both longer saccadic latencies and more reflexive eye movements (toward rather than away from the target) than did the temporal-lobe patients and the nonpatient control group. Performance of all three groups was equivalent on the prosaccade task. These data, along with those of more recent patient studies, have been interpreted as evidence for the role of the frontal regions—and, more specifically, the dorso-lateral prefrontal cortex (DLPFC) and frontal eye fields

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(FEFs)—in the inhibition of reflexive saccades while programming and executing voluntary saccades. Research using positron emission tomography and functional MRI has found that similar brain regions were activated in pro- and antisaccade tasks but that activation levels were higher in the antisaccade task for areas including the FEFs, supplementary eye fields, parietal eye fields, putamen, and thalamus (Desouza, Menon, & Everling, 2003; O'Driscoll et al., 1995; see also Kimmig et al., 2001). Sweeney et al. (1996) reported increased activation in the DLPFC—a brain region associated with working memory and interference control—in an antisaccade as compared with a prosaccade task.

The studies described above, along with a much more extensive literature that has examined eye movements in humans as well as other animals, have begun to map out the neuronal circuits that are responsible for oculomotor control. For example, it is now known that a large number of frontal, parietal, and midbrain regions contribute to oculomotor behavior. Subsets of these brain regions, which are highly interconnected, contribute to different aspects of the saccade behavior exemplified by prosaccade and antisaccade tasks. Although many of the same cortical regions contribute to performance in both of these tasks, it is known that frontal and some midbrain regions such as the substantia nigra play a more substantial role in antisaccade performance than they do in prosaccade performance, particularly with regard to the inhibition of saccades toward the stimulus.

It is interesting to note that researchers have also learned that many of the frontal brain regions that support performance in the antisaccade task are not finished developing until late adolescence (Casey et al., 1997; Huttenlocher, 2002; Paus et al., 1999), and hence, the study of performance in the antisaccade task and its comparison with performance in the prosaccade task has served as a means to examine the development of attentional control in the face of competing stimuli. A number of such studies have been reported in the literature. For example, Fischer, Biscaldi, and Gezeck (1997) studied differences in saccade parameters across the life span (from 8 to 70 years of age) in 281 participants. Although saccadic latency decreased in both pro- and antisaccade tasks from childhood to young adulthood, the more dramatic change over this time period was in the antisaccade task. Prosaccade errors (moving toward rather than away from the stimulus) in the antisaccade task decreased substantially from 8 to 20 years of age (see also Klein & Foerster, 2001; Munoz, Broughton, Goldring, & Armstrong, 1998). These data have been interpreted as a reflection of the maturation of the prefrontal cortex and corresponding improvements in the ability to inhibit prepotent but incorrect responses (Huttenlocher, 2002).

Recently, Theeuwes and colleagues (Godijn & Theeuwes, 2002; Irwin, Colcombe, Kramer, & Hahn, 2000; Kramer, Hahn, Irwin, & Theeuwes, 1999, 2000; Theeuwes, Kramer, Hahn, & Irwin, 1998; Theeuwes, Kramer, Hahn, Irwin, & Zelinsky, 1999) developed another eye movement task that could prove useful in the study of attentional and oculomotor control. In this paradigm, participants were presented with a number of gray circles with small figure 8s inside them. After 1,000 ms, the color of all but one of the circles was changed to red, and the segments of the figure 8s were removed to reveal letters. Participants were instructed to move their eyes from the center of the display to the color singleton (i.e., the uniquely colored item) as soon as they detected the color

change and to identify the letter inside the gray circle. On a subset of trials, a new red circle (i.e., an abrupt onset) appeared simultaneously with the color change, cuing the location of the color singleton target. The abrupt onset never served as the target, nor did it predict the location of the target (as in the antisaccade task).

Under the conditions described above, participants misdirected their eyes to the task-irrelevant onset on a substantial percentage of trials (approximately 20%–40%). It is interesting to note that the great majority of participants were unaware of the occurrence of the task-irrelevant onset, and those few who did notice its appearance (often on a small percentage of the trials on which it actually occurred) said that they never looked at it.

Although, superficially, the antisaccade task and the oculomotor capture task appear quite similar (i.e., capture of the eyes occurs in response to a salient new object), there are some important differences that render their joint administration theoretically interesting in the study of the development of attentional and oculomotor control. First, individuals must actively attend to the new object in the antisaccade task. Otherwise, they will not know where to move their eyes (i.e., in the opposite direction of the stimulus). Second, following the direction of attention to the new object, individuals must inhibit an eye movement to this object and program and execute an eye movement in the opposite direction. Thus, to effectively perform the antisaccade task, individuals must establish and maintain an attentional set to direct attention to the appearance of the new object and use this object to direct their attention and eyes in the opposite direction. On the basis of this analysis, we suggest that capture of the eyes in the antisaccade task is the result of both the failure of top-down or goal-directed influences (i.e., the establishment and maintenance of an attentional set with regard to the new stimulus, which must be attended and then inhibited to perform the task) and the success of bottom-up or stimulus-driven factors (i.e., the appearance of a new object in the visual field, which has previously been shown to capture attention; Yantis, 1996).

In the oculomotor capture task, the new distractor object does not predict the location of the target stimulus (which is unambiguously distinguishable from all of the other stimuli by a unique color). Indeed, the great majority of individuals who have participated in previous experiments with this paradigm have not noticed that a new stimulus—coincident with the color change that marks the location of the target—even appears. Thus, the oculomotor capture task does not, like the antisaccade task, require the establishment and maintenance of an attentional set to actively attend to and subsequently inhibit the new object. Instead, participants must establish a set to attend and rapidly move their eyes to the color singleton target. Capture occurs when the stimulus-driven influence of the onset distractor exceeds the activation level of the target set.

This distinction between the mechanisms that are responsible for the successful performance of these two tasks enables us to ask whether the developmental trajectory differs for attentional and oculomotor control that requires participants to first attend and then inhibit a new object (antisaccade task) and attentional and oculomotor control that requires the adoption of a set concerning only a uniquely colored target (oculomotor capture task). In both cases, stimulus-driven influences (i.e., the ability of new objects to capture attention; Yantis, 1996) compete against goal-directed

influences. However, in the antisaccade task, these goal-directed influences include both the need to attend and then the need to inhibit the new object, whereas in the oculomotor capture task, participants need only maintain a set to attend to the easily distinguishable target. In the present study, we examined the developmental trajectory of these multiple influences on attentional and oculomotor control by administering the prosaccade, antisaccade, and oculomotor capture tasks to 100 individuals, equally divided across five age groups from 8 to 25 years of age.

Method

Participants

One hundred individuals in five age groups—young adults (19–25 years), older adolescents (16–18 years), younger adolescents (13–15 years), older children (10–12 years), and younger children (8–9 years)—participated in this study. All participants had normal or corrected-to-normal vision and passed a standard Ishihara color-blindness test (Ishihara, 1998). Equal numbers of male and female participants comprised each of the age groups. No information regarding the race–ethnicity or socioeconomic status of participants was collected. Participants were recruited through advertisements in the local newspaper and with flyers distributed at local youth centers.

Procedure

The study was approved by the University of Illinois Institutional Review Board. Informed consent was obtained from both the children and their legal guardians. The first session included the collection of demographic data (i.e., age, gender, education), vision testing (i.e., near and far Snellen acuity, color-blindness test), and several psychometric tests to enable us to characterize the participants and to allow for comparison with other studies. These tests included the Kaufman Brief Intelligence Test (Kaufman & Kaufman, 1990); perceptual speed tasks (Box Completion, Digit Copying, Digit–Symbol Copying; Salthouse, 1992); the Wechsler Adult Intelligence Scale—Revised (WAIS–R) Digit Span (Wechsler, 1981); and the WAIS–R Digit Span Reversed. The results of these tests are presented in Table 1.

