Development of Attentional Allocation

in the Dual Task Paradigm

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Abstract

Top-down control over attention was investigated on a dual task in 10-year-olds ($N = 15$) and adults ($N = 21$). The tasks were an auditory Digit Span and a simple visual Response Time task. In four conditions, participants performed neither (no-task), one (Digit Span or Response Time only), or both tasks (dual). Dependent variables were Digit Span accuracy, response time, and pupillary dilation to digits as an estimate of mental effort. Children’s behavioral and psychophysiological responses as a function of sequence length and stimulus position were generally similar to those of adults. Slopes of the functions relating pupillary dilation to memory load were linear and increasing in both groups; shallower in dual than in Digit Span only; and shallower in children than adults. Children’s behavioral results on the Digit Span task began to diverge from those of adults as task demands shifted from passive retention to active rehearsal, but the children did not appear to try harder to compensate for a lower level of behavioral performance. Taken together, the findings suggest that although children allocated their attention in a similar manner as adults, their top-down control over attention in accordance with task difficulty was not yet fully mature.

Key Words: cognitive development, divided attention, working memory, resources, dual task, digit span, task-evoked pupillary responses (TEPRs), pupillary dilation
Introduction

Top-down control over attention refers to attention that is guided by the individual’s intentions, goals, and strategies, rather than by the physical characteristics of stimuli. One of the most common manifestations of control over attention is the ability to divide attention between two tasks, and one of the most common methods of studying divided attention is the dual task paradigm. This paradigm requires participants to allocate attention to two tasks at the same time, usually resulting in impaired behavioral performance on one or both tasks (Meyer & Kieras, 1997; Navon & Miller, 2002). The goal of this study was to use a combination of behavioral and psychophysiological measures to compare attention allocation in a dual task between 10-year-olds and young adults.

Behavioral studies of attention development have long shown that top-down control over attention continues to mature through childhood and adolescence. For instance, in a study on strategies of visual selectivity, Pick and Frankel (1974) found that 12-year-olds were more efficient and flexible than 8-year-olds at adjusting their strategies to task demands. Schiff and Knopf (1985) reached a similar conclusion in a study of dual task performance in 9- and 13-year-olds. The two tasks were a response time (RT) task involving responses to symbols at the center of a computer screen, and a memory task involving letters appearing in peripheral vision. Analyses of eye movements, accuracy and RTs showed that the older children were using more systematic and efficient strategies to divide their attention between the two tasks. The authors concluded that in addition to increases in processing capacity, “the ability to allocate attention in accordance with task demands [also] improves with age” (p. 629).

Manis et al. (1980) studied divided attention in 8-, 12- and 20-year-olds, focusing on age-related differences at different stages of information processing. The main dependent variable
was manual RT on the secondary task (auditory detection) as a function of changes in the
difficulty of the primary task (letter matching). The researchers found greater differences in RT
among age groups toward the later, more resource-demanding stages, and interpreted the
findings to indicate that age-related improvements in performance in the dual task may be
mediated by “improvements in the efficiency of capacity allocation” (p. 157). They suggested
that these improvements may, in turn, be related to increases in automatization and efficiency of
allocation procedures related to the development of meta-cognitive skills.

In a more recent study of 5- and 8-year-olds and adults, Gautier and Droit-Volet (2002)
investigated temporal estimation errors in single versus dual task conditions. The dual condition
had a disproportionate effect on estimation errors in 5-year olds, whereas 8-year-olds and adults
had similar patterns of results. The researchers suggested that age-related differences in the dual
task may be attributable to increases in amount of resources, improvements in efficiency of
resource utilization, or changes in the priorities accorded to the two tasks.

Arguing that age-related differences on dual task paradigms are often confounded with
processing capacity, Irwin-Chase and Burns (2000) attempted to control for capacity by equating
the performance of 8- and 11-year-olds on single tasks before comparing them on a dual task.
Both single tasks required the children to detect visual targets on a screen and to respond with a
button press. The researchers also manipulated priority in the dual condition through instructions
and payoffs. There were no age-related differences in performance when the tasks were given
equal priority. When the tasks had unequal priorities, however, only the 11-year-olds could
allocate attention in accordance with task demands. Noting the similarities between the
performance of the children and the elderly on dual task paradigms, the researchers suggested
that age-related changes in the dual task across the lifespan are not likely to be “due to structural
deficits in the ability to divide attention but in deficits in the management of attention… and the
ability coordinate mental resources” (pp. 80-81).

As is evident from this literature review, a key mechanism invoked to explain normative
development in the dual task is the construct of a limited capacity or reservoir of resources. Most
theorists liken resources to a sort of energy that fuels performance on cognitive tasks, exists in a
limited quantity, and constrains how much we can pay attention to at any time. In the literature
on normal cognitive development, two general hypotheses are that as children grow older, they
have more resources (e.g., Pascual-Leone, 2000) and/or are able to utilize their existing resources
more efficiently (Case, 1991; Swanson, 1999). With more resources or increasing control over
resources, they are able to pay attention to more stimuli, allocate their attention more efficiently
in accordance with task demands, and generally use and benefit from more sophisticated
strategies in complex activities such as the dual task (e.g., Kaye & Ruskin, 1990).

