Developmental Psychology
2010, Vol. 46, No. 2, 337–349

0012-1649/10/$12.00 DOI: 10.1037/a0018541

The Development of Attentional Networks: Cross-Sectional Findings From a Life Span Sample

Florian Waszak
Université Paris Descartes and Centre National de la Recherche Scientifique

Shu-Chen Li
Max Planck Institute for Human Development

Bernhard Hommel
Leiden University

Using a population-based sample of 263 individuals ranging from 6 to 89 years of age, we investigated the gains and losses in the abilities to (a) use exogenous cues to shift attention covertly and (b) ignore conflicting information across the life span. The participants' ability to shift visual attention was tested by a typical Posner-type orienting task with valid and invalid peripheral cues. To tap conflict resolution, we asked participants to perform a color version of the Eriksen-type flanker task. The observed cross-sectional age differences in our data indicate that the ability to deal with conflicting information and the ability to covertly orient attention show different cross-sectional age gradients during childhood and that only conflict resolution mechanisms show a marked negative age difference in old age. Moreover, the data suggest that although the overall performance of the participants can, in part, be accounted for by individual differences in information processing speed, performance in the orienting and conflict task depends on factors related to the specific development of the two attentional systems in question.

Keywords: attentional networks, life span sample, flanker task, orienting task

Throughout life, humans are almost constantly exposed to a multitude of stimuli. Many of these stimuli call for a specific response or are habitually associated with a certain action. However, the brain cannot analyze and react to all of the incoming information to the same extent. Humans therefore need to select the most important aspects of their environment for in-depth processing and to choose among the actions afforded by their surroundings according to the context, the circumstances, and their own intentions. A child in the playground, a young adult driving to work, and a retiree in the casino of a cruise liner—they all have to deal with this necessity of allocating resources to only a small fraction of the incoming stimulation and of selecting among many possible actions.

Attentional Networks

There is increasing evidence that different functions of human attention are served by separable neural networks (Fan, McCandliss, Fossella, Flombaum, & Posner, 2005; Fan, McCandliss, Sommer, Raz, & Posner, 2002; Posner & Petersen, 1990). Although one network has been shown to be related to the function of orienting to stimuli (Corbetta, Kincade, Ollinger, McAvoy, & Shulman, 2000; Desimone & Duncan, 1995; Kastner, Pinsk, De Weerd, Desimone, & Ungerleider, 1999), other networks are implied in alerting (Coull, Frith, Frackowiak, & Grasby, 1996; Posner & Petersen, 1990) and in resolving response conflicts (Botvinick, Nystrom, Fissell, Carter, & Cohen, 1999; MacDonald, Cohen, Stenger, & Carter, 2000). More specifically, *orienting* refers to the ability to enhance the processing of specific aspects of the sensory input by shifting attention to these aspects. *Alerting* is defined as achieving and maintaining an alert state. Mechanisms of *conflict resolution*, finally, deal with the interference exerted by sensory input that facilitates behavioral response tendencies that are incompatible with the currently intended behavior.

Using a single integrated task, Fan and colleagues (Fan et al., 2002, 2005) have confirmed that the three attentional functions can

---

Florian Waszak, Laboratoire Psychologie de la Perception, Université Paris Descartes, Paris, France, and Centre National de la Recherche Scientifique, Paris, France; Shu-Chen Li, Center for Lifespan Psychology, Max Planck Institute for Human Development, Berlin, Germany; and Bernhard Hommel, Cognitive Psychology Unit, Leiden Institute for Psychological Research, Leiden University, Leiden, the Netherlands.

This study is part of the CoOP-MIND study (Li et al., 2004), a collaborative research project (investigating the cooperation and intercorrelation between a broad class of elementary perceptual and cognitive processes, such as memory, visual search, and choice reactions, and psychometrically defined intellectual abilities across life span development) between the Max Planck Institute for Human Development and the Max Planck Institute for Psychological Research, Munich, Germany. In addition to the authors who were directly involved in the present study, other members involved in the CoOP-MIND study were: G. Aschersleben, F. Miedreich, and W. Prinz from the Max Planck Institute for Psychological Research; and U. Lindenberger and the late Paul B. Baltes from the Max Planck Institute for Human Development. We thank Annette Rentz-Luehning and many other student assistants for help in collecting the data.

Correspondence concerning this article should be addressed to Florian Waszak, Laboratoire Psychologie de la Perception, Centre National de la Recherche Scientifique, Université Paris Descartes, Centre Biomédical des Saints Pères, 45 rue des Saints Pères, 75270 Paris CEDEX 06. E-mail: f.waszak@gmx.net

be dissociated. With regard to behavioral measures, estimates of efficiency in alertness, orienting, and conflict resolution were shown to be uncorrelated (Fan et al., 2002), and a neuroimaging analysis revealed very little overlap between the neuroanatomical systems associated with alerting, orienting, and conflict resolution (Fan et al., 2005): Alerting showed strong thalamic involvement and activation of anterior and posterior cortical sites, whereas orienting activated parietal sites and frontal eye fields, and response conflict resolution implicated the anterior cingulate cortex. The present study focused on two of these three attentional networks—that is, the orienting network and the conflict resolution network—and their development across the life span.

In light of the evidence suggesting that attentional orienting and conflict resolution processes are relatively independent of each other, it makes sense to assume that these two abilities may show different developmental age gradients across the life span. This issue is of particular importance at the two ends of the life span. It has been acknowledged that attention plays a central role in various domains of children's cognitive development. On the one hand, the acquisition of knowledge and skills, be it social or nonsocial, is thought to depend on the integrity of basic attentional mechanisms (cf. Bornstein, 1990). Conversely, the dysfunction of attentional mechanisms has been considered to underlie various disorders of development (e.g., Bryson, Landry, & Wainwright, 1997; Townsend, Courschene, & Egaas, 1996). On the other hand, deficits in attentional control during aging are considered to be a major factor in the drop of performance in late adulthood (e.g., McGaughy & Eichenbaum, 2002). In the following, we briefly summarize what is currently known about the development and aging of orienting and conflict resolution abilities.

Life Span Development of Covert Orienting

Exogenously cued, covert orienting has been investigated mainly using Posner's (1980) orienting task. In such a task, participants commonly perform a forced choice reaction to the identity of a visual target stimulus. The experimental manipulation consists of the presentation of a cue (e.g., the brightening of a location marker) immediately preceding the target. The cue may be presented in the same location as the subsequent target (a valid trial) or in a different location (invalid trial). The location of cue and target is determined randomly so as to ensure that the orienting response is not contaminated by higher order expectations. The orienting response that the cue is assumed to evoke is called *covert* because participants are asked to keep fixation at a central mark throughout the trial. The cue is considered to be *exogenous* because it directly indicates the position where the target appears (or does not appear) and is thought to elicit an involuntary shift of attention to that location. Exogenously cued, covert orienting has to be differentiated from another type of attentional orienting that is not considered in the present study: namely, *endogenous*, *overt* orienting of attention that consists of voluntarily (endogenous) shifting the gaze (overt) to the attended region of space.

The comparison of reaction times (RTs) on trials with valid and invalid cues as described above is a measure of the effect of exogenously cued, covert orienting. Slower RTs for invalid trials than for valid trials indicate that participants shifted attention to the cued location, facilitating processing on valid trials but necessitating a time-consuming shift of attention to the target on invalid trials. The cue–target stimulus onset asynchrony (SOA) has a tremendous impact on the RT pattern. Usually, costs and benefits of invalid and valid trials reach a maximum at an SOA of about 50–100 ms. For SOAs longer than about 400 ms, invalid RTs are often shorter than valid RTs are (e.g., Maylor & Hockey, 1985; Posner & Cohen, 1984). It is assumed that this "inhibition of return" biases the visual system to orient away from stimuli that have already been processed (e.g., Klein, 1988). The life span development of inhibition of return is on its own an interesting topic. However, in the present study we concentrate on the early effects of covert orienting, where valid trials show a benefit and invalid trials a cost.

It is rather difficult to derive a coherent picture of exogenously cued covert orientation effects across the life span from extant evidence, because the age groups investigated and the particular paradigms employed differ from study to study (an exception is the study from Brodeur & Enns, 1997, which we describe below). As for childhood development, the processes underlying attentional orienting seem to be operative from very early on: Children show a validity effect—that is, they respond faster when the stimulus appears at the cued location than when it appears at the uncued location (Akhtar & Enns, 1989; Enns & Brodeur, 1989; Brodeur, Trick, & Enns, 1997). The efficiency of orienting seems to increase with age: Five- to 9-year-old children show a larger validity effect than adults, presumably because they are less effective at redirecting attention from the wrongly cued location to the target (Enns & Brodeur, 1989).

At the other end of the life span, a number of studies have compared covert exogenous orienting in young and older adults. Using the same task as Fan et al. (2002, 2005), designed to assess all three components of attention—alerting, orienting, and conflict resolution—simultaneously, Fernandez-Duque and Black (2006) compared the performance of 20- and 72-year-old healthy adults. They reported that orienting was mostly unaffected in older participants. Similar findings have been reported by others (Festa-Martino, Ott, & Heindel, 2004; Greenwood, Parasuraman, & Haxby, 1993; Hartley, Kieley, & Slabach, 1990; Tales, Muir, Bayer, & Snowden, 2002), indicating that healthy aging spares automatic orienting. Thus far, only one study has investigated covert exogenous orienting in a life span sample comprising groups of 6-, 8-, and 10-year-old children, 23- to 25-year-old adults, and 73- to 74-year-old adults (Brodeur & Enns, 1997). Their results suggest that stimulus-driven covert orienting shows relatively little age difference across the life span.