The next two sessions included the performance of the prosaccade and antisaccade tasks on 1 day and the oculomotor capture task on another day. The order of these tasks was counterbalanced across participants.

All participants were tested on a PC—used to control the timing and to record participant's reaction times—with a 21-in. (53.34-cm) color VGA monitor on which the stimuli were presented. Eye movements were re-

corded with an EyeLink I head-mounted eye tracker (SensoMotoric Instruments, Needham, MA) with 250-Hz temporal resolution and 0.2° spatial resolution. This system uses infrared video-based tracking technology to compute the center and size of the pupils in both eyes. An infrared head-tracking system tracked head motion. Even though head motion was measured, the head was stabilized by means of a chin rest located 80 cm from the monitor.

The EyeLink system uses three thresholds to detect saccades, velocity, acceleration, and motion. For our experiment, the thresholds were set at 30°/s (velocity), 8,000°/s² (acceleration), and 0.15° (motion). Saccade detection is done online; thus, output data from the eye tracking system indicated the presence of saccades and fixations. Saccades were considered only if they started within 2° of the central fixation point and ended more than 3° from it.

Saccade latency was taken as the time between the onset of the relevant stimulus and the beginning of a saccade as indicated by the EyeLink system. Maximum angular deviation was determined by calculating the angular deviation from a straight line to the target for each point in the saccade. The largest deviation was recorded as the maximum angular deviation for the saccade. Saccade direction was determined on the basis of location of the saccade end point.

Before the beginning of each experimental session, the headband of the eye tracker with the infrared light sources and cameras was positioned on the participant's head. A chin rest was used to stabilize the head, and participants were asked to avoid making any large head movements. The eye camera was then adjusted until a clear corneal reflection was present. After the threshold for detecting the pupil was set, the system was calibrated. Calibration consisted of having the participant fixate each of nine calibration points arranged in a 3 × 3 grid and presented in a random order. Once the calibration procedure was successfully completed, the experimental session started.

At the start of each trial, the eye position was recalibrated to center so that reliable eye movement measurements could be recorded. Participants pressed the spacebar on the computer keyboard while fixating a central calibration cross to start the trial.

Prosaccade and Antisaccade Tasks

Stimuli used in the pro- and antisaccade tasks consisted of a fixation cross (0.3° × 0.3°) presented in the center of the display and gray circles (3.7° in diameter) with small dots (0.3° in diameter) in their centers. The target circle was displayed either to the left or to the right of the display, approximately 8° horizontally from the center of the display.

At the start of each trial block, participants were instructed as to whether the prosaccade or the antisaccade task would be performed for that block

Table 1
Mean Performance for Each of the Age Groups for the Psychometric Tests Administered in Session 1 of the Experiment

Age group (years)	K-BIT			Perceptual speed ^a			Digit span ^b	
	V	M	C	Box	D copy	DS copy	F	R
8–9	112.2	120.2	118.2	37.7	47.7	26.9	7.3	5.4
10–12	112.1	113.5	115.2	42.1	45.8	29.4	7.9	6.5
13–15	109.5	111.9	112.0	48.4	56.3	36.4	8.4	6.7
16–18	111.3	109.3	111.7	52.9	62.8	38.4	9.1	7.5
19–25	111.3	114.3	114.2	48.5	60.7	41.3	9.4	8.4

Note. K-BIT = Kaufman Brief Intelligence Test (Kaufman & Kaufman, 1990); V = vocabulary; M = matrices; C = composite (IQ); Box = box completion; D copy = digit copying; DS copy = digit-symbol copying; F = forward; R = reversed.

^aSalthouse (1992). ^bWechsler (1981).

of trials. At the start of each trial within a block, the eye tracker was recalibrated to center, as described above. After a participant pressed the spacebar to start the trial, the fixation cross was displayed for 1,000 ms. Participants were instructed to maintain fixation during this period, and they received auditory feedback in the form of a 200-Hz tone if their eyes moved away prior to the target presentation. After this period, the fixation cross disappeared, and the target circle and dot appeared. In prosaccade blocks, the task was to look at the dot in the center of the target circle. In antisaccade blocks, the task was to look in the opposite direction of the target, to a point approximately the same distance from center. No stimulus appeared as a saccade landing point in antisaccade trials.

The experimental session consisted of 180 trials presented in 6 blocks of 30 trials. The session was divided into one block (30 trials) of prosaccade trials, four blocks (120 trials) of antisaccade trials, and a final block (30 trials) of prosaccade trials. Target location was evenly distributed between left and right sides and was randomly intermixed within blocks.

Two measures were analyzed for the prosaccade and antisaccade tasks: saccade accuracy and saccade latency. *Saccade accuracy* refers to whether the initial saccade moved in the correct direction (i.e., toward the cue for the prosaccade task and away from the cue for the antisaccade task). *Saccade latency* is defined as the difference in time between the presentation of the cue to make an eye movement and the beginning of the initial saccade.

Oculomotor Capture Task

A graphic illustration of the oculomotor capture task is presented in Figure 1. The stimuli used in the oculomotor capture task consisted of six gray circles (3.7° in diameter), all but one of which later changed to red, arranged on an imaginary circle with a radius of 12.6° of visual angle. The red and gray circles were matched for luminance. The circles were arranged as if in the 1, 3, 5, 7, 9, and 11 o'clock positions on a clock face, resulting in a separation of 60° of arc between each circle. Each of the circles contained a figure-8 premask ($0.4^\circ \times 0.2^\circ$), which changed to a letter when the color of the circles changed. The letters inside the circles were randomly selected without replacement from the set of *E, F, H, P, S, and U*. The letters were intentionally small so that participants were required to make a saccade to the target circle to discriminate the orientation of the *C* (see below). A $0.3^\circ \times 0.3^\circ$ fixation cross was presented in the center of the display.

The initial display consisted of a central fixation cross and six gray circles with figure 8s inside. This display remained on the screen for 1,000 ms and then changed. All but one of the circles changed color from gray to red. At the same time, line segments from the figure 8s were removed to form letters. In the onset condition, an additional (red) circle appeared in a position not previously occupied by a circle (in the 2, 4, 8, or 10 o'clock position). Participants were instructed to move their eyes toward the gray circle as soon as they detected the color change and to report the orientation of a letter *C* (normal or mirror reversed) that appeared in the gray circle. The display remained until the participant responded. Participants responded by pressing either the *slash* key or the *Z* key on the computer keyboard. The mapping of response key to the orientation of the *C* was counterbalanced across participants. Participants received feedback in the form of a 200-Hz tone if the response was incorrect, and they received feedback on speed and accuracy at the end of each block of trials.

Each participant took part in a single experimental session consisting of 180 trials divided into five blocks of 36 trials each. There were two trial types: *onset trials* (70%; 126 trials), in which an additional circle appeared with an abrupt onset when the color changed, and *additional stimulus control trials* (30%; 54 trials), in which the additional circle was present for the entire trial. Trials were randomly distributed across the entire session.

Four measures were analyzed for the oculomotor task: saccade accuracy, saccade latency, manual reaction time, and manual response accuracy. *Saccade accuracy* refers to whether the initial saccade moved in the correct direction (i.e., toward the color singleton target) or, instead, initially moved in the direction of the onset distractor. *Saccade latency* is defined as the difference in time between the presentation of the target (i.e., the color singleton) and the beginning of the initial saccade. *Manual reaction time* is defined as difference in time between the presentation of the target and the depression of one of the two response buttons. *Manual response accuracy* provides a measure of the proportion of trials on which participants depressed the button corresponding to the correct response (i.e., for the discrimination between normal *C* and reversed *C*).