The construct of resources plays a pervasive role in hypotheses regarding mechanisms of
development in neo-Piagetian and information processing approaches to cognitive development.
However, this construct is notoriously difficult to measure (Meyer & Kieras, 1997). In the
current study, a psychophysiological measure (task-evoked pupillary dilation) was used to
provide a more direct estimate of resource recruitment. It should be emphasized that pupillary
dilation is used to estimate momentary recruitment, not total amount, of resources. Thus, the
purpose of the study was not to compare the absolute amount of resources between children and
adults but to investigate recruitment of available resources in accordance with task demands.

The current study follows from a previous study we conducted with young adults to begin
to investigate the behavioral and psychophysiological correlates of attentional control in healthy
and clinical populations of children and adults (Karatekin, Couperus, & Marcus, submitted). In
general, our studies on resource recruitment are based on theories that regard attention not as a static entity but as a skill (Hirst & Kalmar, 1987) and emphasize the top-down, active, and flexible nature of attentional control. The current study was conducted within the framework of Kahneman’s (1973) theory of attention. According to this theory, level of physiological arousal varies with amount of cognitive resources (or mental capacity) that have to be recruited for task-specific purposes. Further, recruitment of resources is equated with exertion of mental effort and the intensive aspects of attention (i.e., how hard we pay attention). In general, the more difficult a task is, the greater the amount of resources that have to be recruited and the greater the amount of arousal (although this relationship breaks down for very easy or very difficult tasks).

Hence, manifestations of physiological arousal, such as pupillary dilation, can provide estimates of mental effort on tasks of attention. Kahneman emphasized that level of arousal varies with both tonic and phasic factors. Although tonic changes in pupillary diameter are influenced by general factors (e.g., emotional arousal, anxiety, and stress), task-evoked changes in pupillary dilation are phasic changes time-locked to the onset of stimuli requiring cognitive processing.

Pupillary diameter is controlled by the combined activity of the sympathetic and parasympathetic branches of the autonomic nervous system, with input from the central nervous system (Beatty, 1986; Loewenfeld, 1993). Phasic changes in pupillary diameter in response to task demands “reflect the cortical modulation of the reticular core” and level of arousal in accordance with task demands (Beatty, 1982, p. 290).

Especially on tasks that fall within a moderate range of difficulty and make demands on working memory, pupillary dilation increases systematically with load across multiple domains of cognitive functioning (Beatty, 1982, 1986; Loewenfeld, 1993; Steinhauer & Hakerem, 1992).
The pupillary dilation measure is particularly sensitive to memory load on the Digit Span (DS), increasing as each digit is presented and reaching a peak just before participants repeat back the digits. Furthermore, pupillary dilation begins to level off or decrease when the number of digits to be remembered exceeds memory span (Granholm et al., 1996; Kahneman & Beatty, 1966; Kahneman, Onuska, & Wolman, 1968; Peavler, 1974).

In the current study, the same task used in our previous study of adults was administered to an independent sample of college students and 10-year-olds. There were two tasks (a simple visual RT and an auditory DS task) and four conditions. In the no-task condition, participants were exposed to the visual and auditory stimuli for both tasks but instructed to look at the center of the screen and not to attend to the stimuli. In the single task conditions (RT only and DS only), they were instructed to perform either the DS or the RT task and to ignore the stimuli for the other task. In the dual task condition, they were instructed to perform both tasks at the same time, giving equal priority to both. The only differences among the conditions were the instructions and the digits that were presented. Thus, optical factors cannot account for differences in pupillary dilation across conditions. In addition, because there is no overlap in the sensory or response modalities between the two tasks, interference effects are likely to reflect resource limitations rather than structural bottlenecks (Arnell & Duncan, 2001; Bourke, 1997). The dependent variables were accuracy and pupillary dilation to the auditory stimuli on the DS task and manual RTs on the RT task.

In the RT only condition in our previous study of adults, the slopes of the functions relating pupillary dilation to auditory stimulus position (i.e., memory load) within trials were flat or decreasing, indicating that participants were not trying to remember the digits. Children were expected to be slower than adults in this condition. However, if they were able to allocate their
attention as instructed, the slopes of their pupillary dilation functions should be flat and not different from those of adults.

In the DS only condition, children were expected to have lower accuracy than adults. In our previous study of adults, pupillary dilation to the auditory stimuli in this condition increased linearly with each digit to be remembered, peaking at the word “go,” replicating other studies. In the current study, the question was whether the children’s pupillary dilation functions would have linear and increasing slopes. If they were allocating their attention in a similar manner as adults to remember the digits (Gathercole, 1999) and recruiting increasingly larger amounts of resources with increasing memory load, their slopes should be increasing and linear. If they were recruiting more resources than adults to remember the digits, the slopes of their pupillary dilation functions should be steeper. If they were recruiting less resources or reaching capacity sooner, their slopes should be shallower.