Life Span Development of Conflict Resolution

One of the most prominent procedures for studying attentional conflict resolution is the Eriksen flanker task (B. A. Eriksen & Eriksen, 1974). In this task, participants carry out speeded choice reactions to a centrally presented target stimulus, such as a letter. The target is flanked by irrelevant distractor symbols that can be identical with either the present target (a congruent trial) or the alternative target (incongruent trial). Congruent flankers commonly yield shorter RTs than incongruent flankers do (e.g., B. A. Eriksen & Eriksen, 1974; C. W. Eriksen & Hoffman, 1973). That this is not a mere effect of stimulus similarity or coherence is obvious in evidence derived from tasks using many-to-one stimulus–response mappings showing that incongruent flankers mainly interfere if they call for a response other than the target (e.g., Miller, 1991). Thus, it seems that although they are irrelevant to the task, flankers are automatically processed up to response-related stages.

Several developmental studies have shown that the effects of flankers decrease with age (e.g., Enns & Akhtar, 1989; Enns & Cameron, 1987; Ridderinkhof, van der Molen, Band, & Bashore, 1997). However, the reason for the increased susceptibility of younger children to interfering stimuli is under dispute. In a review of earlier studies, Enns (1990) argued that it can be attributed to inefficient selection at the perceptual end of the processing chain. However, Ridderinkhof and van der Molen (1995) compared 5- to 12-year-old children and young adults. Measures derived from ERPs (event-related potentials) suggested that incongruent stimuli delay both stimulus evaluation and response activation. However, there was no difference in the interference effect on stimulus evaluation between age groups. By contrast, the interference effect on correct response activation showed a pronounced age-related reduction, suggesting that response competition is the major source of developmental differences in the ability to resist interference—that is, inefficient selection at the output end of the processing chain (cf. Ridderinkhof et al., 1997).

Concerning the course of development of conflict resolution mechanisms in early life, Goldberg, Maurer, and Lewis (2001) showed that 8- to10-year-olds are slowed more than adults by incompatible distractors. In the same study they showed that attention orienting (endogenous in this case) is already adult-like by 8 to 10 years of age. The authors concluded that the ability to filter out irrelevant information develops comparatively late. Other evidence for a protracted development of filtering mechanisms comes from studies on the classic Stroop (1935) effect—that is, the finding that naming the ink color of color words is more difficult when the color word is incongruent to the ink color compared with a neutral condition of, say, solid color patches (see MacLeod, 1991, for a review). Early work on developmental changes during childhood indicated that the magnitude of the Stroop interference diminishes throughout childhood and even into early adulthood (Comalli, Wapner, & Werner, 1962). Similar trends have been reported when nontarget pictures (Day & Stone, 1980) or printed words (Guttentag & Ornstein, 1990) interfered with picture naming.

Concerning developmental changes during late life, the literature is rather equivocal. On the one hand, some studies have yielded evidence of preserved functioning well into later adulthood. In a study from Wright and Elias (1979), older adults were, if anything, less susceptible to distractors than young adults, presumably due to a narrow "perceptual window" that protects older participants from interference from the periphery. Similarly, two studies by Zeef and colleagues (Zeef & Kok, 1993; Zeef, Sonke, Kok, Buiten, & Kenemans, 1996) showed age differences in flanker interference to be relatively small and even nonsignificant, especially with large target–flanker distances (however, see below for a discussion of the ERPs reported by Zeef and colleagues). On the other hand, some studies investigating response and error monitoring found that older adults compare unfavorably with younger adults and show decreased amplitudes in relevant ERP components, such as the error-related negativity (e.g., Mathalon et al., 2003; Mathewson, Dywan, & Segalowitz, 2005; Nieuwenhuis et al., 2002; West, 2004; West & Moore, 2005). To sum up, the ability to filter out conflicting information during cognitive processing seems to develop rather slowly during childhood and adolescence. Whether or not this ability shows a marked decline in later life is still controversial.

Aim of Study

In a review on the development of selective attention, Plude, Enns, and Brodeur (1994) pointed out that, almost without exception, the dozens of studies they covered compared ages at one end of life or the other, rather than investigating age differences across the life span. Evidently, data meant to elucidate the different reasons for less than optimal performance at either end of life are only conclusive if they are based on comparable measurements on participants across a wide range of ages. To our knowledge, this shortcoming has not been remedied yet. The present study examined the development of two aspects of the attention network—covert orienting and response conflict resolution—from a life span perspective. It encompassed age groups ranging from early childhood to late life and involved continuous age sampling. We recruited participants from a large population-based sample (Li et al., 2004; cf. Trick & Enns, 1998; Williams, Ponesse, Schachar, Logan, & Tannock, 1999), using city registry information to minimize the effects of positive selection (i.e., using only highly educated, very healthy, or affluent individuals). Furthermore, because of rapid changes in development from ages 6 to 15 and rapid age-related declines from ages 60 to 89, we oversampled at the younger and older ends of the age range. At the outset, it should be underscored that our study could only offer evidence on potential differences in the cross-sectional age gradients of the two attentional mechanisms of interest. Generalizations from cross-sectional data to longitudinal developmental effects need to be drawn very cautiously, as cohort effects and age-related differences in rate of change cannot be adequately addressed in cross-sectional designs (e.g., Kraemer, Yesavage, Taylor, & Kupfer, 2000; Sliwinski & Buschke, 1999).

The large sample spanning a wide age range allowed us to address a number of questions that are hard to tackle with small samples covering only discrete segments of the life span at one end of the life or the other. First, we were able to directly compare the improvement in performance during childhood and adolescence with the decline in performance during later life without the lack of methodological coherence that is inherent in the comparison of early gains and late losses across different studies. Second, in contrast to extreme age group designs, the sample allowed for the estimations of cross-sectional age gradients across more or less continuous age groups. Although there are a few studies that used discrete samples representing the most important stages of the entire life span (Brodeur & Enns, 1997, investigated covert exogenous orienting; Comalli et al., 1962, investigated the Stroop effect; see above), to our knowledge neither covert exogenous orienting nor conflict resolution have ever been studied with a population-based sample that encompassed all ages from early childhood to late adulthood. By comparing the cross-sectional age gradients of the two attentional systems (assessed on the same population sample), we were able to assess whether, and in which sense, conflict resolution and covert exogenous orienting may develop differently. As outlined above, there were reasons to expect that the age differences in conflict resolution mechanisms would show a rather slowly rising gradient during childhood and adolescence and a declining gradient in late life. As for covert exogenous orienting, the rising gradient during childhood and adolescence was expected to be steeper than that of conflict resolution mechanism but was expected to show little, if any, age-related differences in old age.

The main goal of the study was to investigate the age gradients of the two mechanisms in question. However, as a side story, we also examined the relation between these two attentional systems by correlating orienting and conflict resolution indices. Given the observations of Fan et al. (2002) in adults, we expected correlations to be low, reflecting the relative independence of the systems. We also investigated whether correlations differ between the age groups.

Method

Participants

The tasks investigated in this study were part of a large multisession, multivariate study on life span differences in the organization of intellectual abilities and underlying basic cognitive and sensory processes (Li et al., 2004). The overall study assessed measures of intelligence, basic information processing, and sensory functioning with more than 30 tests and tasks. Each participant attended four 1-hr sessions.

To obtain a population-based life span sample, we randomly drew the parent sample of our study from a list of 1,920 individuals (ages ranging from 6 to 89 years) provided by the Berlin City Registry, Berlin, Germany. The sample was stratified by age and sex. Because of rapid changes in cognitive development from age 6 to 15, one-year age bins were used for this range. In view of the developmental stability that is manifested in late adolescence and adulthood, 11 four-year age bins were used for the age range from 16 to 59. Finally, in light of data showing rapid age-related declines in many domains of cognitive functioning, 10 three-year age bins were used for the age range from 60 to 89.

To recruit participants, we sent a total of 1,873 invitation letters, and a total of 356 individuals agreed to participate in the study. Hence, the participation rate for the entire sample is 19%. It is highest for individuals in the age range from childhood to early adolescence (45.7%), followed by individuals in the range from late adolescence to middle adulthood (19.9%), and lowest for individuals in older adulthood (10.5%). Thus, it should be noted that our older sample was likely to be more positively selected than the other age groups. The positive selectivity, if it is there, would, however, make our study more conservative rather than liberal with respect to observing negative age effects in old age. Of the 356 participants who initially agreed to participate, some did not attend all measurement sessions. Excluding these participants, the effective sample in our analyses included 263 participants in 31 age bins.

The 263 participants were further subdivided into 18 age groups, which reflected a compromise between theoretically reasonable age ranges and comparable group sizes. The results shown in Table 1 are based on groups of 6–7, 8–9, 10–11, 12–13, 14–15, 16–21, 22–27, 28–34, 35–42, 43–48, 49–53, 54–58, 59–63, 64–67, 68–71, 72–76, 77–80, and 81–88 years, each including 12–20 participants. The participants performed the experimental tasks with either normal or corrected vision.

