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Attention allocation in the dual-task paradigm as measured through behavioral and psychophysiological responses

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Abstract

We investigated attention allocation in a dual-task paradigm using behavioral and pupillary measures. We used an auditory digit span (DS) and a simple visual response time (RT) task. Participants were administered four conditions in which they performed neither task (no-task), a single task (DS or RT only), or both tasks (dual). Dependent variables were DS accuracy, RT, and task-evoked pupillary responses (TEPRs) to digits as estimates of mental effort. Participants maintained almost the same level of DS accuracy on dual as on DS only and sacrificed speed on the RT task. As expected, TEPRs increased linearly with memory load in both DS only and dual. Although TEPRs were initially higher in dual than in DS only, the slope of the increase was shallower in dual. Results suggest that TEPRs can elucidate mechanisms of attention allocation by distinguishing between effectiveness (level of behavioral performance) and efficiency (the costs of that performance in mental effort).

Descriptors: Divided attention, Dual task, Working memory, Resources, Mental effort, Task-evoked pupillary responses

We often have to pay attention to several tasks at the same time, such as driving and talking. Understanding how we divide our attention among several tasks simultaneously while still retaining our ability to perform these tasks with reasonable efficiency is an important area of study for both theoretical and practical reasons. One of the most useful methods for studying divided attention is the dual-task paradigm. This paradigm involves performing two tasks concurrently, resulting in impaired behavioral performance on one or both tasks. The goal of the current study was to investigate allocation of attention in the dual-task paradigm from a functional perspective using a combination of psychophysiological and behavioral measures.

There have been two major approaches to the study of interference effects in the dual-task paradigm (for reviews, see Meyer & Kieras, 1997; Navon & Miller, 2002). One approach emphasizes structural and processing bottlenecks, that is, neurobiological substrates or processing stages that cannot be devoted to carrying out two tasks at the same time (Pashler & Johnston, 1998). The second approach emphasizes functional limitations. Researchers taking this perspective often posit a hypothetical and finite entity, defined in terms of "energy," "capacity," or "resources," that constrains how much information we can process at any given time.

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This second approach has led to two lines of investigation. One of these lines has been concerned with characterizing the architecture of resources—that is, the total amount of resources we have and whether they come from a single, undifferentiated pool or from multiple pools. However, these questions still remain unresolved due to the difficulty of operationalizing the construct of resources (Meyer & Kieras, 1997). A second line of research is concerned with *how* resources are allocated as we pay attention. In this line of research, the total amount or architecture of resources is not as important as how we allocate those resources among tasks on a moment-to-moment basis depending on task instructions and our needs and priorities. Rather than viewing attention as a "resource," these researches see attention as a "skill" (Hirst & Kalmar, 1987) and emphasize the top-down, active, and flexible nature of attentional control (e.g., Meyer & Kieras, 1997).

One of the foremost researchers to emphasize the active nature of attentional control was Kahneman (1973). His theory is also still one of the few that proposes a relatively specific neurobiological substrate for the construct of resources. Formulated in reaction to structural theories of attention, Kahneman's theory accounts for performance on attention-demanding tasks by emphasizing functional considerations. Several aspects of this theory are relevant to the current study. First, Kahneman proposed that level of physiological arousal is closely related to amount of resources (i.e., mental capacity). In this theory, recruitment of resources is equated with exertion of mental effort and with how hard we pay attention (i.e., the "intensive" aspects of attention). Second, Kahneman viewed level of physiological arousal in dynamic terms and noted that it is affected by both tonic factors (e.g., fatigue) and phasic factors (e.g., task demands). Third, he listed several factors that determine level of arousal and policy of resource allocation among tasks, including bottom-up factors (e.g., an enduring predisposition to attend to physically salient stimuli) and top-down factors (e.g., evaluation of task demands on resources). In general, the more difficult a task, the more resources required, and the greater the arousal. However, this relationship holds only for tasks in the moderate range of difficulty. If a task is too easy or too difficult (e.g., due to poor sensory input, time constraints, limitations in memory capacity, or inaccessibility of information from long-term memory), level of arousal is not systematically linked to performance. Finally, Kahneman noted that manifestations of physiological arousal, such as momentary increases in pupillary diameter in response to task demands (task-evoked pupillary responses; TEPRs), can provide estimates of mental effort on tasks of attention.