Finally, performance in the dual task was examined to determine test if the children were able to allocate their attention in accordance with task demands when performing both tasks at the same time. In our previous study of adults, RTs slowed down from the RT only to the dual condition, but DS accuracy showed only a minimal decrease from the single to the dual condition. The current study tested if the children would differ from adults in terms of how they allocated their attention and if they would be disproportionately hurt by the demands of the dual condition compared to adults. In the previous study, pupillary dilation was initially higher in the dual condition but increased more slowly with memory load compared to the DS only condition. In the current study, the children’s pupillary dilation functions were examined to determine if they would show similar patterns of results as their memory capacity was reached.

Method
Participants

The adult participants were students at the University of Minnesota (4 male, 17 female). Their ages ranged from 18 to 27 years ($M = 20$ years, 7 months; $SD = 27$ months). Eighteen were Caucasian, one was Asian, one Caucasian-Hispanic, and one was Native American. They were recruited from undergraduate classes, notices posted on campus, and acquaintances of the research team. Inclusionary criteria (based on self-report) were: no current or past significant neurological or psychiatric disturbance, no history of alcohol or substance abuse, no current use of psychoactive medications, normal or corrected-to-normal vision, English as the native language, no recreational drugs during the week prior to the testing session, and no more than one glass of alcohol during the 24 hours preceding the session. Participants received either monetary compensation or course credit for an introductory psychology course.

The children (7 male, 8 female) were recruited from the Infant Participant Pool, a database maintained by the Institute of Child Development. They were chosen on the basis of age and gender. All had recently turned 10 ($M = 10$ years, 1 month, $SD = 0.5$ months). Fourteen were Caucasian, and one was African-American. Inclusionary criteria (based on parent report during a phone screening interview) were: no current or past significant neurological or psychiatric disturbance, no reading disorder, no use of psychoactive medications, normal or corrected-to-normal vision, and English as the native language. The children received monetary compensation and small prizes at the end of each task to motivate them to remain on task.

Participants were administered several other tasks over two sessions on separate days (results on the other tasks are reported elsewhere). The dual task (i.e., the four conditions described in this paper) was always administered first.

Apparatus
Stimuli were presented using a custom software program that linked the timing of stimulus presentation with a second computer that recorded eye movements. Participants were seated 69 cm in front of a VGA color monitor (39 cm diagonal) on which the stimuli were displayed. The experiment was conducted in a room with normal ambient illumination. The luminance of the screen on which the stimuli were displayed was 140 cd/m².

A custom-built 4-button button box was used, with 1.5 cm square buttons arranged horizontally with 1.5 cm between each pair of buttons. Participants used the index finger of their dominant hand to press the rightmost or the leftmost button. Responses were recorded using custom designed software on the computer that presented the stimuli.

Horizontal and vertical coordinates of the center of the pupil and pupillary diameter were recorded using a video-based eye monitor (ISCAN Eye Tracking Laboratory, Model ETL-400), which has a temporal resolution of 60 Hz and a spatial resolution of 1°. The spatial resolution for measurement of pupillary diameter was 0.037 mm. A camera and an infrared light source used to illuminate the pupil were positioned in front of the computer screen on which the stimuli were presented, below eye level and 40 cm from the participants’ eye. The camera recorded the movements of the participants’ left eye. Because the camera could automatically compensate for small head movements, participants’ heads were not restrained. Behind the participants was a computer controlling the video camera. This computer was used to visually track and record eye position and pupil diameter. A custom software program was written to combine the eye tracking and pupillary data with stimulus presentation and manual response data.

Eye position was calibrated individually for each participant at the beginning of the testing session by having him or her look at small pictures of mosquitoes in the center and 4 corners of the screen, and entering these positions on the computer as the target of the gaze. The
calibration procedure was repeated between conditions as necessary.

Procedure

The procedure was almost identical to the procedure used in our prior study with adults (Karatekin et al., submitted). The only differences were as follows: (a) instead of 5-, 7- and 9-digit sequences, we used 4-, 6- and 8-digit sequences in the current study, (b) the instructions included a story about a troll guarding a rocky piece of land, (c) the visual stimuli were modified from a fixation cross at the center of the computer screen and a football appearing across the screen to a small picture of a troll and a rock, respectively.