Table 1
Simple Reaction Time (RT) Task, Orienting Task, and Conflict Task Performance Measures as a Function of Age Group

			Orienting task				Conflict task					
		SRT	RT (*SEM*)		p(c)		RT (*SEM*)			p(c)		
Age group (years)	*N*	RT (*SEM*)	Invalid	Valid	Invalid	Valid	Incomp.	Neutral	Comp.	Incomp.	Neutral	Comp.
6–7	18	530 (33)	1008 (48)	957 (42)	4.9	4.8	959 (42)	905 (41)	847 (42)	9.9	6.8	7.4
8–9	19	449 (23)	841 (39)	781 (33)	3.8	2.6	808 (48)	758 (46)	737 (40)	8	4.1	3.3
10–11	15	324 (17)	708 (22)	670 (21)	2.4	2.5	717 (36)	652 (29)	628 (31)	5.9	2.5	2.2
12–13	17	322 (19)	640 (25)	624 (27)	3.5	3.4	672 (30)	636 (34)	583 (21)	5	2.1	2.5
14–15	12	314 (15)	558 (30)	532 (32)	2.9	2.4	615 (34)	574 (32)	545 (31)	3.2	2.4	1
16–21	12	323 (20)	579 (29)	551 (28)	2.2	2.3	633 (30)	611 (32)	583 (31)	3.9	2	1.7
22–27	14	277 (11)	520 (26)	493 (24)	0.9	1.4	540 (32)	515 (32)	500 (34)	4.2	1	0.5
28–34	15	318 (28)	514 (21)	489 (20)	1.4	0.7	523 (31)	511 (31)	490 (33)	3.3	1	0.8
35–42	15	313 (21)	500 (15)	475 (15)	1.1	1	515 (25)	487 (23)	474 (24)	2.4	0.8	1.4
43–48	13	318 (20)	565 (22)	535 (17)	0.9	1.2	550 (24)	523 (24)	508 (25)	2.6	1.2	0.5
49–53	12	313 (17)	557 (30)	531 (26)	1.2	1.4	590 (20)	556 (22)	544 (24)	1.9	2.1	1.7
54–58	13	324 (18)	560 (18)	532 (16)	0.8	0.4	567 (22)	526 (21)	530 (24)	2.1	1.9	1.3
59–63	14	368 (31)	636 (33)	600 (32)	0.3	0.7	625 (35)	603 (30)	581 (33)	1.8	0.8	0.5
64–67	14	348 (21)	614 (38)	577 (34)	0.9	1	658 (31)	635 (33)	608 (29)	3.2	1	2.4
68–71	12	380 (28)	648 (24)	614 (22)	1.4	1.4	665 (36)	641 (39)	612 (33)	2.7	1.8	0.9
72–76	13	371 (25)	673 (23)	641 (23)	1.5	0.6	647 (21)	599 (22)	578 (19)	2.1	1.8	1.6
77–80	15	383 (21)	686 (26)	652 (24)	2.3	1.5	705 (39)	675 (41)	643 (43)	2.7	1.2	1.8
81–88	20	411 (25)	668 (18)	640 (17)	2.4	1.8	680 (26)	667 (26)	616 (22)	9.9	6.8	7.4

Note. Orienting task: mean RTs and mean percentage correct for invalid and valid trials; mean percentage correct for invalid and valid trials. Conflict task: mean RTs and mean percentage correct for incompatible, neutral, and compatible trials. SRT = mean simple RTs; SEM = standard error of the mean; p(c) = mean percentage correct; Incomp. = incompatible; Comp. = compatible.

Educational level and employment status were two additional demographic variables for which information was also available for our sample. Children and teenagers of our sample all attended schools appropriate for their ages. As for adult participants, we compared years of education between two age groups that covered, respectively, young and middle adulthood (22 to 59 years old) and older adulthood (60 to 88 years old). The same age grouping was also used for further correlational analysis that is reported in a later section. Of the participants in young and middle adulthood, 9.5% received 9 years of school education, 31.8% received 10 years, 32.9% received up to 13 years, and 24.7% attended a university. For participants in older adulthood, 19.3% received 9 years of school education, 24.1% received 10 years, 36.1% received up to 13 years, and 19.3% attended a university. Concerning employment status, 69.4% of the participants in young and middle adulthood were working at a regular job. As expected, only 7.2% of the older adults still held a job.

Apparatus, Stimuli, and Procedure

Custom-made programs running under DOS on standard PCs controlled the attentional tasks. In these tasks, participants responded by touching one of two touch-sensitive metal plates with the index finger of the left or right hand.

Orienting task. To measure the participants' ability to shift visual attention, we ran a typical Posner-type orienting task with valid and invalid peripheral cues (Posner, 1980). Each trial began with the presentation of a gray fixation cross and two thin (1 pixel) gray frames on a black background. The two frames of about 1.5 × 1.5 cm each were visible during the whole trial, about 1.5 cm above and below the central fixation cross (center to center). After a blank interval of 800 ms, one of the rectangles was "flashed" (i.e., presented in bright white color) for 100 ms. After another 100 ms, the target (either a vertical or a tilted bar) was presented in one of the frames. In 50% of all trials the target appeared in the cued frame (validly cued trials), and in the other 50% it appeared in the uncued frame (invalidly cued trials). Participants were instructed to respond as fast as possible to the identity of a target stimulus by pressing one of two keys on the response pad. Before the test session, two practice blocks of eight trials each (2 stimuli × 2 stimulus locations × 2 cue locations, randomly ordered) were administered. The test session comprised seven blocks of 24 trials each (three repetitions of each of the eight possible conditions), amounting to a total of 168 test trials.

Conflict task. A color version of the Eriksen-type flanker task (B. A. Eriksen & Eriksen, 1974) was used to tap conflict resolution, with two stimulus–response alternatives and a neutral condition. After an intertrial interval of 1,200 ms, each trial began with the presentation of a central gray fixation cross for 500 ms. After another blank interval of 500 ms, the stimulus appeared: a red or green circle about 0.7 cm in diameter. The target circle was surrounded by four flanker circles, 1 cm above and below and to the left and right (center to center). In compatible trials, the four flankers had the same color as the target, whereas in incompatible trials they had the color of the alternative target. In neutral trials, their color was blue, a color that was not assigned to any response. Participants were instructed to respond as fast as possible to the color of the central target by pressing one of two keys on the response pad. The test session was preceded by three practice blocks of six trials each (2 stimuli × 3 compatibility conditions, randomly ordered). The test session comprised seven blocks of 18 trials each (three repetitions of each of the six possible conditions), amounting to a total of 126 test trials.

General processing speed. In addition to the attentional tasks, the participants' general information processing speed was measured. We did so by assessing participants' performance in a simple reaction time task. Participants were asked to respond as fast as possible by pressing the key of a response device as soon as any stimulus (either a square or a circle) appeared on the center of the screen. The simple RT task comprised 30 trials, half performed with the left and half with the right index finger. A trial began after an intertrial interval of 1,000 ms, with the presentation of a central fixation cross for 500 ms. The fixation cross was then followed by a random delay interval from 500 to 3,499 ms, after which a stimulus was presented for 1,500 ms on the screen. Responses were valid only if made during the stimulus duration. Viewing distance was about 80 cm.

Data Aggregation

Orienting task. Individual orientating-effect scores were computed for RTs and errors by subtracting median RTs and mean percentage correct [p(c)] for valid-cuing trials from the measures obtained for invalid-cuing trials. Group means were computed for each of the 18 age segments. Moreover, overall performance levels were computed by averaging RTs and error rates across validity conditions.

Conflict task. Individual conflict–effect RT and p(c) scores were computed by subtracting median RTs and mean percentage correct for compatible trials from the measures from incompatible trials. Overall performance levels were computed by averaging RTs and error rates across compatibility conditions. Moreover, facilitation (compatible vs. neutral) and interference (incompatible vs. neutral) was assessed by subtracting median RTs for compatible and incompatible trials, respectively, from those for neutral trials.

We calculated overall performance levels in the orienting and the conflict task because, as outlined in detail below, we intended to investigate the correlation not only between the conflict and the orienting effect but also between the general performance levels in these two tasks.

Processing speed. For each participant, we computed median reaction times from the simple reaction task.

Data Analysis: Reliabilities of the Conflict and Orienting Measures

We computed Cronbach's alpha on the basis of RTs for compatible and incompatible trials (flanker task). Furthermore, reliability of the cost score was computed on the basis of individual difference scores between compatible and incompatible trials. The reliabilities of the compatible and incompatible trials were very high (.96 for compatible trials and .97 for incompatible trials). As expected, the reliability of the difference score involving individual differences in RTs between the two conditions was lower: .44. Similarly, we computed Cronbach's alpha for valid and invalid trials, as well as for difference scores between valid and invalid trials (Cuing task). The reliability of RTs assessed in trials with valid and nonvalid cues was very high (.98 for valid trials and .98 for invalid trials). The reliability of the difference score was lower: .40. In summary, RTs assessed by both tasks were found to have high reliabilities within each of the two tasks. The cost scores computed on the basis of RT differences between conditions, however, were only moderately reliable for both the conflict and orienting measures. The lower reliability of the measures based on difference scores is to be expected (cf. Rogosa & Willett, 1983).

Results

Overall Performance Level

Overall RTs and overall p(c) underwent an analysis of variance (ANOVA) with task (orienting task vs. conflict task) as within-participants factors and age group (18 age groups) as a between-participants factor. The ANOVA on the RT data yielded a significant main effect of age group, $F(17, 245) = 17.71$, $p < .001$, and a significant interaction of Age Group × Task, $F(17, 245) = 1.82$, $p < .05$.