Pupillary diameter is controlled by the combined activity of the sympathetic and parasympathetic branches of the autonomic nervous system in conjunction with input from the central nervous system that reflects dynamic interactions between the frontal lobes and the midbrain (Beatty, 1986; Loewenfeld, 1993). The relation between pupillary diameter and TEPRs has been likened to the relation between spontaneous electroencephalogram records and event-related potentials (ERPs; Beatty, 1982). *Tonic* changes in pupillary diameter are influenced by general factors, such as level of emotional arousal, anxiety, and stress. TEPRs, on the other hand, are *phasic* changes in pupillary diameter time-locked to the onset of stimuli requiring cognitive processing. The magnitude of TEPRs is independent of baseline pupillary diameter over a wide range of values, suggesting that they reflect separable processes (Beatty, 1982). Correlations between TEPR amplitudes and indices of autonomic function (e.g., heart rate, galvanic skin response) are not high, consistent with the hypothesis that neural control of TEPRs lies at the intersection of the autonomic and central nervous systems (Loewenfeld, 1993). Similarly, although TEPRs and ERPs covary, they are not perfectly correlated, suggesting that they reflect different aspects of information processing (Steinhauer & Hakerem, 1992). Thus, TEPRs "likely reflect the cortical modulation of the reticular core" and level of arousal in accordance with task demands (Beatty, 1982, p. 290).

Although the nature of attentional control in Kahneman's theory is underspecified, the empirical connection highlighted in this theory between TEPRs as a measure of physiological arousal and task difficulty has proven to be robust. Especially on tasks that fall within a moderate range of difficulty and involve a working memory component, the amplitude of TEPRs increases systematically with task difficulty across different cognitive domains (Beatty, 1982, 1986; Loewenfeld, 1993; Steinhauer & Hakerem, 1992). TEPRs are particularly sensitive to memory load on the Digit Span (DS) task, increasing as each digit is presented and reaching a peak just before participants repeat back the digits. Furthermore, TEPRs begin to level off or decrease when the number of digits to be remembered exceeds memory span (Granholm, Asarnow, Sarkin, & Dykes, 1996; Kahneman & Beatty, 1966; Kahneman, Onuska, & Wolman, 1968; Peavler, 1974). Although small in magnitude (maximum TEPRs are generally on the order of 0.4–0.5 mm), TEPRs are very reliable; significant effects can be observed in a few trials (Beatty & Lucero-Wagoner, 2000).

Although TEPRs can yield valuable information about resource allocation and elucidate mechanisms of attentional control, there have been relatively few dual task studies of TEPRs. In two related studies, Kahneman and colleagues (cited in Kahneman, 1973, pp. 20–22) presented participants with sets of four digits and instructed them to mentally add one to each digit and repeat the new sequence at the end of the trial. At the same time, participants monitored the occurrence of a target letter in a continuous stream of visually presented letters or held in mind a briefly flashed letter until the end of the digit transformation task. In both studies, participants were instructed to give priority to the digit transformation task. As expected, TEPRs increased with each digit to be remembered on the digit task, peaking just before participants began to repeat back the digits. In addition, the probability of failure on the secondary task paralleled the TEPR curves, increasing with each digit to be remembered and decreasing as participants began to recall the digits. These converging results indicate that "the physiological and behavioral measures are independent indices of the momentary effort invested in the primary task" (Kahneman, 1973, p. 22).

In the current study, we followed up on this investigation by using both behavioral measures and TEPRs to examine allocation of attention to an auditory DS and a visual simple response time (RT) task in the dual-task paradigm. These two tasks was chosen for three reasons. First, because there is no overlap in the sensory or response modalities between the tasks, interference effects should reflect resource limitations rather than structural bottlenecks (Arnell & Duncan, 2002; Bourke, 1997). Second, the only differences among the conditions were the instructions and the digits that were presented. Therefore, optical factors cannot account for TEPR differences across conditions. Third, we intended to follow up this study with studies of clinical populations in whom behavioral performance on the DS and simple RT tasks is relatively preserved. Thus, this combination of tasks should make it easier to rule out group differences in behavioral performance on the single tasks as a factor in impairments in allocation of attention in the dual task (Greene, Hodges, & Baddeley, 1995).