Results

Psychometric Tests

The psychometric tests were performed to enable the characterization of the study participants. The mean scores obtained by

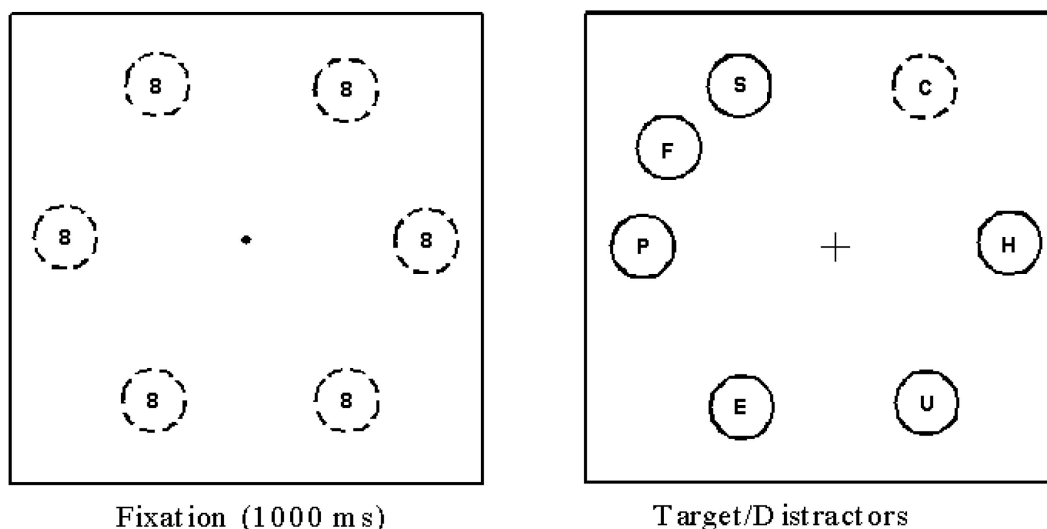


Figure 1. A graphic illustration of the oculomotor capture task.

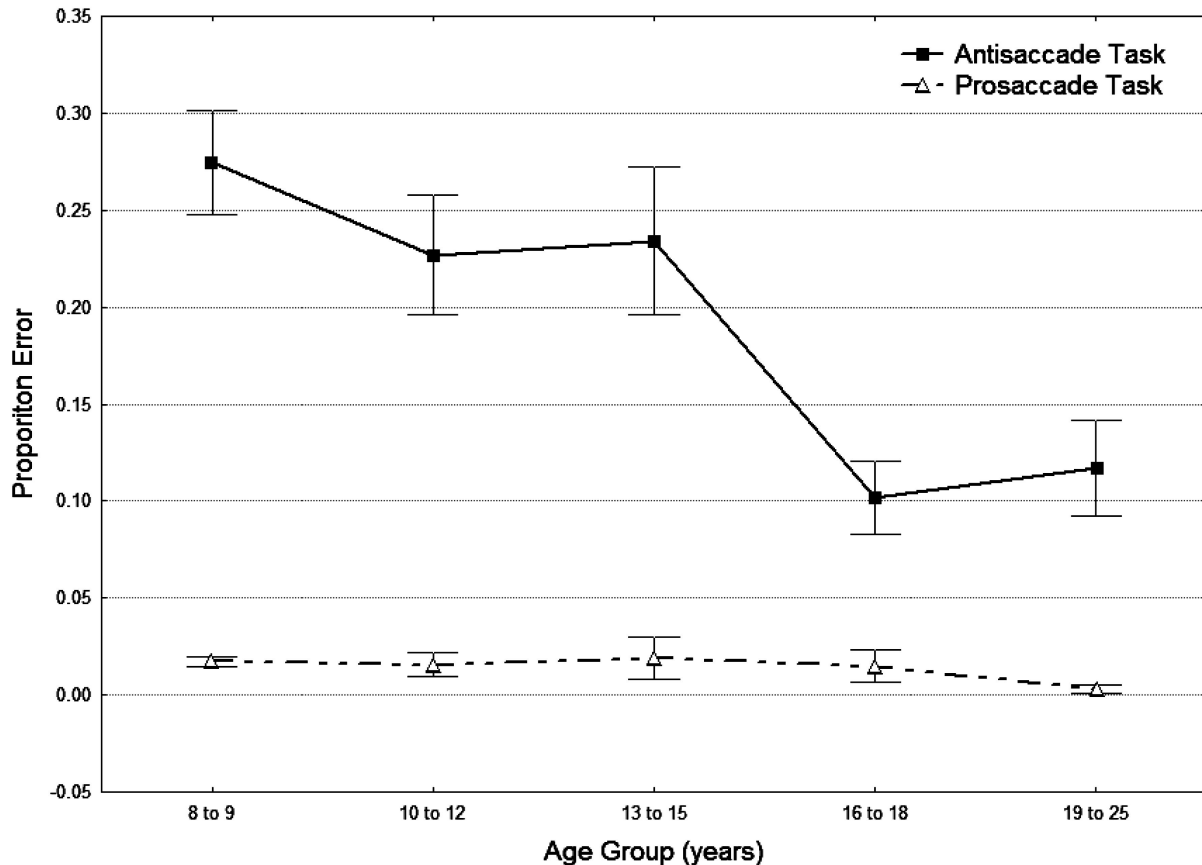


Figure 2. Saccade direction accuracy for each age group in the pro- and antisaccade tasks. Error bars represent standard deviations.

different age groups are presented in Table 1. The age group variable was analyzed with five levels (8–9, 10–12, 13–15, 16–18, and 19–25 years). No significant differences were found on the Kaufman Brief Intelligence test ($p > .16$). However, consistent with the extant literature (Kail, 1995, 2000), performance did improve with age on the three perceptual speed tests: box completion, $F(4, 94) = 4.0$, $ES = 0.41$, $p < .01$; digit copying, $F(4, 94) = 3.7$, $ES = 0.47$, $p < .01$; and digit-symbol copying, $F(4, 94) = 5.3$, $ES = 0.55$, $p < .01$. Performance also improved with age for reverse (or backward) digit memory span, $F(4, 94) = 5.3$, $ES = 0.48$, $p < .01$, and forward digit memory span, $F(4, 94) = 2.1$, $ES = 0.19$, $p < .09$. These data are consistent with the general literature on the development of perceptual speed and short-term memory, and they also suggest that the age groups were statistically equivalent in IQ.

Prosaccade and Antisaccade Tasks

We report two saccade variables to characterize participants' oculomotor behavior in the pro- and antisaccade tasks. These variables are the directional accuracy of the initial saccade and the latency of the initial saccade.

Saccade accuracy. These data were analyzed with a repeated measures analysis of variance (ANOVA) with age as a between-

participants factor and condition (pro- and antisaccade task) as a within-participant factor. An error was recorded if the initial saccade away from fixation did not land within 4° of the correct location.

There was a significant main effect of age (see Figure 2), $F(4, 95) = 6.26$, $ES = 0.31$, $p < .001$, with accuracy increasing with increased age of the participants. There was also a main effect of condition, $F(1, 95) = 181.88$, $ES = 0.66$, $p < .001$. Accuracy was higher in the prosaccade condition (97%–100% correct) than in the antisaccade condition (73%–90% correct).