Figure 1 shows mean overall median RTs as a function of age group separately for the orienting and the conflict task. The figure shows for both tasks a U-shaped pattern of rise and fall: Performance in both tasks is substantially slower at the extremes of the life span than during the years of peak performance, between 22 and 42 years of age. To test further whether the age gradients of the overall RT level are different in the two tasks, we fitted a combined exponential growth-and-decline function (cf. Cerella & Hale, 1994; Li et al., 2004) to the *z*-transformed data of both tasks: $y = a \times \exp(-b \times x) + c \times \exp[d \times (x - 1)] + 1$. The parameters a and b capture the initial performance level and constant rate of change of the growth function, whereas c and d reflect the initial performance level and the constant rate of change of the decline function. The fitted functions are presented in Figure 2.

The figure shows that the fitted curves are very similar for both tasks. The rate parameters at both ends of the life span are almost equal. The similarity of the functions is also reflected in the fact that forcing the best fitting function for one task on the data of the other task does not result in a strong reduction of variance accounted for by the estimated curve compared to the best fitting function. For the orienting task, the coefficient of determination drops from .96 to .95; for the conflict task it drops from .92 to .91. It seems, therefore, that the overall RT level of the orienting and the conflict tasks follows the same age gradient. The analysis of the error data revealed a similar pattern of results (see Table 1). The ANOVA yielded a significant main effect of age group, $F(17, 245) = 7.97$, $p < .001$.

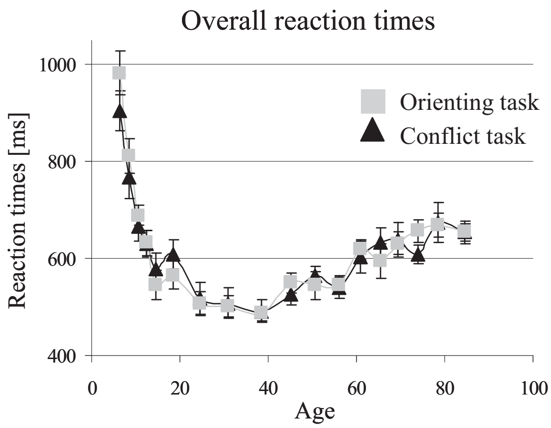

Figure 1. Mean overall reaction time performance in the orienting and the conflict task by age group. Error bars indicate the standard error of the mean.

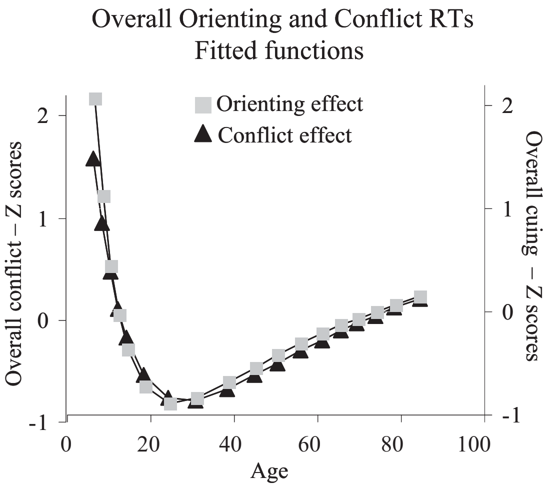

Figure 2. Combined exponential growth-and-decline function fitted to the *z*-transformed overall reaction time data of the orienting and the conflict task. The functions are aligned at peak performance. Orienting effect: $y = 10.604 \times \exp(-0.154 \times x) + (-8.41) \times [\exp(-0.015 \times x - 1)] + 1$; $r = .96$. Conflict effect: $y = 7.558 \times \exp(-0.108 \times x) + (-9.585) \times [\exp(-0.017 \times x - 1)] + 1$; $r^2 = .92$.

Conflict and Orienting Effects

RT and p(c) effects underwent ANOVA with task as a within-participants factor and age group as a between-participants factor. The ANOVA on the RT data yielded significant main effects of task, $F(1, 245) = 53.90$, $p < .001$, and age group, $F(17, 245) = 4.20$, $p < .001$, and a significant interaction of Age Group × Task, $F(17, 245) = 1.78$, $p < .05$.

Figure 3 shows averaged orienting and conflict resolution effects based on median RT difference scores as a function of Age Group. The figure shows that, in strong contrast to overall RTs, the age gradients of the orienting effect and the conflict resolution effect differ enormously. Both orienting and conflict resolution performance improve during the early years of the life span, but they do so with different gradients. The cross-section age gradient of the orienting cost drops rather quickly, with children as young as 10 to 11 years old showing adult-like performance. A contrast comparing the performance of the 6–7 and 8–9 age groups with the group showing peak performance (defined as the 35–42 age group, which showed shortest overall RTs) was highly significant (6–7 and 8–9 vs. 35–42: $p < .005$, two-tailed). However, already the 10–11 age group did not differ significantly from adults (10–11 vs. 35–42: $p > .25$, two-tailed).

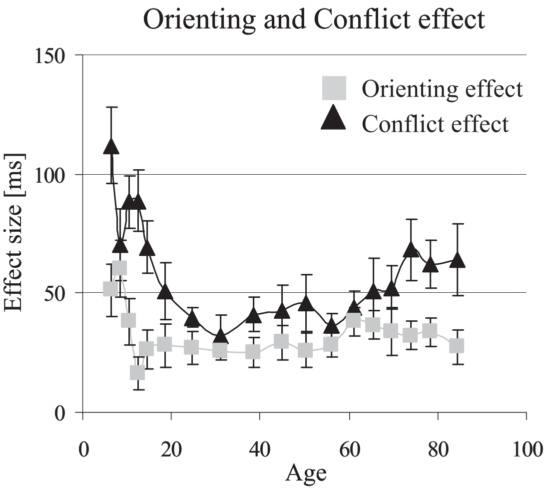

Figure 3. Mean orienting and conflict effect (reaction time) by age group. Error bars indicate the standard error of the mean.

Conflict resolution, in contrast, exhibits a rather protracted development during childhood: even by 14–15 years of age, adolescents do not show adult-like performance. A contrast comparing the performance of the 6–7, 8–9, 10–11, 12–13, and 14–15 age groups with the peak performance group (35–42) was highly significant (6–7, . . . , 14–15 vs. 35–42: $p < .001$, two-tailed). Moreover, even the comparison between the 14–15 age group alone and the 35–42 age group reached significance (14–15 vs. 35–42: $p < .05$, two-tailed), showing that even by 14–15 years of age, adolescents do not show adult-like performance. Paired sample *t* tests comparing the conflict and the orienting effects in early life show the conflict cost to be larger in almost all age groups between 6 and 15 (all ps $< .02$), except for the 8- to 9-year-olds ($> .2$). Taken together, the results demonstrate that the age gradients of the two tasks are different for the younger age groups.

As concerns performance in later life, attentional orienting seems to be pretty much spared from the typical decline in performance. Accordingly, the orienting task does not show a pronounced U-shaped form. Even by 81–88 years of age, validity effects are not larger than throughout adulthood. A contrast comparing the performance of groups between 64 and 88 years of age with the group showing peak performance (64–67, 68–71, 72–76, 77–80, and 81–88 vs. 35–42) failed to reach significance ($p < .25$). In contrast to the orienting task, the conflict effect increases after the age of 67, resulting in the U-shaped form of rise and fall. The same contrast run on the orienting effect reached significance ($p < .05$). Paired sample *t* tests comparing the conflict and the orienting effects in later life show that the conflict cost is larger in all age groups from 72 years on (all ps $< .03$). Taken together, the results demonstrate that the age gradients of the two tasks are different for the older age samples.

The task by age group interaction, as well as the results of the planned comparisons, was further followed up by analyzing the rate parameters of the growth and decline age gradients of the two attentional mechanisms. Figure 4 shows the fitted combined exponential growth-and-decline function to the *z*-transformed orienting and conflict resolution effects. The figure shows that, contrary to the overall RTs shown in Figure 2, the fitted curves of the orienting and conflict effects show different rate parameters and shapes. The rate parameter for the growth part of the age gradient is much lager for the orienting (.225) than for the conflict effect (.046), indicating that the reduction of cost as a function of age is smaller and slower in the conflict task. For the age gradients in later life, the opposite is true. The decline parameter of the cuing task is very small ($-.004$) compared with the decline parameter of the conflict task ($-.021$). As a consequence, forcing the best fitting function for one task on the data of the other task resulted in a strong reduction of variance accounted for by the estimated curve compared to the best fitting function. For the orienting task, the coefficient of determination drops from .63 to .42; for the conflict task, it drops from .85 to .61. This demonstrates that the orienting and the conflict effect follow different age gradients. The analysis of the error data revealed a similar pattern of results (see Table 1), but the ANOVA did not yield any significant effect.

Facilitation and Interference in the Conflict Task

RT data underwent ANOVA with compatibility (compatible vs. incompatible vs. neutral) as a within-participants factor and age group (18 age groups) as a between-participants factor. Both main effects and the interaction were significant: compatibility, $F(2, 490) = 190.12$, $p < .001$; age group, $F(17, 245) = 10.79$, $p < .001$; Compatibility × Age Group, $F(34, 490) = 2.92$, $p < .001$. Figure 5 shows mean RT facilitation and interference scores. The figure indicates substantial facilitation and interference in all age groups but particularly strong effects in early ages.