All participants were administered four conditions. In the no-task condition, they were presented with visual and auditory stimuli but instructed to ignore them and to look at the center of the screen throughout the trials. In the single-task conditions (RT only and DS only), they performed either the DS or the RT task. In the dual task condition, they performed both tasks at the same time. The conditions were identical in all respects except for the instructions and the digits that were presented. We predicted that DS accuracy would be lower and RTs longer in the dual- than in the single-task conditions. Based on previous studies using the DS task (Granholm et al., 1996; Kahneman & Beatty, 1966; Kahneman et al., 1968; Peavler, 1974), we expected to find linear increases in TEPRs to the auditory stimuli as a function of memory load on the DS task. We then compared TEPRs to the auditory stimuli between the single- and dual-task conditions.

STUDY 1

Method

Participants

Participants were 24 healthy adults (9 men, 15 women) at the University of Minnesota. They ranged in age from 18 to 30 ($M = 21.04$, $SD = 1.71$) and consisted of 21 Caucasian, 1 African American, 1 Asian-American, and 2 Hispanic-American individuals. Participants were recruited from Psychology and Child Psychology classes, notices posted on campus, and acquaintances of the research team. Inclusionary criteria (based on participant 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 native language, no recreational drug use during the week prior to the testing session, and no more than one glass of alcohol during the 24 h preceding the session. Participants gave informed consent and were advised that they were participating in a study of cognitive processes, such as learning, memory, and attention. Participants received either monetary compensation or credit toward a requirement for an introductory psychology course at the university. One individual was excluded due to excessive blinking during testing.

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/m^2.

A custom-built four-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 either 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° over the range of visual angles used in the present study. 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 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/her look at dots in the center and four 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 due to excessive head movements by the participant.

Procedure

DS task. The DS task was adapted from Granholm, Morris, Sarkin, Asarnow, and Jeste (1997). In all conditions, each trial began with the word "ready" presented for 640 ms through a loudspeaker. After the word "ready," participants heard five-, seven-, and nine-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 stimulus lasted between 240 and 800 ms. All auditory stimuli were presented at approximately 65–75 dbs.

RT task. In all conditions, participants were presented with a picture of a small red-and-black football (1.5 cm × 1 cm) cm) on a white background that appeared randomly for 200 ms in one of the four quadrants of the screen (a football was used as the stimulus in anticipation of a follow-up study of children). 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 football. The football appeared at pseudorandom intervals between the words "ready" and "go" on the DS task, with the constraint that each ball appeared 750 to 1,000 ms before the onset of the following auditory stimulus. There were 96 footballs in each condition, with 6 footballs during 5-digit sequences, 8 footballs during 7-digit sequences, and 10 footballs during 9-digit sequences.

Experimental conditions. All participants were administered four conditions. 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 give equal priority to both tasks. The no-task condition was always presented first. The order of the other three conditions was counterbalanced across participants. A fixation cross remained on the screen throughout the task, and participants were asked to keep their eyes on the cross for the duration of the task. There was 1 practice trial and 12 experimental trials in each condition: 3 (sequence length) × 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 two points were awarded for each correct digit recalled in the correct location in the sequence, one point was awarded for each correct digit recalled that was not in the correct location, and one 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 two 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.

TEPRs. To measure pupillary responses, 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 raising 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 postblink 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.

TEPRs were defined as the magnitude of the adjusted maximum pupillary dilation during the 1,500 ms after the onset of the stimulus. To measure TEPRs, we first subtracted pupillary diameter at each 17-ms interval from the baseline pupillary diameter for that stimulus. Baseline for the auditory stimuli was defined as the average pupil dilation during the 100 ms preceding the first digit on that trial. Baseline for the visual stimuli was defined as the average pupil dilation during the 100 ms preceding each stimulus. Instead of using the observed peak value of the resulting pupillary waveform to calculate the magnitude of the TEPRs, 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 TEPR 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 average TEPR value over a prespecified time after stimulus onset because this method could have confounded time to reach peak TEPR value with the peak itself. The adjusted TEPR 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 TEPR data, calculated separately for every auditory stimulus in each trial, were then averaged across the four trials for each sequence length in each condition.