DS Task. The DS task was adapted from Granholm et al. (1997). In all conditions, each trial began with the word “ready” presented for 640 ms through a loudspeaker. After the word “ready,” participants heard 4-, 6-, and 8-digit sequences, with each digit presented once every 2 s beginning 3 s after the onset of the word “ready.” The three sequence lengths were presented in random order; the same order was used for all participants in all conditions. Additionally, the digits on each trial were presented in random order, with the constraint that the same digit did not appear twice in the same sequence. The same digits were used for all participants. The word “go” was presented 2 s after the onset of the last digit. In the DS only and dual conditions, this stimulus cued participants to repeat back the digits. They were given 1 s to recall each digit in the sequence; however, they were allowed to speak the digits at their own pace. Instructions emphasized that they should try to remember as many digits as they could in the correct order, even if they could not remember the whole string of digits. They then heard the word “stop,” and, 2 s after its onset, the word “rest.” All auditory stimuli were spoken by a male and digitally recorded onto sound files, and each word lasted between 240 and 800 ms. All words were presented at approximately 65-75 dbs.
RT Task. In all conditions, participants were presented with a picture of a small rock (1.5 cm x 1.5 cm) on a white background that appeared randomly for 200 ms in one of the four quadrants of the computer screen. In the RT only and dual conditions, participants were instructed to press a button with the index finger of their dominant hand as soon as they saw the rock. The rock appeared at pseudo-random intervals between the words “ready” and “go,” with the constraint that each rock appeared 750 to 1000 ms before the onset of the following auditory stimulus. There were 84 rocks in each condition, with 5 rocks during 4-digit sequences, 7 rocks during 6-digit sequences, and 9 rocks during 8-digit sequences.

Experimental Conditions. All participants were administered 4 conditions: no-task, DS only, RT only, and dual task. The only differences among the conditions were the instructions and the particular digits that were presented. All other aspects of the procedure and stimuli were identical across conditions. In the no-task condition, participants were instructed to look at the center of the screen and to listen to the digits, but to not try to remember them and to ignore the visual stimuli. In the single-task conditions (RT only and DS only), they performed either the DS or the RT task. They were instructed to ignore the auditory stimuli in the RT only condition and to ignore the visual stimuli in the DS only condition. In the dual-task condition, they performed both tasks at the same time and were instructed to emphasize DS accuracy and speed on the RT task equally. The no-task condition was always presented first. The order of the other three conditions was counterbalanced across participants. A small troll remained on the screen throughout the trials, and participants were asked to keep their eyes on the troll throughout the conditions. There was 1 practice trial and 12 experimental trials in each condition: 3 (sequence length) x 4 (replications). The time to complete all four conditions was approximately 30 min.

Dependent Variables
Accuracy on the DS Task. Accuracy on the DS task was measured using a scheme adapted in part from Peavler (1974), whereby 2 points were awarded for each correct digit recalled in the correct location in the sequence, 1 point was awarded for each correct digit recalled that was not in the correct location, and 1 point was subtracted for digits that were repeated or were not in the original sequence. The accuracy score was based on percent accuracy for each sequence length in each condition. Verbal responses to the DS task were recorded by an experimenter sitting behind the participant.

Manual RTs to the Visual Stimuli. The data from the eye monitor were merged with the data from the computer that presented the stimuli, and an algorithm was used to analyze the latency of manual responses following stimulus presentation. Manual responses occurring less than 100 ms after the onset of the visual stimuli and manual RTs that were more than 2 standard deviations above the participant’s own condition mean were not analyzed. Because the sampling rate of the eye monitor determined the temporal resolution of the merged data file, RTs were accurate to within 16.7 ms.

Pupillary dilation. To measure pupillary dilation, we first removed artifacts resulting from blinks and saccades from the raw data. Blinks and saccade-related artifacts were defined as (a) the pupil diameter falling below 1.86 mm or above 5.96 mm, or (b) the horizontal or vertical positions of the eye falling outside the limits of the screen, or (c) the diameter of the pupil changing by more than 0.74 mm over 16.7 ms, or (d) velocity of the eye movement between two consecutive records exceeding 80°/s. When blinks were detected, an algorithm used pre- and post-blink values to perform a linear interpolation of the pupillary values throughout the duration of the blink, starting 34 ms before and ending 34 ms after the identified blink. Data were discarded for blinks lasting longer than 500 ms.
Task-evoked pupillary dilation was defined as the magnitude of the adjusted maximum pupillary dilation during the 1500 ms after the onset of the stimulus. To measure pupillary dilation, we subtracted pupillary diameter at each 17-ms interval from the baseline diameter for that stimulus. Baseline for the auditory stimuli was defined as average pupillary diameter during the 100 ms preceding the first digit on that trial. Baseline for the visual stimuli was defined as average pupillary diameter during the 100 ms preceding each stimulus. Instead of using the observed peak value of the resulting pupillary waveform to calculate the magnitude of pupillary dilation, we used a least-squares method to fit a quadratic curve to the data in the neighborhood of the peak value. In fitting this curve, the values at the peak and 67 ms before and after the peak were used. The maximum point of this quadratic curve was used as an adjusted peak. The magnitude of the pupillary dilation was defined as the height of the adjusted peak. Because this value was based on nine data points, this procedure was expected to yield a more stable estimate than the height of the observed peak as measured by one data point. We did not take the average diameter value over a prespecified time after stimulus onset because this method could have confounded the time to reach peak pupillary dilation with the peak itself. The adjusted pupillary dilation data of each participant were visually inspected to remove outliers resulting from gross artifacts that were not corrected by the algorithms (i.e., large and sudden changes in pupil diameter). The adjusted pupillary dilation data, calculated separately for each auditory stimulus in each trial, were then averaged across the four trials for each sequence length in each condition.