The combined exponential growth-and-decline function (see above) fitted to the *z*-transformed interference and facilitation data revealed a steeper growth parameter for the flanker interference (.122) than for flanker facilitation (.031). The opposite was the

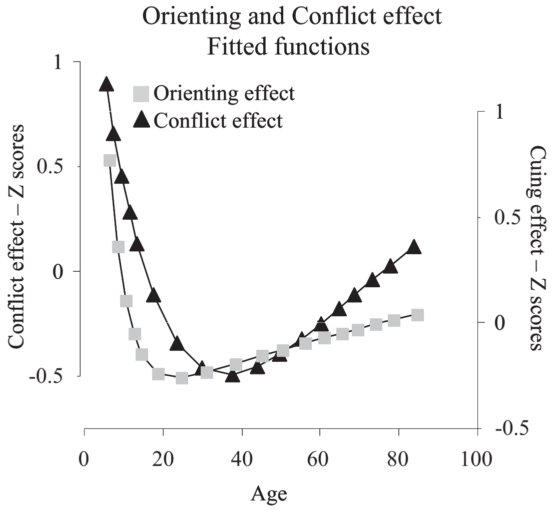

Figure 4. Combined exponential growth-and-decline function fitted to the *z*-transformed reaction time effects of the orienting and the conflict task. The functions are aligned at peak performance. Orienting effect: $y = 5.038 \times \exp(-0.225 \times x) + (-3.912) \times [\exp(-0.004 \times x - 1)] + 1$; $r^2 = .63$. Conflict effect: $y = 6.664 \times \exp(-0.046 \times x) + (-15.642) \times [\exp(-0.021 \times x - 1)] + 1$; $r^2 = .85$.

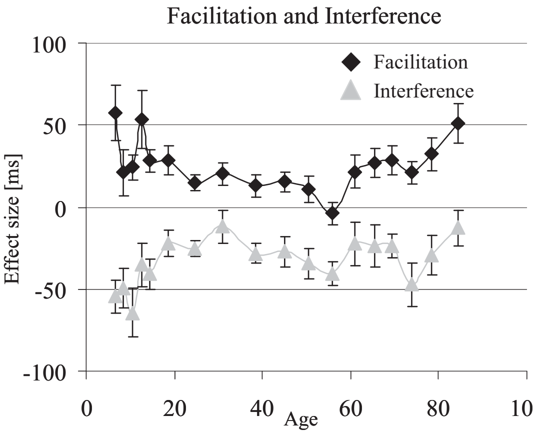

Figure 5. Mean facilitation and interference effects in the conflict task by age group. Error bars indicate the standard error of the mean.

case for the decline parameter (facilitation: .04; interference: –.002). However, given the variability of the facilitation and the interference scores, these data should be interpreted with caution.

The age gradients for orienting and conflict effects suggest that the underlying mechanisms contributing to age-related differences in these two processes may develop differently, with the former improving earlier during childhood than the latter and only the latter declining in later life (see Figures 3 and 4). In contrast, the age functions of the overall RTs show the same U-shape in both tasks (see Figures 1 and 2). These findings suggests that although factors affecting age differences in the processing speed of these two tasks may be interdependent, factors affecting life span age differences in orienting and conflict resolution are likely to be specific. Furthermore, factors affecting life span age differences in the efficiency of the two attentional systems may not be tightly linked to the development of processing speed in general. To explore these interpretations further, we analyzed intertask correlations.

Correlations

First, we computed Pearson correlation coefficients between orienting and conflict effects. If orienting and conflict resolution systems are independent, these correlations should be low (see Figure 6D). Second, we computed Pearson correlations between overall RTs in the orienting task and overall RTs in the conflict task (see Figure 6A). If the similarity of the U-shaped pattern of the general speed level (see Figures 1 and 2) is due to both tasks depending on the same underlying factor(s), overall RTs of the two attentional tasks should highly correlate. Figures 6A and 6D show that both our expectations were met: Whereas overall RTs correlated highly ($r = .833$, $p < .001$), orienting and conflict effects did not ($r = –.015$, $p > .5$). It should be kept in mind that the low correlation between orienting and conflict effects may in part be due to the moderate reliabilities of these measures. However, correction coefficient after correcting for reliability attenuation is still close to 0.0 (−.035), indicating that orienting and conflict effects are not systematically related.

Moreover, we computed correlations between the participants' general information processing speed as assessed by simple RTs, on the one hand, and overall performance and RT effects for the two attentional tasks, on the other. To the extent that individual differences in speed of processing account for differences in the efficiency of the two attentional systems and in the overall RT level of the two tasks, simple RTs should correlate with orienting and conflict effects as well as the overall RTs of these tasks. Figures 6E and 6F indicate that both the orienting and the conflict effects correlate only very moderately (but significantly) with processing speed (orienting: $r = .28$, $p < .01$; conflict: $r = .23$, $p < .01$). In contrast, as shown in Figures 6A and 6B, overall RTs of both the orienting and the conflict task highly correlate with processing speed ($r = .68$, $p < .01$, and $r = .66$, $p < .01$, respectively).

We also computed Pearson correlations between overall RTs and orienting and the conflict effects, on the one side, and choice RTs, on the other side. We did so because one can argue that a choice reaction task is closer to the processing basics of the two attention tasks we used. The pattern of results was exactly the same (orienting effect: $r = .28$, $p < .01$; conflict effect: $r = .26$, $p < .01$; overall orienting task RT: $r = .86$, $p < .01$; overall conflict task RT: $r = .78$, $p < .01$).

Finally, we checked whether the pattern of correlations differed between the 6–21, 22–59, and 60–88 age groups. The three groups reflect a compromise between theoretically reasonable age ranges and comparable group sizes. Table 2 shows separately for the three age groups the Pearson correlations between overall performance RT in the orienting task and in the conflict task, as well as between the orienting and the conflict effects. As the table shows, overall performance RTs highly correlate in all age groups, whereas the correlations between orienting and conflict costs are all close to zero. In the same vein, we computed partial correlations between overall performance RTs, orienting effect, and conflict effect, respectively, controlling for the participants' age and age squared. This yielded similar patterns of results. The coefficients are shown in the rightmost column of Table 2.

Discussion

The present study addressed several related questions concerning age differences in attentional orienting and conflict resolution across the life span. The first was whether the cross-sectional age gradients of conflict resolution and covert exogenous orienting would differ, indicating that factors affecting the age differences in these two attentional mechanisms are independent and do not overlap entirely.

In this regard, our data clearly demonstrate that attentional orienting and conflict resolution yield different age gradients during child development as well as during aging. The age gradient of the orienting effect shown in Figures 3 and 4 indicates that the maturation of the mechanisms underlying covert exogenous orienting response is completed by 10–11 years of age. This is in line with studies showing that stimulus-driven covert orienting undergoes relatively minor developmental change in early life (cf., Brodeur & Enns, 1997). Our data also mirror the findings from Goldberg et al. (2001) showing that endogenous covert orienting is already adult-like by 8–10 years of age. This similarity in the development of endogenous and exogenous orienting may be taken to corroborate the view that both these types of attention shift are mediated by the same fronto-parietal neural network