A significant Age \times Condition interaction was observed, $F(4, 95) = 6.14$, $ES = 0.25$, $p < .001$, such that performance in the prosaccade trials was stable; all age groups performed equally well at 97%–100% accuracy. However, in the antisaccade condition, children 8–15 years old (73%–76% accuracy) performed significantly more poorly than those 16–25 years old (88%–90% accuracy), $F(1, 95) = 24.47$, $ES = 0.29$, $p < .001$.¹ Thus, these data replicate, for both the pro- and antisaccade tasks, saccade accuracy data obtained from childhood to young adulthood by other inves-

¹ We used Tukey's honestly significant difference test to examine contrasts between conditions within significant main effects and interactions. All reported effects are significant at $p < .01$.

tigators (Fischer et al., 1997; Klein & Forester, 2001; Munoz et al., 1998).

Saccade latency. These data were analyzed with a repeated measures ANOVA with age as a between-participants factor and condition (pro- and antisaccade task) as a within-participant factor. This analysis included only correct trials.

A main effect was obtained for age (see Figure 3), $F(4, 95) = 7.95$, $ES = 0.35$, $p < .001$. Overall, as age increased, saccade latency decreased. A main effect was also obtained for condition such that latencies were significantly longer in the antisaccade trials (272 ms) than they were in the prosaccade trials (195 ms), $F(1, 95) = 232.56$, $ES = 0.71$, $p < .001$.

An Age \times Condition interaction was also observed, $F(4, 95) = 3.73$, $ES = 0.27$, $p < .01$. There was a decrease in saccade latency with age; however, the rate of decrease was different for each condition. In the prosaccade condition, there was a decrease from age 8 to age 12 that was significantly different from the latencies displayed by participants 13–25 years of age, $F(1, 95) = 19.01$, $ES = 0.24$, $p < .001$. However, in the antisaccade condition, there was a decrease in saccadic latencies until age 16, $F(1, 95) = 104.58$, $ES = 0.36$, $p < .001$. Like the saccade accuracy data reported above, the saccade latency data, in the pro- and antisaccade tasks, were quite similar to those reported by other research-

ers (Fischer et al., 1997; Klein & Forester, 2001; Munoz et al., 1998).

Oculomotor Capture Task

We analyzed a number of different dependent variables to characterize performance in the oculomotor capture task. These variables include saccade accuracy, manual response errors, manual reaction time, and saccade latency.

Saccade accuracy. These data were analyzed with a repeated measures ANOVA with age as a between-participants factor and condition (onset, additional stimulus control) as a within-participant factor. There was a significant main effect of condition (see Figure 4), $F(2, 190) = 139.55$, $ES = 0.60$, $p < .001$. Participants were significantly more accurate in the control than in the onset distractor condition. Neither age nor the Age \times Condition interaction was significant ($ps > .40$). Figures 5 and 6 illustrate the landing point of the initial saccade when an onset distractor was present. As can be seen from the figures, a substantial percentage of the saccades were directed to the onset distractor position across age groups and onset distractor locations.

Manual response errors. Manual response error data (i.e., errors in determining whether a C or a reversed C appeared in the

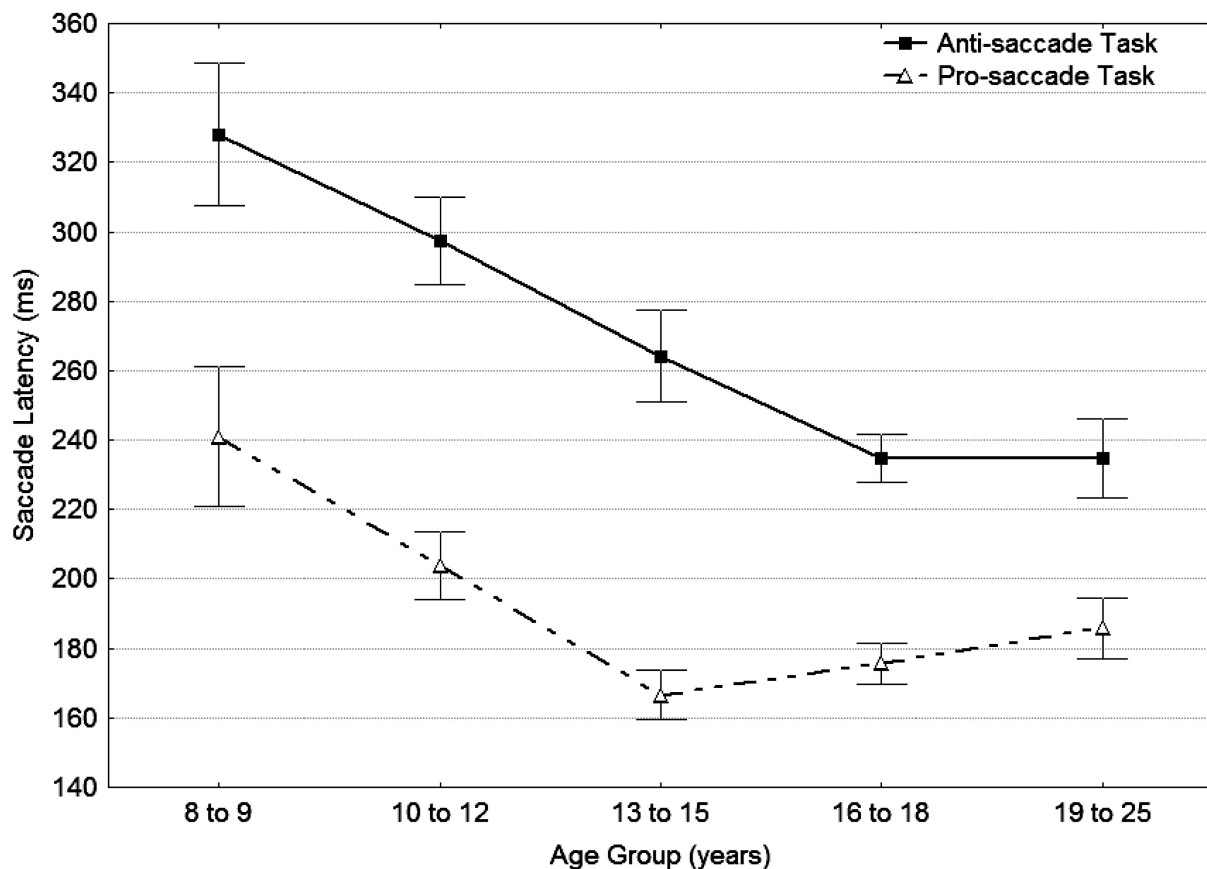


Figure 3. Saccade latency for each age group in the pro- and antisaccade tasks. Error bars represent standard deviations.