Our previous had study suggested that there were condition differences in absolute diameter at the beginning of the trials. Although these differences were ruled out as an explanation for the differences in pupillary dilation (Karatekin et al., submitted), we nevertheless defined all pupillary dilations to the auditory stimuli as proportional increase in pupillary dilation.
in the single and dual conditions compared to the no-task condition. Specifically, we redefined pupillary dilation as the absolute value of the adjusted peak during the 1.5 s after each stimulus divided by the corresponding values in the no-task condition (averaged across the 4 no-task trials for each sequence length). Thus, identical values were used to compare conditions. Because the no-task condition was used to standardize the data, it was excluded from subsequent analyses.

However, this method of analysis could not dissociate the effects of visual and auditory stimuli on pupillary dilation. That is, the data indicated that pupillary dilations to each subsequent visual stimulus increased linearly throughout the trials in the DS only and dual conditions but remained flat in the RT only condition, in parallel fashion to pupillary dilations to the auditory stimuli. Therefore, it appeared that the pupillary dilation to the visual stimuli was being overshadowed by the pupillary dilation to the auditory stimuli. Therefore, pupillary dilations to the visual stimuli were not analyzed further.

Data Analysis

Preliminary analyses were conducted to test for order effects within each group. T tests (p = .01) were used to compare the DS only and dual conditions of participants who were administered the DS only before the dual condition with the data of those who were administered the dual before the DS only condition. Tests on DS accuracy, manual RTs, pupillary dilation in response to the first digit and the word “go” for each sequence length yielded no significant results. Similar analyses were conducted to compare the RT only and dual conditions. Only one comparison reached significance. Therefore, the data were collapsed regardless of administration order. Data were analyzed with mixed- or repeated-measures ANOVAs, and significant findings were followed up with Bonferroni-corrected t tests. Effect size (d) was calculated by dividing the difference in group means by the pooled standard deviation. It should be noted that when the
word “go” is included, there were 5, 7, and 9 auditory stimuli in the 4-, 6- and 8-digit sequences, respectively.

Results

RT Only

As shown in Figure 1, RTs in this condition averaged 268.5 ms in adults (SD = 42.5) and 306.2 ms (SD = 43.8) in children. As expected, a 2 (group) x 3 (sequence length) ANOVA showed that children were slower than adults to respond to the visual stimuli, $F(1, 34) = 9.37, p = .004, d = 0.59$, but that there was no effect of sequence length and no interaction.

Figure 2 displays pupillary dilation as a function of the serial position of the auditory stimuli. Results replicated our previous study; pupillary dilation decreased with each digit that was presented. Slopes of the functions relating pupillary dilation to memory load were based on group averages within each sequence length and condition. As can be seen in Table 1, the slopes of the functions were negative in both children and adults. Group x stimulus position (5, 7 or 9) ANOVAs comparing pupillary dilation of the groups within each sequence length showed no effect of group or interactions between group and stimulus position.

DS Only

As shown in Figure 1, DS accuracy was near the ceiling level for 4-digit sequences but decreased with each increase in sequence length in both groups. As expected, a group x sequence length ANOVA showed that children were less accurate than adults, $F(1, 34) = 32.22, p < .001, d = 1.40$. There was also a group x sequence length interaction, $F(2, 68) = 13.56, p < .001$. Follow-up t tests showed that children were less accurate than adults on the 6- and 8-digit sequences, ($d$s = 1.31 and 1.29, respectively). Although they were also less accurate on the 4-digit sequences, the difference did not reach significance ($p = .051, d = 0.66$). The interaction
was further explicated by comparing the groups on the differences in accuracy between 4- and 6- and between 6- and 8-digit sequences. The drop in accuracy from 4- to 6-digit sequences was greater in children than in adults ($d = 1.26$), but the groups did not differ in the drop in accuracy from 6- to 8-digit sequences ($d = 0.16$).

As shown in Figure 2, adults’ pupillary dilations increased systematically with each digit from the first digit to the word “go,” replicating the results of our previous study. The children’s pupillary dilation functions resembled those of adults but were shallower. Linearity accounted for most of the variance due to memory load in the pupillary dilation functions of both groups (see Table 1). Two (group) x 4-, 6- or 8 (sequence length) ANOVAs showed group x linear trend interactions for 6-digit, $F(1, 34) = 5.15, p = .03$, and 8-digit sequences, $F(1, 33) = 12.82, p = .001$. As can be seen in Table 1, the children’s slopes were shallower than those of the adults for the longer sequences.