Results

Data analyses were conducted using repeated-measures ANOVAs, followed by planned contrasts ($p = .05$). Post hoc t tests were conducted at $p = .01$. Effect size (d) was calculated by dividing the difference in group means by the pooled standard deviation. Slopes of the functions relating TEPR to memory load were based on group averages within each sequence length and condition. It should be noted that when the word "go" is included, there were 6, 8, and 10 auditory stimuli in the five-, seven-, and nine-digit sequences, respectively.

Preliminary analyses were conducted to test for order effects. Independent-samples 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, and absolute pupillary diameters at baseline for auditory stimuli yielded no significant results. Similar analyses were conducted to compare the RT-only and dual conditions for participants who were administered RT-only before the dual condition and those who were administered the dual before the RT-only condition. No significant order effects were found. Therefore, the data of all participants were collapsed regardless of administration order.

As can be seen in Figure 1, absolute pupillary diameters at the beginning of the trials were higher in the dual- than in the single-task conditions, potentially complicating the interpretation of condition differences in TEPRs. T tests comparing average pupil dilation 1 s before the first digit in the DS-only and dual conditions were not significant for five and nine digits, but significant for seven digits, $t(23) = 2.38$, $p = .03$. T tests comparing the RT-only and dual conditions were almost significant for seven digits, $t(23) = 1.96$, $p = .06$, and significant for nine digits, $t(23) = 2.18$, $p = .04$. Therefore, to guard against spurious results related to condition differences in absolute diameters, TEPRs to the auditory stimuli were redefined as proportional increase in TEPRs in the DS-only, RT-only, and dual conditions compared to the no-task condition. Specifically, we redefined TEPRs 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 four no-task trials for each sequence length). Thus, identical values were used to compare conditions. The TEPR values of each participant for each sequence length were averaged across the four trials for that sequence length within each condition. 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 versus auditory stimuli on TEPRs. That is, the data indicated that TEPRs to each subsequent visual stimulus increased linearly throughout each trial in the DS-only and dual conditions, but remained flat in the RT-only condition, in parallel fashion to TEPRs to the auditory stimuli. Therefore, it appeared that the TEPRs to the visual stimuli were being overshadowed by the TEPRs to the auditory stimuli. Consequently, TEPRs to the visual stimuli were not analyzed further.

Behavioral Analyses

The first goal of this study was to examine behavioral responses (DS accuracy and manual RTs) as a function of sequence length and condition.