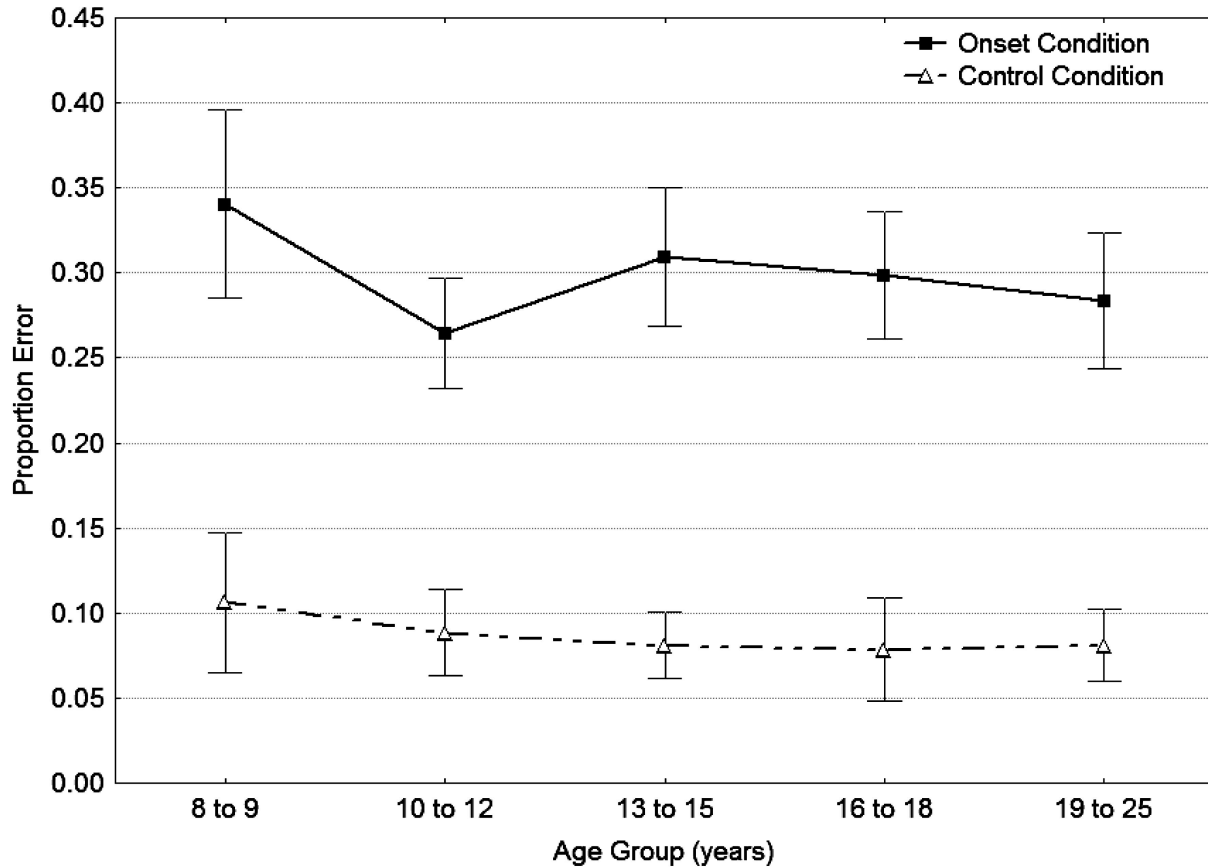


Figure 4. Saccade direction accuracy for each age group in the onset distractor and control conditions of the oculomotor capture task. Error bars represent standard deviations.

uniquely colored target stimulus) were analyzed with a repeated measures ANOVA with age as a between-participants factor and condition (onset, additional stimulus control) and eye movement direction (to target, to distractor) as within-participant factors. No significant main effects or interactions were obtained ($ps > .30$). Error rates ranged between 1% and 10% across participant groups and conditions.

Manual reaction times. These data were analyzed with a repeated measures ANOVA with age as a between-participants factor and condition (onset, additional stimulus control) and initial saccade direction (to target, to distractor) as within-participant factors. A significant main effect was observed for age. Younger children were slower to respond than older children or young adults (see Figure 7), $F(4, 21) = 6.38$, $ES = 0.54$, $p < .002$. A significant main effect was also obtained for initial saccade direction. Reaction times were shorter when participants initially moved their eyes to the target ($M = 1,098$ ms) than when they initially moved their eyes to the distractor ($M = 1,208$ ms; see Figure 8), $F(1, 21) = 15.83$, $ES = 0.43$, $p < .001$. There was also a trend for all groups to have shorter reaction times in the control condition (1,099 ms) than in the onset condition (1,157 ms), $F(2, 42) = 2.77$, $ES = 0.17$, $p < .07$.

Saccade latency. These data were analyzed with a repeated measures ANOVA with age as a between-participants factor and condition (onset, control) and initial saccade direction (to target, to distractor) as within-participant factors. There was a significant effect of age on saccade latency (see Figure 9), $F(4, 21) = 3.73$, $ES = 0.41$, $p < .019$. The youngest three age groups had longer saccade latencies than did the older age groups. There was also a main effect of eye movement direction, $F(1, 21) = 34.43$, $ES = 0.51$, $p < .000$ (mean to the target: 342 ms; mean to the distractor: 258 ms). Latencies were longer when the eyes went first to the target than when they went first to the distractor.

Relationship Between Eye Movement Accuracy Data and Psychometric Performance

Previous research has shown that individuals who possess better working memories also make fewer direction errors on the anti-saccade task (Kane, Bleckley, Conway, & Engle, 2001) and that concurrent performance of antisaccade tasks with working memory tasks results in increased saccade direction errors on the antisaccade task (Roberts, Hager, & Heron, 1994). Given these

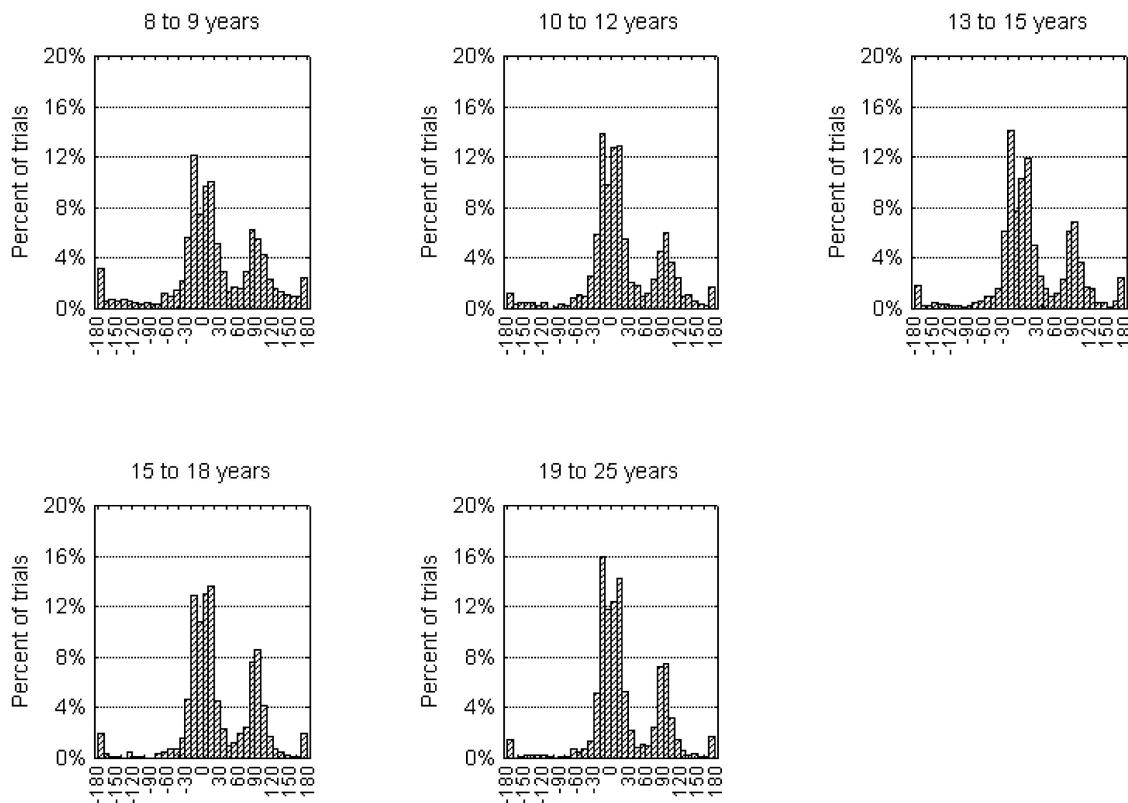


Figure 5. Indication of the landing location of the initial saccade away from fixation for the onset distractor trials in the oculomotor capture task. These plots represent the condition in which the onset distractor was separated by 90° from the target stimulus. The x-axis numbers represent that angular deviation of the initial saccade from the target location (target location = 0).

data, we decided to examine the relationship between performance on our psychometric measures of processing speed (i.e., box completion, digit copying, and digit-symbol copying) and memory span (i.e., forward and backward digit span) and saccade direction accuracy on the prosaccade, antisaccade, and oculomotor capture tasks.