A group x sequence length ANOVA on pupillary dilation to the word “go” showed no effect of group, but an effect of sequence length, $F(2, 66) = 5.26, p = .008$, and an interaction, $F(2, 66) = 3.59, p = .033$. Pairwise comparisons between sequence lengths within each group showed that adults’ pupillary dilations to “go” were smaller on 4-digit than on 6- or 8-digit sequences ($d = 0.058$ and 0.59, respectively), but the latter two did not differ from each other, $d = -0.02$. Children’s pupillary dilations were marginally smaller on 4- than on 6-digit sequences ($p = .041, d = 0.24$) and on 8- than on 6-digit sequences ($p = .019, d = 0.45$), but did not differ between 4- and 8-digit sequences, $d = 0.18$. Pairwise comparisons between groups at each sequence length yielded no significant results.

**Dual Task**

Figure 1 displays manual RTs and DS accuracy in the single and dual task conditions. As
expected, participants were slower to respond to the visual stimuli in the dual than in the single task (RT only). Average drop in DS accuracy from the single (DS only) to the dual task was 4% in adults and 1% in children. Thus, as in the previous study, participants appeared to have maintained accuracy on the DS task at the expense of maintaining speed on the RT task.

A 2 (group) x 2 (RT only vs. dual) x 3 (sequence length) ANOVA on RTs yielded an effect of group, $F(1, 34) = 12.79$, $p = .001$, $d = .70$, and a 3-way interaction, $F(2, 68) = 3.12$, $p = .051$. Follow-up condition x sequence length ANOVAs within each group showed that, as predicted, adults’ RTs were longer in the dual than in the RT only condition, $F(1, 20) = 16.31$, $p = .001$, $d = .62$. No other result reached significance. In children as well, RTs were longer in the dual than in the RT only condition, $F(1, 14) = 7.503$, $p = .016$, $d = .79$. In addition, the sequence effect approached significance, $F(2, 28) = 2.99$, $p = .066$, and the interaction was significant, $F(2, 28) = 10.879$, $p < .001$. Pairwise comparisons between RTs at each sequence length yielded no significant results in the RT only condition. In the dual condition, RTs were faster to 4- than to 6- and 8-digit sequences ($p_s = .013$ and .005, and $d_s = 0.18$ and 0.31, respectively). Although RTs were faster to 6- than to 8-digit sequences, the difference did not reach significance ($p = .09$, $d = 0.14$). Pairwise comparisons were also conducted between the RT only and dual conditions at each sequence length. The differences were significant for 6- and 8-digit sequences ($p_s = .017$ and .002, $d_s = 0.79$ and 0.77, respectively), but not for 4-digit sequences ($p = .31$, $d = 0.62$).

Similar analyses on DS accuracy yielded an effect of group, $F(1, 34) = 30.59$, $p < .001$, $d = 1.17$, sequence, $F(2, 68) = 9.04$, $p < .001$, a group x sequence interaction, $F(2, 68) = 13.76$, $p < .001$, and a 3-way interaction approaching significance, $F(2, 68) = 2.67$, $p = .076$. Follow-up condition x sequence length ANOVAs within groups showed that adults’ DS accuracy was lower in the dual than in the DS only condition, $F(1, 20) = 6.37$, $p = .020$, $d = .50$, and that there was
an interaction, $F(2, 40) = 3.43, p = .045$. Pairwise comparisons between conditions at each sequence length showed lower accuracy in the dual than in the DS only condition for 8-digit ($d = .48$), but not for 6- or 4-digit sequences ($ds = .47$ and -.26, respectively). In contrast, there was no effect of condition in children ($p = .580, d = 11$), and no interaction ($p = .458$).

As can be seen in Table 1, linearity accounted for most of the variance in the pupillary dilation functions of the adults. In children, however, the proportion of variance accounted for by linearity decreased from the 4- to the 6- and 8-digit sequences. In general, the functions relating pupillary dilation to the serial position of the auditory stimuli were shallower in dual than in DS only and shallower in children than in adults. These observations were confirmed by analyses of linear trends. Two (group) x 2 (DS only vs. dual) x 5, 7, or 9 (auditory stimulus position) ANOVAs within each sequence length yielded no effects of group. However, analyses of linear trends showed condition x stimulus position interactions for 6-digit, $F(1, 34) = 6.89, p = .013$, and 8-digit sequences, $F(1, 33) = 8.33, p = .007$. There were also group x linear trend interactions for 6-digit, $F(1, 34) = 5.74, p = .022$, and 8-digit sequences, $F(1, 33) = 10.72, p = .002$. A 2 (group) x 2 (DS only vs. dual) x 3 (sequence length) ANOVA on pupillary dilations to the word “go” yielded no significant results.

### Absolute Pupillary Diameter

Figure 3 displays absolute pupillary diameter in children and adults. As can be seen in this figure, the children’s absolute diameters were larger than those of adults. However, both groups show very similar patterns of pupillary dilation as a function of condition and memory load. Statistical analysis on group x stimulus interactions yielded a similar pattern of results to those reported above, although some of the results did not reach significance as there was a great deal of variability in absolute diameters. Thus, the results reported above cannot be attributed to
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the fact the children had smaller diameters at the start of the trials.