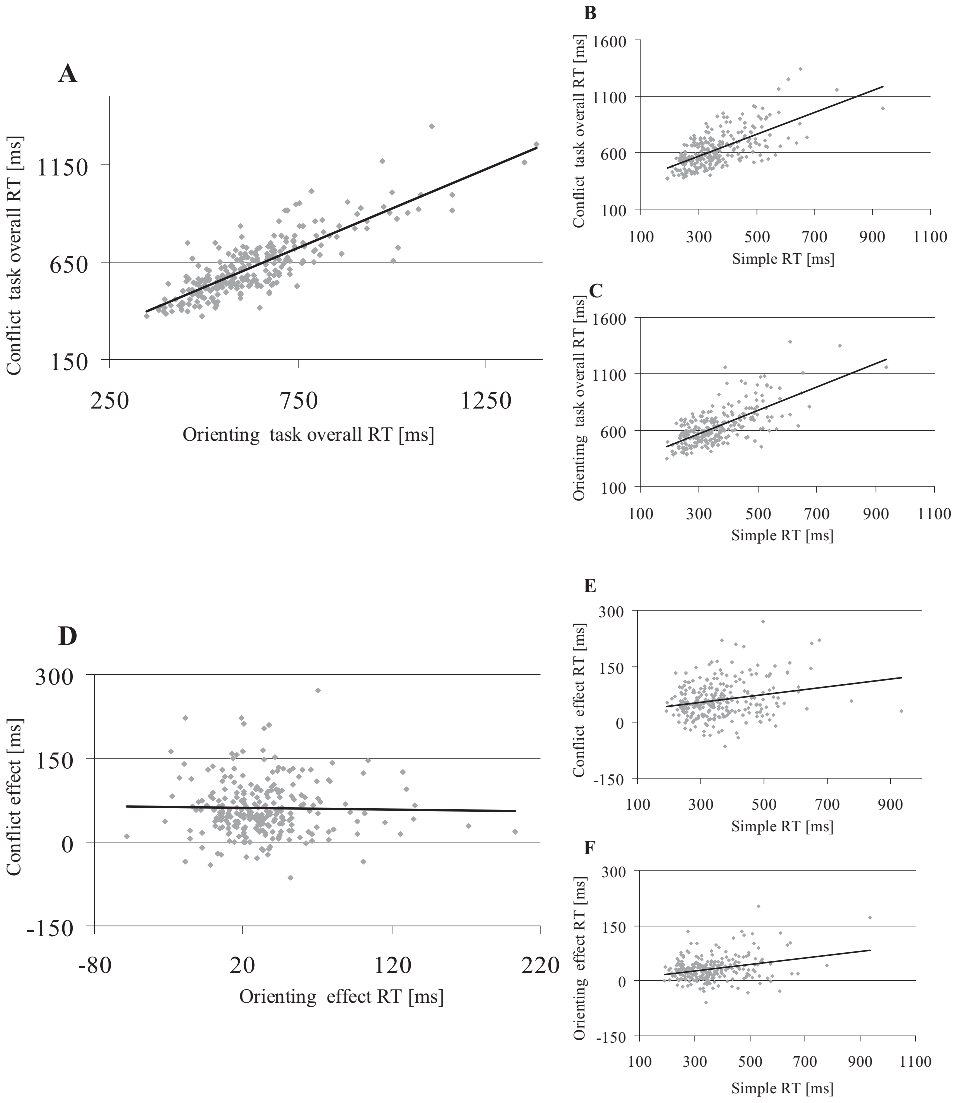

Figure 6. A: Individual overall reaction times (RTs) in the conflict task as a function of overall RT performance in the orienting task; $R^2 = .695$. B–C: Individual overall RTs in the conflict task and in the orienting task as a function of simple RTs; $R^2 = .4325$ and $.4582$, respectively. D: Individual conflict RT effect as a function of orienting RT effect; $R^2 = .0003$. E–F: Individual conflict RT effect and individual orienting RT effect as a function of simple RTs; $R^2 = .0522$ and $.0831$, respectively. Each plot shows linear regression lines.

(Peelen, Heslenfeld, & Theeuwes, 2004). Our results are also in accordance with the fact that the parietal structures that are assumed to mediate orientation effects mature rather fast. Casey, Tottenham, Liston, and Durston (2005) report that synaptogenesis and synaptic pruning in the parietal cortex are finished by about the age of 10.

In strong contrast to the orienting effect, the age gradient of the conflict effect (see Figures 3 and 4) indicates that conflict resolution mechanisms improve much more gradually across the age groups until early adulthood: Even by 15 years of age, adolescents show considerably more interference than adults. Our data thus confirm the protracted development of filtering mechanisms shown by early work on developmental changes in the ability to ignore distracting information (Goldberg et al., 2001) and to withstand Stroop interference (e.g., Comalli et al., 1962).[1] The relatively slow pace of the development of conflict-resolution mechanisms may be due to the protracted neurophysiological maturation of the responsible brain areas. Glucose metabolism in the frontal cortex, which is crucial for ignoring distractor infor-

---

[1] There is evidence that inhibition is not a unitary function. Kramer, Humphrey, Larish, Logan, and Strayer (1994), for example, showed that the decrease in the efficiency of inhibitory processing with aging is not a general phenomenon, but that different subtypes of inhibitory control can show different aging functions. Hence, generalization from one type of task involving conflict resolution–inhibition to another must be done with caution.

Table 2
Pearson Correlations Between Overall RTs in the Conflict Task and in the Orienting Task and Between Conflict RT Effect and Orienting RT Effect

Correlation	Age bin 6–21	Age bin 22–59	Age bin 60–88	Partial correlations controlled for Age	Partial correlations controlled for Age^2
Overall RT conflict task and overall RT orienting task	$.83^{**}$	$.65^{**}$	$.71^{**}$	$.82^{**}$	$.83^{**}$
Conflict effect and orienting effect	−.08	−.117	.02	−.021	−.023

** $p < .01$, two-tailed.

mation (e.g., Duncan, 1986; Godefroy & Rousseaux, 1996), has been demonstrated to show a rather late development (Chugani, 1994). Moreover, Huttenlocher (1979, 1990) has demonstrated that synaptic density of the frontal cortex does not reach adult levels until the age of 15. This nicely fits the finding of the present study that the 16–21 age group was the first to show adult-like performance in the conflict task. Thus, conflict resolution may develop rather slowly because it strongly relies on the slowly developing frontal cortex.

As concerns age differences at the other end of the life span, the relatively flat age gradient of the orienting task across the adult age groups indicates that attentional orienting mechanisms are not subject to much decline during aging. Thus, using a population-based sample spanning all age groups, our data confirm earlier evidence indicating that healthy aging might spare automatic orienting (e.g., Fernandez-Duque & Black, 2006; Festa-Martino, Ott, & Heindel, 2004). However, note that the question is unlikely to be settled once and for all. There is evidence that attentional orienting, despite very similar behavioral performance measures of older and younger participants, undergo age-related changes in later life that are measurable with ERPs: Lorenzo-Lopez et al. (2002) reported age-related changes in P1 amplitude, an electrophysiological marker of covert attention, for longer SOAs. Thus, it may be that developmental changes in later life are too subtle to be observed with behavioral measures. Notice also that our older sample was much more positively selected than the other age groups. This makes our study rather conservative with respect to observing negative age effects in old age.

As concerns effects of aging in the conflict task, our data confirms studies showing that performance in tasks tapping into mechanisms of conflict resolution decreases in later life (e.g.,Li, Hämmerer, Müller, Hommel, & Lindenberger, 2009; Mathalon et al., 2003; Mathewson et al., 2005 Nieuwenhuis et al., 2002; West, 2004; West & Moore, 2005) This is also in accordance with findings from Zeef et al. (1993, 1996), who observed ERP differences between young and old adults that suggest that elderly participants are less able to inhibit incorrect motor activity in response to the incongruent flankers.

Taken together, we conclude that our data show that the ability to deal with conflicting information improves much more slowly during early life than the ability to covertly orient attention and that only mechanisms of conflict resolution show a marked decline in functioning during later life.

As concerns the question of whether the development of orienting and conflict mechanisms are relatively independent, our results show that there are some general similarities but also some differences in childhood and late life performance. As illustrated in Figures 1 and 2, the age functions of the overall reaction times follow the typical U-shaped pattern in both tasks (see Li et al., 2004). The pattern is very similar for both tasks and thus suggests that there common factors might underlie the age differences in the overall performance level of both tasks. This result would be in accordance with the prominent general-resource account of life span development that attributes age-related differences in cognitive capabilities to the development of information processing speed across the life span (e.g., Cerella & Hale, 1994; Kail & Salthouse, 1994). Whereas child development is associated with gains in information-processing speed (e.g., Kail, 1991), cognitive aging is related to the general slowing of information processing (e.g., Salthouse, 1996).

The notion that the overall performance level in both tasks strongly depends on a common speed factor is corroborated by the fact that the levels of performance in the two attentional tasks are highly correlated (see Figure 6A): Individuals that are fast in the orienting task are also fast in the conflict task. This is true for individuals of all phases of life: children and adolescents, young and older adults (see Table 2). In turn, the notion that information processing speed is the common factor behind this high correlation gets support from the fact that overall performance of both the orienting and the conflict task is highly correlated with RTs from a simple reaction task.

However, as discussed before, the life span age gradients of the orienting and the conflict effect shown in Figures 3 and 4 differ at both ends of the life span. For conflict resolution, people show the typical U-shaped function. However, as concerns covert orienting, people do not loose in late life what they gained in early life. Moreover, during childhood, the age gradients of orienting and conflict resolution differ from each other substantially. The difference in pattern of results between the overall performance level (Figures 1 and 2) and the orienting and conflict effects (Figures 3 and 4) suggests that the efficiency of the stimulus-driven attentional orienting response and of attentional filtering mechanisms bears on factors other than the common factor influencing the overall performance level. This notion is further substantiated by the finding that in all phases of life (see Table 2), the orienting and conflict effect are entirely uncorrelated (despite the high correlation in overall RT level) and that they correlate only moderately with simple RTs (Figure 6D–6F).

We would like to point out that the results of the correlation analysis must be interpreted with caution. These findings need to be qualified by the moderate reliability of the conflict and orienting measures. Whereas it is expected that complex executive tasks similar to the tasks used in the present study tend to show low or moderate reliability (e.g., Friedman & Miyake, 2004; Rabbitt, 1997), this may in part also contribute to the lower correlations between them. Furthermore, one caveat of the current cross-sectional study is that if a common factor were to affect both the orienting and conflict monitoring mechanisms but with a time-lagged effect, such lead–lag relations could not be detected in correlations based on cross-sectional data. Future investigations to further scrutinize the unique and shared factors that affect the development of attentional networks will require longitudinal designs.

One factor that has frequently been suspected to be involved in handling conflict is inhibition. Inhibition accounts assume that many cognitive tasks require the efficient inhibition of irrelevant information and unwanted, stimulus-driven response tendencies. Accordingly, improvements in performance in early life are attributed to the strengthening of inhibitory mechanisms (e.g., Dempster, 1992; Diamond, 1990; Harnishfeger, 1995), whereas cognitive aging is assumed to be due to the decline of efficient inhibitory mechanisms (e.g., Dempster, 1992; Hasher & Zacks, 1988). As mentioned above, the development of inhibitory mechanisms may be paced by the slow neurophysiologic maturation of the frontal cortex. Using event-related fMRI, Bunge, Dudukovic, Thomason, Vaidya, and Gabrieli (2002) investigated differences in brain activation between children (8–12 years old) and adults related to interference suppression and response inhibition. Consistent with the findings presented above, children were less able to withhold inappropriate responses than were adults and were more susceptible to interference from the environment. With respect to interference suppression, children recruited different prefrontal brain regions than adults did, which according to Bunge et al. (2002) may suggest a shift in cognitive strategy between childhood and adulthood. Moreover, adults but not children recruited the right ventrolateral prefrontal cortex for the purpose of cognitive control. These findings suggest that the observed behavioral deficits of children compared with adults are associated with an inability to recruit prefrontal cortex regions in a manner similar to healthy young adults. Similarly, the decline in performance in later life could be due to loss in prefrontal suppression functions (e.g., Chao & Knight, 1997).