The results of the Kane et al. (2001) and Roberts et al. (1994) studies suggest significant correlations between saccade direction errors in the antisaccade task and performance on the backward but not the forward digit span task. This follows, because backward digit span entails working memory (i.e., encoding and maintaining a set of digits in memory while also reversing their order), whereas forward digit span represents a short-term but not a working memory task (i.e., this task does not entail operations on the encoded items—a hallmark of working memory tasks). Kane et al. and Roberts et al. did not find a significant relationship between saccade direction errors and working memory on the prosaccade task, presumably for at least two reasons: (a) Very few saccade direction errors are observed for prosaccade performance, and (b) working memory demands are minimal for this task. To our knowledge, the relationship between working memory and saccade direction errors on the oculomotor capture task has not been examined. However, given the reduced working memory demands in the

oculomotor capture as compared with the antisaccade task, we might expect to find small correlations between backward digit span and direction errors on the oculomotor capture task. Predictions about the relationship between the processing speed measures and saccade direction accuracy are more uncertain, although one may expect faster participants to be capable of more quickly aborting an erroneous response.

The correlation data are presented in Table 2. As can be seen in the table, the correlation between working memory performance and saccade direction errors was only significant for the antisaccade task, consistent with previous observations (Kane et al., 2001). This relationship was not observed for the prosaccade or oculomotor capture tasks. The relationship between processing speed and saccade errors was also small for these tasks. However, processing speed correlations were larger for the antisaccade measures.

Discussion

The main goal of the current study was to examine the developmental time course of attentional and oculomotor control as indexed by three eye movement measures: the prosaccade task, the antisaccade task, and the oculomotor capture task. Previous studies have found small and often insignificant changes in saccade di-

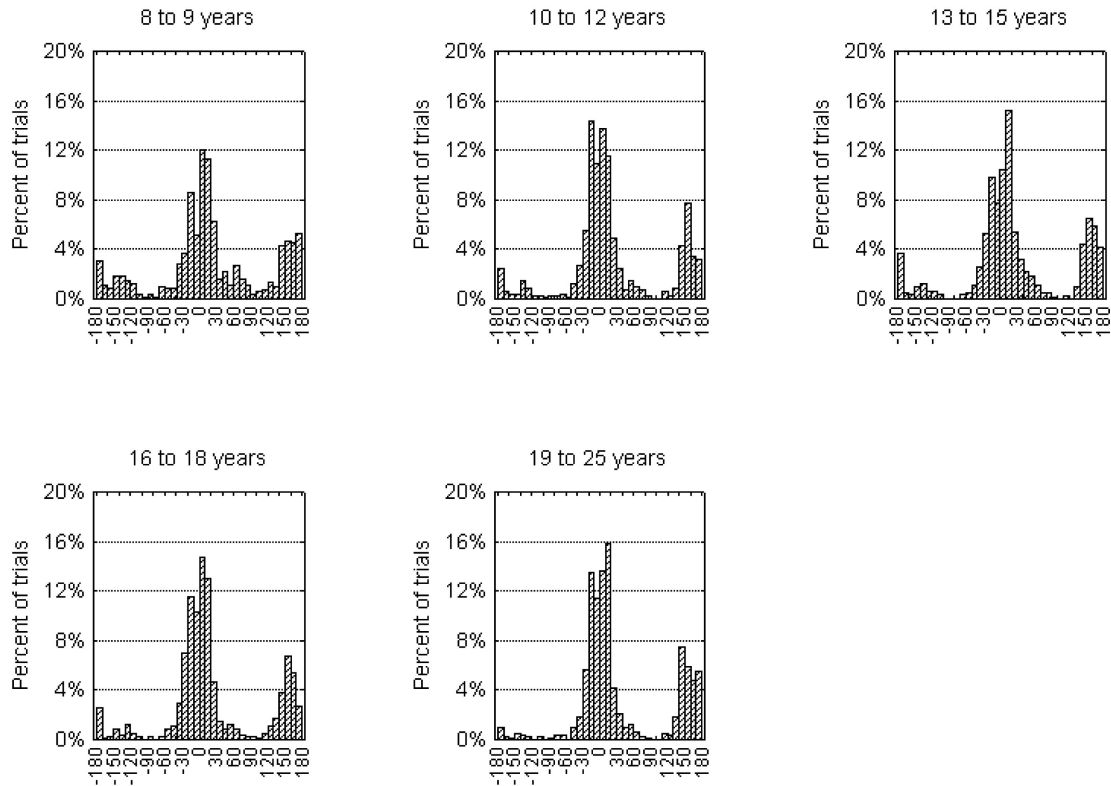


Figure 6. Indication of the landing location of the initial saccade away from fixation for the onset distractor trials in the oculomotor capture task. These plots represent the condition in which the onset distractor was separated by 150° from the target stimulus. The x -axis numbers represent that angular deviation of the initial saccade from the target location (target location = 0).

reaction accuracy in the prosaccade task while also observing improvements from childhood to midteens in the accuracy of performance in the antisaccade task. Like manual reaction times, saccade latencies decrease, in both the pro- and antisaccade tasks, from childhood to the midteens. These data have been interpreted to suggest the gradual development of the ability to control attention and the eyes, particularly when stimulus-driven and goal-directed influences are placed in opposition (Fischer et al., 1997; Klein & Forster, 2001; Munoz et al., 1998). Indeed, the present eye movement results, especially in the antisaccade task, are consistent with the general observation across a number of different tasks that the development of effective inhibitory processes coincides with the maturation of prefrontal regions of the brain (Cepeda et al., 2001; Jones et al., 2003; Kirkham & Diamond, 2003; Schul et al., 2003).

The examination of performance in the oculomotor capture task, along with performance in the antisaccade task, enabled us to further isolate the nature of developmental changes in the ability to control the eyes and attention. More specifically, our study enabled us to examine attentional control in situations in which the stimulus-driven influence of the sudden appearance of a new object competes with the requirement to attend to and later inhibit this object (i.e., the antisaccade task) as compared with a situation in which participants need only maintain a set

for a uniquely defined target (i.e., the oculomotor capture task). As illustrated in Figures 4, 5, and 6, the proportion of trials on which the eyes are initially misdirected to the onset distractor is age invariant in the oculomotor capture task. This pattern of data is observed even though, like performance in the antisaccade task, saccadic latency decreases from childhood to the midteens. Therefore, the differential pattern of misdirected saccades in the antisaccade and the oculomotor capture paradigms cannot be attributed to age-related differences in response speed in these two tasks.