Discussion

The goal of the study was to use behavioral and psychophysiological measures to compare allocation of attention in the dual task between 10-year-olds and adults. First, performance on the single task conditions was examined. The RT only condition made no demands on working memory. The demands of this condition were to sustain attention, to press a button as quickly as possible in response to visual stimuli appearing in peripheral vision, and to refrain from attending to the digits. Children were, on average, 40 ms slower than adults. However, their pupillary dilation functions closely resembled those of adults. Thus, both groups appeared to have followed instructions to attend to the visual stimuli. There was no evidence that either group was trying to remember the digits or that the children were less efficient than adults in inhibiting attention to the digits.

The demands of the DS only condition were to ignore the visual stimuli and to learn and recall variable numbers of digits. As expected children’s DS accuracy was lower than that of adults. Accuracy was near ceiling level on 4-digit sequences in both groups, although children were slightly, but not significantly, less accurate. Adults’ accuracy remained high for 6-digit sequences, whereas children’s accuracy dropped. The groups showed equally large drops in accuracy from 6- to 8-digit sequences. Pupillary dilation increased linearly with each digit to be remembered in both groups, consistent with the hypothesis that both groups were recruiting increasingly larger amounts of resources as they tried to learn the digits. However, the rate of increase in pupillary dilation with memory load was smaller in children than in adults for 6- and 8-digit sequences. The shallower slopes in the children indicate that their pupillary dilation increased less in relation to memory load than adults, suggesting that the children allocated fewer
At the point when participants were about to repeat back the digits, adults had higher pupillary dilations for 6- and 8-digit than for 4-digit sequences, whereas children had the highest pupillary dilations on 6-digit sequences. Thus, the children appeared to have recruited fewer resources than adults once the memory load began to approach or exceed their capacity.

In the dual task, which made the greatest demands on top-down control over attention, participants had to divide their attention between two tasks. Both groups were slower to respond to the visual stimuli on the RT task in the single than in the dual condition. RTs were constant across sequence lengths in the RT only condition in both groups. In the dual condition, adults’ RTs did not increase with increasing sequence length, whereas children’s RTs did. Adults’ DS accuracy declined slightly from the single to the dual condition, whereas children’s accuracy did not differ between conditions. The slopes of the pupillary dilation functions were shallower in the dual than in the DS only condition and shallower in children than in adults for 6- and 8-digit sequences.

Thus, the children appear to have processed the stimuli in a similar manner as adults on both the single and dual tasks. On the DS task, their behavioral results began to diverge from those of adults as the task demands began to shift from passive retention to active rehearsal. However, they did not appear to be trying harder than adults to compensate for a lower level of behavioral performance. Taken together, results suggest that although the 10-year-olds allocated their attention between dual tasks and across increasing loads in a similar manner as adults, their ability to recruit sufficient resources at higher loads was not yet fully mature.

These results support previous research on attention development which has attributed age-related changes in performance on divided attention tasks to improvements in top-down
control over attention. The current study extends these findings by using a psychophysiological measure to provide a more direct estimate of resource recruitment rather than relying on behavioral measures alone to interpret age-related differences.

As noted above, task-evoked pupillary dilations are used to estimate momentary recruitment, not total amount, of resources. Therefore, it could be argued that the children had less resources to recruit than adults (e.g., Pascual-Leone, 2000). However, this explanation cannot account for differences in the rate of increase in pupillary dilation as a function of memory load.

Other limitations of the study have been noted in our previous paper. These include the fact that participants were instructed to emphasize performance on the two tasks equally in the dual condition. In future studies using this paradigm, it would be advisable to instruct them to try to maintain the same level of accuracy on the DS task in the dual as in the DS only condition. In addition, task-evoked pupillary dilations peak between 0.5 and 2 s after the stimulus (Beatty, 1982; Steinhauer & Hakerem, 1992), which makes them unsuitable for answering questions about the fine-grained temporal characteristics of attention allocation in the dual task, such as whether participants were rapidly switching attention back and forth between tasks or performing them in parallel. In addition, we were unable to assess pupillary dilations to the stimuli in the secondary task independently of pupillary dilations to the auditory stimuli. Therefore, we had to rely on behavioral data alone to gauge the extent to which performance on the primary task interfered with performance on the secondary task. Another limitation was that only adults and 10-year-olds were included as participants. Further investigations of top-down control of attention will need to include more age groups to study mechanisms of development in detail.