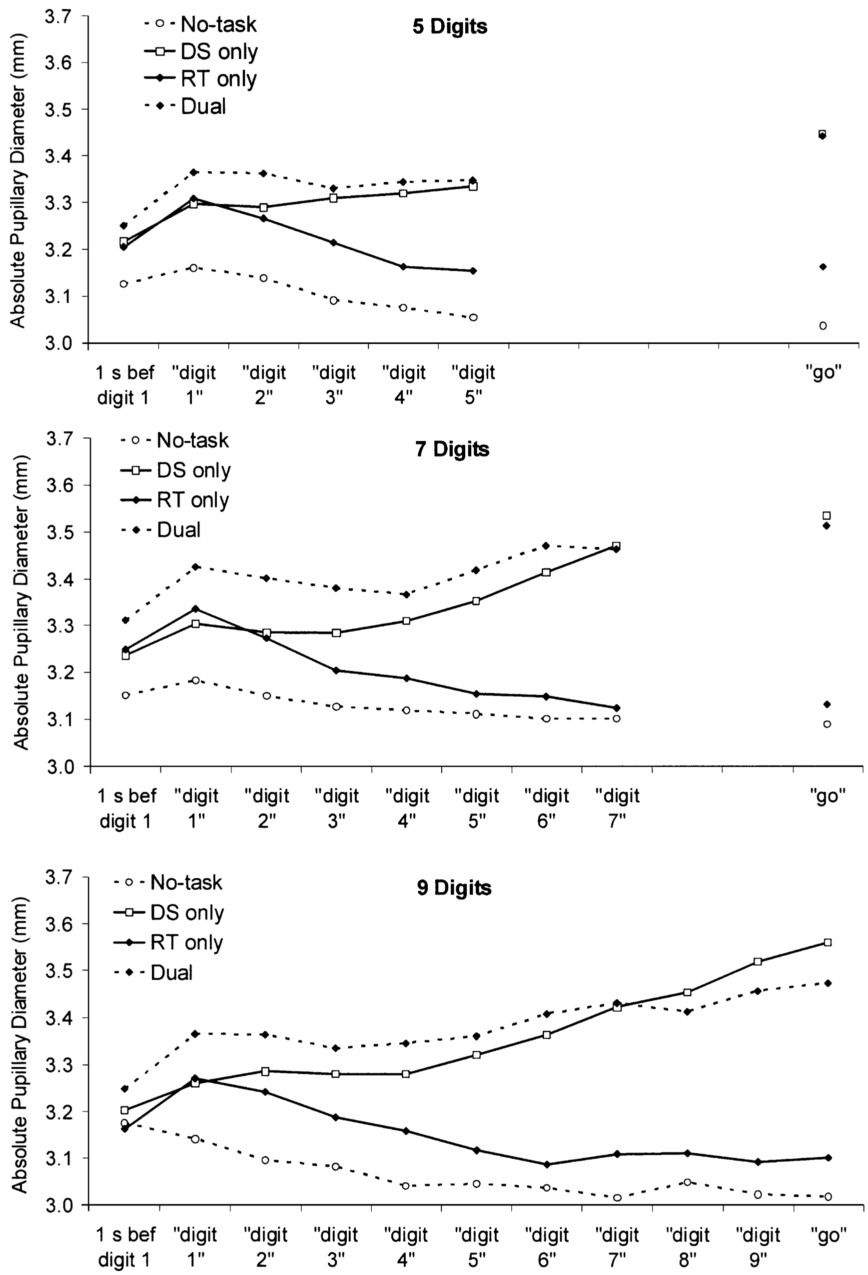

Figure 1. Pupillary diameters (in millimeters) in Study 1 as a function of condition and sequence length. For purposes of comparison across studies, pupillary diameter averaged over the 1 s before the onset of the first was 3.13 mm ($SD = 0.45$) in the no-task condition, 3.22 mm ($SD = 0.50$) in RT only, 3.20 mm ($SD = 0.53$) in DS only, and 3.25 mm ($SD = 0.55$) in the dual condition. DS: digit span. RT: response time.

DS accuracy. We predicted that DS accuracy would be lower in the dual than in the DS-only condition. We also expected that it would decrease as a function of sequence length. However, we did not make predictions regarding an interaction between condition and sequence length. As shown in Figure 2, DS accuracy was at ceiling levels for the five-digit sequences ($M = 98\%$, $SD = 3\%$) and decreased to an average of 85% ($SD = 11\%$) for the seven-digit sequences and 63% ($SD = 10\%$) for the nine-digit sequences. DS accuracy averaged across the three sequence lengths was lower by only 3% in the dual than in the DS-only condition ($d = 0.33$). A repeated-measures 2 (condition) $\times$ 3 (sequence) ANOVA showed that the condition effect was in the predicted direction (DS-only higher than dual) but did not reach significance, $F(1,23) = 3.66$, $p = .068$. There was a large effect of sequence length, $F(2,46) = 161.31$, $p < .001$. The Condition $\times$ Sequence interaction was not significant, $p = .882$. The sequence effect was followed up with a planned linear trend test. As expected, the result was significant, $F(1,23) = 295.03$, $p < .001$.