Even though these performance patterns are consistent with inhibition-based approaches to cognitive development and aging, we would like to emphasize that alternative interpretations are possible. As pointed out by MacLeod, Dodd, Sheard, Wilson, and Bibi (2003), the successful inhibition of distractor-induced behavioral tendencies may be achieved by other means than direct inhibition. Logically speaking, if a distractor activates some action tendency A while the present task goal actually favors tendency B, the resulting competition may be resolved by inhibiting A but just as well by facilitating B. Evidence supporting a conflict-resolution mechanism based on facilitation has been reported recently by Egner and Hirsch (2005). Using event-related fMRI, these authors analyzed the brain processes evoked by the detection of response conflict, which in this study was induced through Stroop-type stimuli. Rather than reducing the activation of irrelevant stimulus representations (which would indicate active inhibition), conflict detection induced a stronger activation of relevant representations. Interestingly, this increase in activation was mediated by signals from the dorsolateral prefrontal cortex, which is held responsible for translating action goals into top-down support for goal-related processes (Desimone & Duncan, 1995; Miller & Cohen, 2001). Applied to the present study, this may mean that efficiency in managing conflict relies on prefrontal systems responsible for the maintenance of action goals, which in turn facilitates target selection, but not on systems devoted to active inhibition. Accordingly, it is possible that the developmental trends we observed in relation to conflict resolution in the flanker task reflect the protracted development during child development and the deterioration during aging of prefrontal systems needed for goal maintenance.

One last aspect of the results deserves to be discussed. Figure 5 shows that compared with neutral trials, participants of all age groups reacted faster in compatible trials and slower in incompatible trials. In incompatible trials, the flanker had a different color that was associated with a competing response. In neutral trials, the flankers also had a different color than the target, but they were not associated to a response. Thus, the detrimental effect of incompatible flankers on target processing compared with neutral flankers must be due to the interference induced by the flankers activating the incompatible (and currently wrong) motor response. The degree of perceptual interference between flankers and target was the same in these two conditions. In compatible trials, the flankers had the same color as the target (and therefore activated the same response). The RT benefit of trials with compatible flankers may thus be caused by the facilitation of stimulus–response translation due to the flankers activating the correct response. However, in principle it could also be due to the lack of perceptual interference between target and flanker.

Our data show age-related changes for both contrasts. They do not exclude the possibility that the susceptibility of children and adolescents to conflicting stimuli has to be attributed in part to inefficient selection at the perceptual end of the processing chain (Enns, 1990). However, they clearly corroborate the notion that the efficiency of the selection at the output end of the processing chain is one source of developmental differences in the ability to resist interference (e.g., Ridderinkhof & van der Molen, 1995).

In summary, using a large population-based sample ranging from 6 to 89 years of age, we showed that the ability to use exogenous cues to shift attention covertly, on the one side, and to ignore distractors, on the other side, have different age functions. Our data suggest that the ability to deal with conflicting information improves much slower during early life than the ability to covertly orient attention. Moreover, only conflict resolution shows a marked decline in functioning during later life. The data also show that factors related to performance in the orienting and the conflict task are influenced by the specific development of the two attentional systems and are independent from factors related to overall performance level.

References

Akhtar, N., & Enns, J. T. (1989). Relations between covert orienting and filtering in the development of visual attention. *Journal of Experimental Child Psychology, 48,* 315–334.

Bornstein, M. H. (1990). Attention in infancy and the prediction of cognitive capacities in childhood. In J. Enns (Ed.), *The development of attention: Research and theory* (pp. 3–19). Amsterdam, the Netherlands: North-Holland.

Botvinick, M., Nystrom, L. E., Fissell, K., Carter, C. S., & Cohen, J. D.

(1999, November 11). Conflict monitoring versus selection-for-action in anterior cingulated cortex. *Nature, 402,* 179–181.

Brodeur, D. A., & Enns, J. T. (1997). Covert visual orienting across the lifespan. *Canadian Journal of Experimental Psychology, 51,* 20–35.

Brodeur, D. A., Trick, L. M., & Enns, J. T. (1997). Selective attention over the lifespan. In J. A. Burack & J. T. Enns (Eds.), *Attention, development, and psychopathology* (pp. 74–94). New York, NY: Guilford Press.

Bryson, S. E., Landry, R., & Wainwright, J. A. (1997). A componential view of executive dysfunction in autism: Review of recent evidence. In J. A. Burack & J. T. Enns (Eds.), *Attention, development, and psychopathology* (pp. 232–259). New York, NY: Guilford Press.

Bunge, S. A., Dudukovic, N. M., Thomason, M. E., Vaidya, C. J., & Gabrieli, J. D. E. (2002). Immature frontal lobe contributions to cognitive control in children: Evidence from fMRI. *Neuron, 33,* 301–311.

Casey, B. J., Tottenham, N., Liston, C., & Durston, S. (2005). Imaging the developing brain: What have we learned about cognitive development? *Trends in Cognitive Sciences, 9,* 104–110.

Cerella, J., & Hale, S. (1994). The rise and fall in information processing rates over the life span. *Acta Psychologica, 86,* 109–197.

Chao, L. L., & Knight, R. T. (1997). Prefrontal deficits in attention and inhibitory control with aging. *Cerebral Cortex, 7,* 63–69.

Chugani, H. T. (1994). Development of regional brain glucose metabolism in relation to behavior and plasticity. In G. Dawson & K. W. Fisher (Eds.), *Human behavior and the developing brain* (pp. 153–175). New York, NY: Guilford Press.

Comalli, P. E., Wapner, S., & Werner, H. (1962). Interference effects of the Stroop color–word test in children, adulthood, and aging. *Journal of Genetic Psychology, 100,* 47–53.

Corbetta, M., Kincade, J. M., Ollinger, J. M., McAvoy, M. P., & Shulman, G. L. (2000). Voluntary orienting is dissociated from target detection in human posterior parietal cortex. *Nature Neuroscience, 3,* 292–297.

Coull, J. T., Frith, C. D., Frackowiak, R. S., & Grasby, P. M. (1996). A frontoparietal network for rapid visual information processing: A PET study of sustained attention and working memory. *Neuropsychologia, 34,* 1085–1095.

Day, M., & Stone, C. A. (1980). Children's use of perceptual set. *Journal of Experimental Child Psychology, 29,* 428–445.

Dempster, F. N. (1992). The rise and fall of the inhibitory mechanism: Toward a unified theory of cognitive development and aging. *Developmental Review, 12,* 45–75.

Desimone, R., & Duncan, J. (1995). Neural mechanisms of selective visual attention. *Annual Review of Neuroscience, 18,* 193–222.

Diamond, A. (1990). The developmental and neural bases of memory functions as indexed by the AB and delayed response tasks in human infants and infant monkeys. *Annals of the New York Academy of Sciences, 608,* 267–317.

Duncan, J. (1986). Disorganization of behavior after frontal lobe damage. *Cognitive Neuropsychology, 3,* 271–290.

Egner, T., & Hirsch, J. (2005). Cognitive control mechanisms resolve conflict through cortical amplification of task-relevant information. *Nature Neuroscience, 8,* 1784–1790.

Enns, J. T. (1990). Relations between components of visual attention. In J. T. Enns (Ed.), *The development of attention: Research and theory* (pp. 139–158). Amsterdam, the Netherlands: Elsevier.

Enns, J. T., & Akhtar, N. (1989). A developmental study of filtering in visual attention. *Child Development, 60,* 1188–1199.

Enns, J. T., & Brodeur, D. A. (1989). A developmental study of covert orienting to peripheral visual cues. *Journal of Experimental Child Psychology, 48,* 171–189.

Enns, J. T., & Cameron, S. (1987). Selective attention in young children: The relations between visual search, filtering, and priming. *Journal of Experimental Child Psychology, 44,* 38–63.

Eriksen, B. A., & Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. *Perception & Psychophysics, 15,* 143–149.

Eriksen, C. W., & Hoffman, J. E. (1973). The extent of processing of noise elements during selective encoding from visual displays. *Perception & Psychophysics, 14,* 155–160.

Fan, J., McCandliss, B. D., Fossella, J., Flombaum, J. I., & Posner, M. I. (2005). The activation of attentional networks. *NeuroImage, 26,* 471–479.

Fan, J., McCandliss, B. D., Sommer, T., Raz, A., & Posner, M. I. (2002). Testing the efficiency and independence of attentional networks. *Journal of Cognitive Neuroscience, 14,* 340–347.

Fernandez-Duque, D., & Black, S. E. (2006). Attentional networks in normal aging and Alzheimer's disease. *Neuropsychology, 20,* 133–143.

Festa-Martino, E., Ott, B. R., & Heindel, W. C. (2004). Interactions between phasic alerting and spatial orienting: Effects of normal aging and Alzheimer's disease. *Neuropsychology, 18,* 258–268.