The findings raise several questions regarding the development of attention allocation in
accordance with task demands, including the ability to divide attention, to anticipate and prepare for more difficult tasks, and to match resource recruitment to task difficulty. One set of questions concerns the constraints on the normal development and functioning of these attentional “skills” (Hirst & Kalmar, 1987). An obvious constraint involves data limitations. In the current study, for example, the children may have had a smaller memory capacity than adults, perhaps mediated by a slower rate of information processing or rehearsal (Chuah & Mayberry, 1999; Cowan, 1999; Fry & Hale, 1996; Kail & Park, 1994) or a faster rate of information decay from memory buffers (Baddeley & Hitch, 2000; Henry, 1991). Thus, if the children reached the data-limited portion of the performance-resource function (Norman & Bobrow, 1975) sooner than adults, the marginal utility of additional resource expenditure would not have been very high. Although this explanation can explain the shallower pupillary dilation slopes in children in both the DS only and dual conditions, it would not account for group differences at the beginning of the trials.

Brain development is likely to impose another constraint on top-down control over attention. The differences in the pupillary dilation functions of the children and adults in the current study may be reflecting differences in the maturity of cortical-subcortical networks regulating rapid adjustments in arousal level in cognitively demanding tasks.

Within these constraints, strategic factors and meta-cognitive skills also provide an impetus for attentional development. In the current study, the groups did not appear to be using widely different strategies to perform the tasks. Nevertheless, participants were not interviewed about the strategies they used, and strategy was not held constant across conditions or groups. Thus, questions remain regarding the nature of the strategies used by the participants, and the resource costs of these strategies for children versus adults (Guttentag, 1997). Future studies could address these questions by investigating the emergence, utilization, and automatization of
strategies at different levels of difficulty on the same task, and by comparing differences in the
efficiency and effectiveness of these strategies at different ages (Guttentag & Ornstein, 1990;
Hockey, 1997; Schumacher et al., 1999; Siegler, 1996).

Allocation of attention in accordance with task demands plays a crucial role not only in
normal development but also in aging (e.g., Grossman et al., 2002; Müller & Knight, 2002) and
disorders of attention such as schizophrenia and Attention-Deficit/Hyperactivity Disorder
(Karatekin, 2001). A common finding in all these populations is that the more difficult a task is,
the more likely one is to find group differences between young and old participants and between
healthy and disordered individuals. Although these differences are usually attributed to general
factors such speed of processing or level of intellectual functioning, another hypothesis might be
that group differences on the more difficult tasks stem from differences in top-down control over
attention in accordance with task demands. Therefore, multi-method studies that directly
compare mechanisms of development and impairment in attentional skills across populations
could be helpful in distinguishing among maturational, compensatory and abnormal processes.
Acknowledgements

I am grateful to Christopher Bingham, Ph.D., for providing statistical help with calculations involving pupillary dilation; David Marcus, Nicholas Davenport, and Michelle Siegel for helping with data collection and analysis; and to the students, the children and their families who participated in the study.
References


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Psychol, 35: 986-1000.
### Table 1

Slope (% Increase in Pupillary Dilation/Digit) and Linearity of the Functions Relating Pupillary Dilation to Memory Load in the Single and Dual Task Conditions in Children and Adults

<table>
<thead>
<tr>
<th></th>
<th>4 Digits</th>
<th>6 Digits</th>
<th>8 Digits</th>
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<tr>
<td><strong>Slope</strong></td>
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<tr>
<td><strong>Adults</strong></td>
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<td></td>
</tr>
<tr>
<td>RT Only</td>
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<td>-0.4%</td>
<td>-0.7%</td>
</tr>
<tr>
<td>DS Only</td>
<td>2.1%</td>
<td>2.5%</td>
<td>1.9%</td>
</tr>
<tr>
<td>Dual</td>
<td>1.4%</td>
<td>1.5%</td>
<td>1.0%</td>
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<tr>
<td><strong>Children</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>RT Only</td>
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<td>-0.1%</td>
<td>-0.5%</td>
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<tr>
<td>DS Only</td>
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<td>1.7%</td>
<td>0.9%</td>
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<td>Dual</td>
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<td><strong>Linearity</strong></td>
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<tr>
<td><strong>Adults</strong></td>
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</tr>
<tr>
<td>RT Only</td>
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<td>50%</td>
<td>84%</td>
</tr>
<tr>
<td>DS Only</td>
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<td>90%</td>
<td>97%</td>
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<tr>
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<td><strong>Children</strong></td>
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<tr>
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<td>58%</td>
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</tbody>
</table>
Figure Captions

Figure 1. (a) Manual response times (RTs; ms) and (b) Digit Span (DS) accuracy (% correct) in the single and dual task conditions in children and adults.

Figure 2. Pupillary dilation (% increase over no-task) to the auditory stimuli as a function of condition and sequence length in (a) adults vs. (b) 10-year-olds. DS = Digit Span. RT = Response Time.

Figure 3. Absolute pupillary diameter (mm) to the auditory stimuli as a function of condition and sequence length in adults and children in (a) 4-digit, (b) 6-digit, and (c) 8-digit sequences. a = adults; c = children. DS = Digit Span. RT = Response Time.
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(a) (b)
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(a) 4 digits

(b) 6 digits

(c) 8 digits

Absolute Pupillary Diameter (mm)

- a, no-task
- a, DS
- a, RT
- a, dual
- c, no-task
- c, DS
- c, RT
- c, dual