We suggest—on the basis of the age-related dissociation of the saccade accuracy effects in the antisaccade and oculomotor capture tasks—that the ability to exert top-down control in opposition to attentional capture engendered by stimulus-driven influences (e.g., the sudden appearance of a new object in the visual field) exists by 8 years of age. However, the ability to maintain multiple top-down sets (e.g., inhibit an eye movement to a salient stimulus and move the eyes in the opposite direction of this stimulus—as in the antisaccade task) seems to take substantially longer to develop and, indeed, may be related to the continued development of working memory well into the midteen years (Cowan, Saults, & Elliot, 2002; Gathercole, Pickering, Ambridge, & Wearing, 2004). Indeed, the time course of the development of saccadic control in the antisaccade task mimics the time course of working memory as

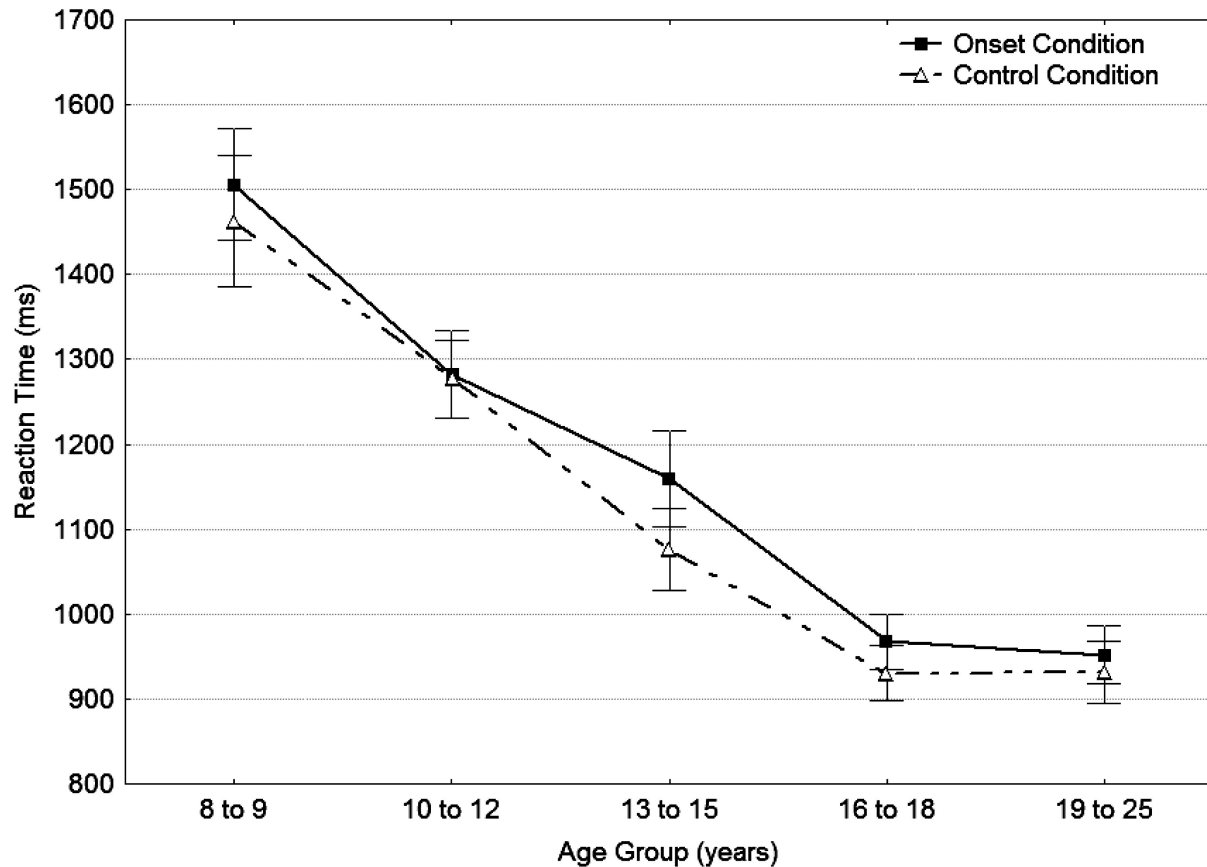


Figure 7. Mean manual reaction times as a function of age group and condition for the oculomotor capture task. Error bars represent standard deviations.

indexed by performance in the reverse digit span task (see Table 1). The correlation between reverse digit span and saccade accuracy was .59 in the antisaccade task but only .13 in the oculomotor capture task. The relatively strong relationship between working memory and saccade errors in the antisaccade task has been previously established in the literature (Kane et al., 2001; Roberts et al., 1994).

Although the current study was not intended to test any specific models of oculomotor control or the manner in which model parameters might change during the course of development, it is interesting to consider the present data within the context of a particular class of models that have been specifically designed to examine the influence of top-down and bottom-up factors on saccade control. This class of models, referred to as *competitive integration models* (Kopeck, 1995; Trappenberg, Dorris, Munoz, & Klein, 2001), suggests that saccade programming is a competition between activation at multiple locations represented in a saccade map. The execution of a saccade is triggered when the activation at one of the locations in the saccade map exceeds a threshold value. Competitive integration models also incorporate activation based on top-down (i.e., based on expectancies, instructions, and experience) and bottom-up (i.e., from stimulus features such as

onsets, the appearance of new objects, and well-learned stimulus-response relationships) input to the saccade map. Furthermore, these models assume that the bottom-up activations in the saccade map are brief and can be inhibited by location-specific inhibition engendered by top-down input and information, such as the intention to move the eyes to a color singleton. Capture of attention and the eyes occurs when location-specific inhibition occurs after the activation threshold has been reached at the location of the bottom-up activation.

One variant of the competitive activation model, proposed by Godijn and Theeuwes (2002), has been contrasted with an independent horse race model with saccade data obtained in a oculomotor capture paradigm like the one used in the present study. The *independent horse race model* suggests that (a) multiple saccade programs, based on top-down and bottom-up inputs, are independent of each other, and (b) the destination of the initial saccade depends on which program is completed first. Thus, unlike competitive activation models, the independent horse race model does not incorporate the possibility of multiple activations, with facilitatory and inhibitory interactions, in a single saccade map. The data obtained in a series of experiments were consistent with competitive integration models (Godijn & Theeuwes, 2002). Interestingly, data from all of the

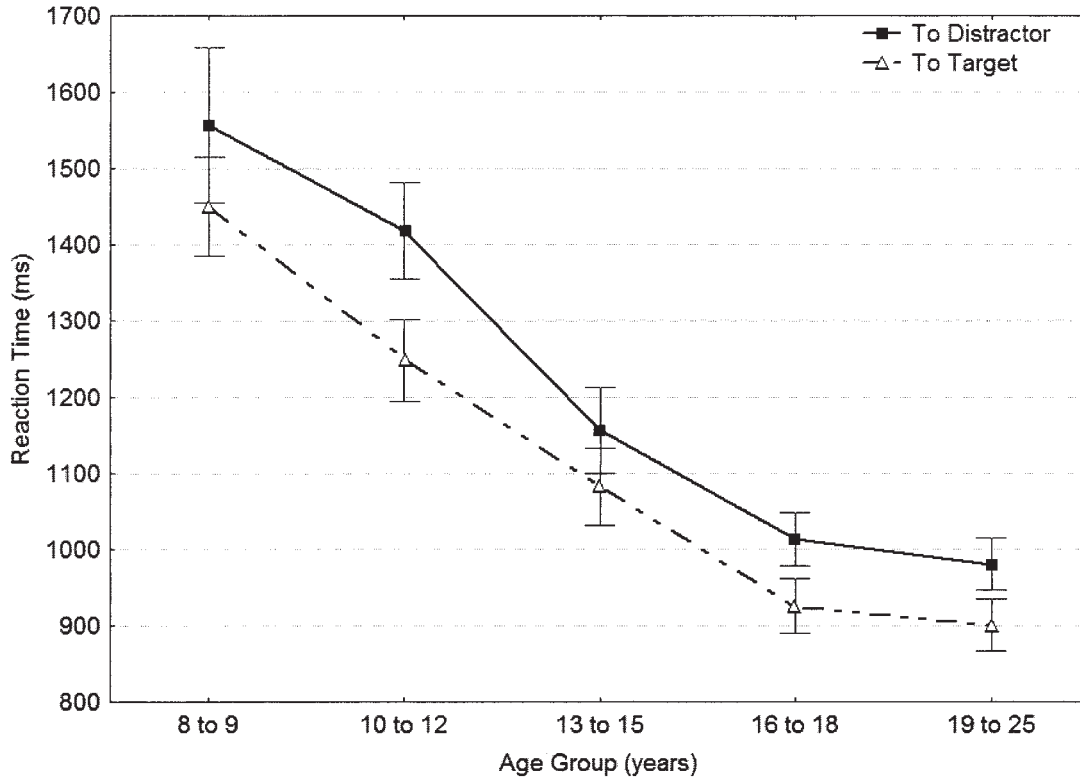


Figure 8. Mean manual reaction times as a function of age group and direction of initial saccade away from fixation for the oculomotor capture task. Error bars represent standard deviations.