Friedman, N. P., & Miyake, A. (2004). The Relations among inhibition and interference control functions: A latent-variable analysis. *Journal of Experimental Psychology: General, 133,* 101–135.

Godefroy, O., & Rousseaux, M. (1996). Divided and focused attention in patients with lesion of prefrontal cortex. *Brain and Cognition, 30,* 155–174.

Goldberg, M. C., Maurer, D., & Lewis, T. L. (2001). Developmental changes in attention: The effect of endogenous cueing and of distractors. *Developmental Science, 4,* 209–219.

Greenwood, P. M., Parasuraman, R., & Haxby, J. V. (1993). Changes in visuospatial attention over the adult lifespan. *Neuropsychologia, 31,* 471–485.

Guttentag, R. E., & Ornstein, P. A. (1990). Attentional capacity and children's memory use. In J. T. Enns (Ed.), *The development of attention: Research and theory* (pp. 305–320). Amsterdam, the Netherlands: Elsevier.

Harnishfeger, K. K. (1995). The development of cognitive inhibition: Theories, definitions, and research evidence. In F. N. Dempster (Ed.), *Interference and inhibition in cognition* (pp. 175–204). London, England: Academic Press.

Hartley, A. A., Kieley, J. M., & Slabach, E. H. (1990). Age differences and similarities in the effects of cues and prompts. *Journal of Experimental Psychology: Human Perception and Performance, 16,* 523–537.

Hasher, L., & Zacks, R. T. (1988). Working memory, comprehension, and aging: A review and a new view. *The Psychology of Learning and Motivation, 22,* 193–225.

Huttenlocher, P. R. (1979). Synaptic density in human frontal cortex: Developmental changes and effects of aging. *Brain Research, 163,* 195–205.

Huttenlocher, P. R. (1990). Morphometric study of human cerebral cortex development. *Neuropsychologia, 28,* 517–527.

Kail, R. (1991). Developmental change in speed of processing during childhood and adolescence. *Psychological Bulletin, 109,* 490–501.

Kail, R., & Salthouse, T. A. (1994). Processing speed as a mental capacity. *Acta Psychologica, 86,* 199–225.

Kastner, S., Pinsk, M. A., De Weerd, P., Desimone, R., & Ungerleider, L. G. (1999). Increased activity in human visual cortex during directed attention in the absence of visual stimulation. *Neuron, 22,* 751–761.

Klein, R. M. (1988, August 4). Inhibitory tagging system facilitates visual search. *Nature, 334,* 430–431.

Kraemer, H. C., Yesavage, Y. A., Taylor, J. L., & Kupfer, D. (2000). How can we learn about developmental processes from cross-sectional studies, or can we? *American Journal of Psychiatry, 157,* 163–171.

Kramer, A. F., Humphrey, D. G., Larish, J. F., Logan, G. D., & Strayer, D. L. (1994). Aging and inhibition: Beyond a unitary view of inhibitory processing in attention. *Psychology and Aging, 9,* 491–512.

Li, S.-C., Hämmerer, D., Müller, V., Hommel, B., & Lindenberger, U. (2009). Lifespan development of stimulus–response conflict cost: Similarities and differences between maturation and senescence. *Psychological Research, 73,* 777–785.

Li, S.-C., Lindenberger, U., Hommel, B., Aschersleben, G., Prinz, W., & Baltes, P. B. (2004). Transformations in the couplings among intellectual abilities and constituent cognitive processes across the life span. *Psychological Science, 15,* 155–163.

Lorenzo-Lopez, L., Doallo, S., Vizoso, C., Amenedo, E., Holguin, S. R., & Cadaveira, F. (2002). Covert orienting of visuospatial attention in the early stages of aging. *NeuroReport, 13,* 1459–1462.

MacDonald, A. W., Cohen, J. D., Stenger, V. A., & Carter, C. S. (2000, June 9). Dissociating the role of the dorsolateral prefrontal and anterior cingulated cortex in cognitive control. *Science, 288,* 1835–1838.

MacLeod, C. M. (1991). Half a century of research on the Stroop effect: An integrative review. *Psychological Bulletin, 109,* 163–203.

MacLeod, C. M., Dodd, M. D., Sheard, E. D., Wilson, D. E., & Bibi, U. (2003). In opposition to inhibition. *The Psychology of Learning and Motivation, 43,* 163–214.

Mathalon, D. H., Bennett, A., Askari, N., Gray, E. M., Rosenbloom, M. J., & Ford, J. M. (2003). Response-monitoring dysfunction in aging and Alzheimer's disease: An event-related potential study. *Neurobiology of Aging, 24,* 675–685.

Mathewson, K. J., Dywan, J., & Segalowitz, S. J. (2005). Brain bases of error-related ERPs as influenced by age and task. *Biological Psychology, 70,* 88–104.

Maylor, E. A., & Hockey, R. (1985). Inhibitory component of externally controlled covert orienting in visual space. *Journal of Experimental Psychology: Human Perception and Performance, 11,* 777–787.

McGaughy, J., & Eichenbaum, H. (2002). It's time to pay attention to attention in aging. *Learning and Memory, 9,* 51–152.

Miller, J. O. (1991). The flanker compatibility effect as a function of visual angle, attentional focus, visual transients, and perceptual load: A search for boundary conditions. *Perception & Psychophysics, 49,* 270–288.

Miller, E. K., & Cohen, J. D. (2001). An integrative theory of prefrontal cortex function. *Annual Review of Neuroscience, 24,* 167–202.

Nieuwenhuis, S., Ridderinkhof, K. R., Talsma, D., Coles, M. G. H., Holroyd, C. B., Kok, A., & van der molen, M. W. (2002). A computational account of altered error processing in older age: Dopamine and error-related processing. *Cognitive, Affective, & Behavioral Neuroscience, 2,* 19–36.

Peelen, M. V., Heslenfeld, D. J., & Theeuwes, J. (2004). Endogenous and exogenous attention shifts are mediated by the same large-scale neural network. *NeuroImage, 22,* 822–830.

Plude, D. J., Enns, J. T., & Brodeur, D. A. (1994). The development of selective attention: A lifespan overview. *Acta Psychologica, 86,* 227–272.

Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology, 32,* 3–25.

Posner, M. I., & Cohen, Y. (1984). Components of visual orienting. In H. Bouma & D. G. Bouwhuis (Eds.), *Attention and performance: Vol. X* (pp. 531–556). Hillsdale, NJ: Erlbaum.

Posner, M. I., & Petersen, S. E. (1990). The attention system of the human brain. *Annual Review of Neuroscience, 13,* 25–42.

Rabbitt, P. (1997). Introduction: Methodologies and models in the study of executive function. In P. Rabbitt (Ed.), *Methodology of frontal and executive function* (pp. 1–38). Hove, England: Psychology Press.

Ridderinkhof, K. R., & van der Molen, M. W. (1995). A psychophysiological analysis of developmental differences in the ability to resist interference. *Child Development, 66,* 1040–1056.

Ridderinkhof, K. R., van der Molen, M. W., Band, G. P. H., & Bashore, T. R. (1997). Sources of interference from irrelevant information: A developmental study. *Journal of Experimental Child Psychology, 65,* 315–341.

Rogosa, D. R., & Willett, J. B. (1983). Demonstrating the reliability of the difference score in the measurement of change. *Journal of Educational Measurement, 20,* 335–343.

Salthouse, T. A. (1996). The processing-speed theory of adult age differences in cognition. *Psychological Review, 103,* 403–428.

Sliwinski, M., & Buschke, H. (1999). Cross-sectional and longitudinal relationships among age, cognition, and processing speed. *Psychology and Aging, 14,* 18–33.

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology, 18,* 643–662.

Tales, A., Muir, J. L., Bayer, A., & Snowden, R. J. (2002). Spatial shifts in visual attention in normal ageing and dementia of the Alzheimer type. *Neuropsychologia, 40,* 2000–2012.

Townsend, J., Courschene, E., & Egaas, B. (1996). Slowed orienting of covert visual–spatial attention in autism: Specific deficits associated with cerebellar and parietal abnormality. *Development and Psychopathology, 8,* 563–584.

Trick, L., & Enns, J. (1998). Life span changes in attention: The visual search task. *Cognitive Development, 13,* 369–386.

West, R. (2004). The effects of aging on controlled attention and conflict processing in the Stroop task. *Journal of Cognitive Neuroscience, 16,* 103–113.

West, R., & Moore, K. (2005). Adjustments of cognitive control in younger and older adults. *Cortex, 41,* 570–581.

Williams, B., Ponesse, J., Schachar, R., Logan, G. D., & Tannock, R. (1999). Development of inhibitory control across the life span. *Developmental Psychology, 25,* 205–213.

Wright, L. L., & Elias, J. W. (1979). Age differences in the effects of perceptual noise. *Journal of Gerontology, 34,* 704–708.

Zeef, E. J., & Kok, A. (1993). Age-related differences in the timing of stimulus and response processes during visual selective attention: Performance and psychophysiological analyses. *Psychophysiology, 30,* 138–151.

Zeef, E. J., Sonke, C. J., Kok, A., Buiten, M. M., & Kenemans, J. L. (1996). Perceptual factors affecting age-related differences in focused attention: Performance and psychophysiological analyses. *Psychophysiology, 33,* 555–565.

Received August 7, 2007
Revision received June 12, 2009
Accepted October 29, 2009 ■