paradigms used in the present study—prosaccade, antisaccade, and oculomotor capture tasks—have been well fit by competitive integration models (Godijn & Theeuwes, 2002; Kopecz, 1995; Trappenberg et al., 2001). However, on the basis of the saccade data obtained in the present study, an important question is how a competitive integration model might account for the differential developmental trajectories of saccade errors in the antisaccade and oculomotor capture tasks. One possibility, articulated above, is that children have a difficult time maintaining multiple goals in working memory, such as the requirement to attend to but not look at the cue and then look in the opposite direction in the antisaccade task. Failure to maintain these goals may, in turn, reduce the effective inhibition of the cue-directed saccades in the saccade map in the antisaccade task. In the oculomotor capture task, participants need to maintain only a single goal—that is, to move their eyes rapidly to the color singleton—because the onset distractor does not predict the location of the target. Thus, in this case, the goal maintenance required may be within the capabilities of the children.

The analysis of the differential developmental trajectories of saccade direction errors in the antisaccade and oculomotor capture tasks within the context of competitive integration models raises another interesting issue—the nature of the inhibitory processes. In the antisaccade task, inhibition of a response to the cue location is both explicit and intentional. This follows, because participants must be aware of the location of the cue and, indeed, use this cue

to guide their eyes in the opposite direction. However, in the oculomotor capture task, inhibition is implicit and nonintentional, given that the onset distractor is not predictive of the target location. Hence, it would appear conceivable that two qualitatively different types of inhibition are used in these two paradigms, with an automatic and implicit form of inhibition playing a central role in the oculomotor capture task, whereas an intentional and effortful variety of inhibition subserves, for the most part, performance in the antisaccade task. The automatic inhibitory process may develop earlier than the intentional, effortful inhibitory process. Indeed, this differential inhibitory conceptualization of age differences in oculomotor control is not incompatible with the goal-maintenance view espoused above. Both of these hypothetical mechanisms could play a role in the differential developmental trajectory observed in the present data. Future studies will be needed to further examine these hypotheses.

We believe that one additional issue deserves a brief comment. In the present article, we have treated attention and eye movements as if they are tightly coupled and reflect similar processes. Although it is clear that observers can shift covert attention and maintain fixation (Posner, 1980), it has also become clear that covert attention does indeed precede saccades, regardless of whether a saccade is the result of top-down, bottom-up, or some combination of both processes (Henderson & Hollingworth, 1999; Hoffman, 1998; Hoffman & Subramaniam, 1995; Kowler, Anderson, Doshier, & Blaser, 1995; Peter-

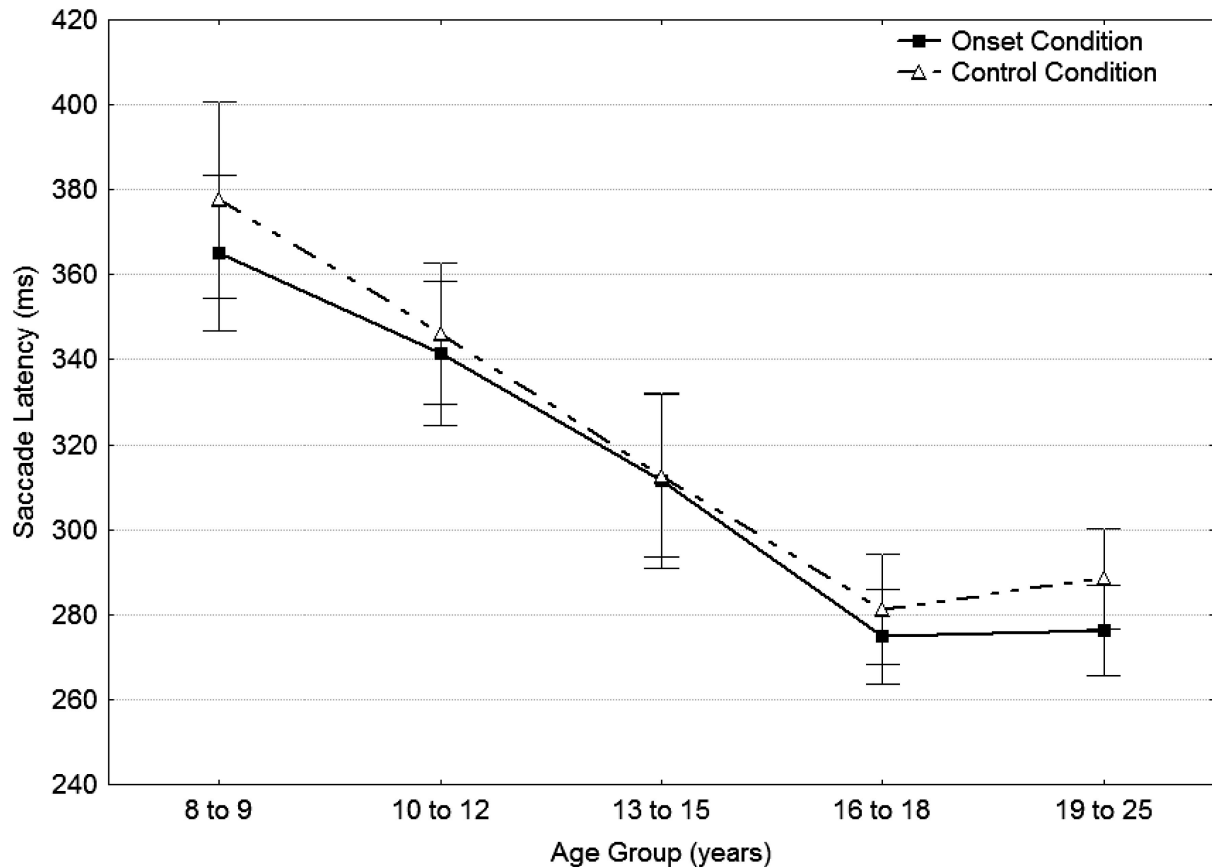


Figure 9. Mean saccadic latencies for the initial eye movement away from fixation as a function of age and saccade direction for the oculomotor capture task. Error bars represent standard deviations.

son, Kramer, & Irwin, 2004; Sheliga, Craighero, Riggio, & Rizzolatti, 1997). Therefore, we believe that it is reasonable to argue that the age-related differences and similarities exhibited in the saccade measures in our study do reflect both covert and overt attentional processes.

Table 2

Pearson Product-Moment Correlations Between Psychometric Measures of Processing Speed, Short-Term Memory, and Working Memory and Saccade Direction Accuracy in the Prosaccade, Antisaccade, and Oculomotor Capture Tasks

Psychometric test	Saccade direction accuracy		
	Prosaccade task	Antisaccade task	Oculomotor capture task
Box completion ^a	.02	.19	.08
Digit copying ^a	.09	.21	.11
Digit-symbol copying ^a	.12	.17	.05
Forward digit span ^b	-.06	.27	.05
Backward digit span ^c	.08	.59	.13

^a Measure of processing speed (Salthouse, 1992). ^b Measure of short-term memory (Wechsler, 1981). ^c Measure of working memory (Wechsler, 1981).

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