Manual RTs. We predicted that RTs to the visual stimuli would be longer in the dual than in the RT-only condition. As

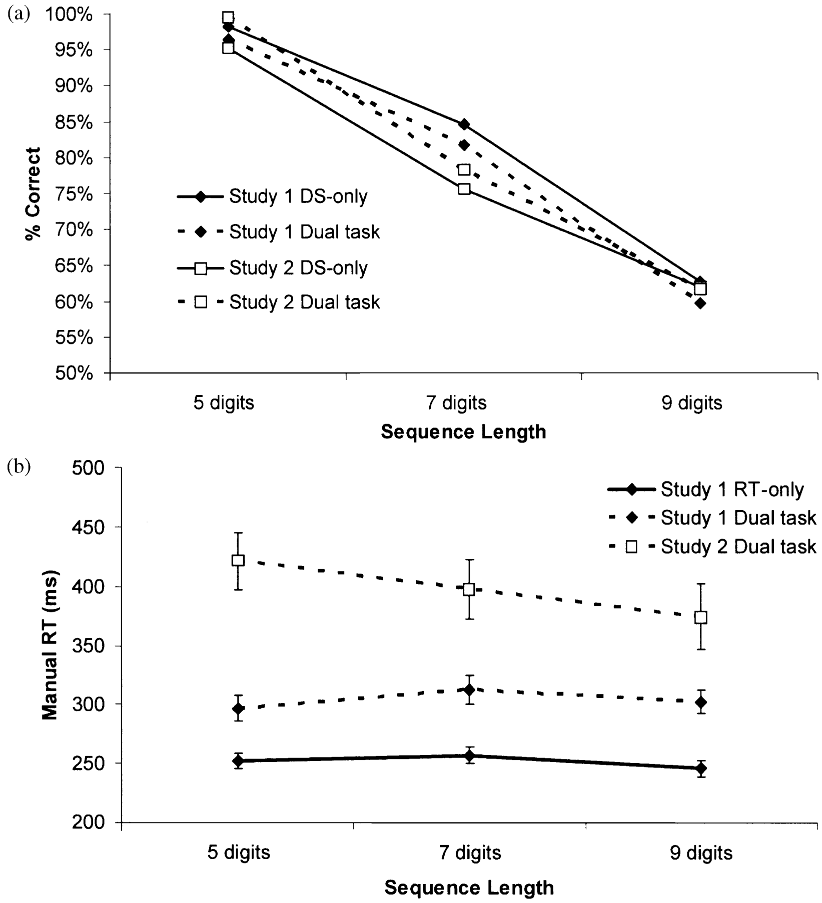

Figure 2. (a): Digit span accuracy (percent correct) and (b) manual response times (in milliseconds) as a function of condition and sequence length in Studies 1 and 2. Error bars represent 95% confidence intervals. DS: digit span. RT: response time.

participants did not know the length of the sequence beforehand, we did not expect RTs to change as a function of sequence length. Figure 2 displays manual RTs as function of sequence length and condition. As predicted, RTs were longer in the dual condition ($M = 304.6$ ms, $SD = 53.1$) than in the RT-only condition ($M = 251.4$ ms, $SD = 33.1$). A repeated measures 2 (condition) × 3 (sequence) ANOVA confirmed that the effect of condition was significant, $F(1,23) = 33.51$, $p < .001$, $d = 1.04$. There was also an effect of sequence length, $F(2,46) = 5.71$, $p = .006$, but no interaction. Follow-up t tests indicated that RTs to seven-digit sequences were significantly (by approximately 10 ms) longer than RTs to both five-digit, $t(47) = 3.06$, $p = .004$, $d = 0.19$, and nine-digit sequences, $t(47) = 3.25$, $p = .002$, $d = 0.19$, but that RTs to five- and nine-digit sequences did not differ from each other ($d = 0.004$).

Psychophysiological Analyses

The second goal of the study was to examine TEPRs to the auditory stimuli as a function of sequence length and condition. We predicted that TEPRs would increase linearly from the first digit to the word "go" for each sequence length within the DS only and dual conditions, and we tested if this linear trend differed between the two conditions. Figure 3 displays TEPRs as a function of condition for each sequence length, and Table 1 displays the slopes of the functions relating TEPR (based on group averages) to auditory stimulus position (from the first digit to the word "go") and the percentage of variance accounted for by linearity in each function. As can be seen in this table, the slopes of the functions ranged from 1.3 to 1.4 (percent change in TEPR/digit) in the DS-only condition and from 0.8 to 1.0 in the dual condition. In contrast, the slopes were negative and ranged from -0.3 to -0.4 in the RT-only condition. Percentage of variance accounted for by linearity was above 80% for all sequence lengths in the DS-only and dual conditions. However, these values were generally lower in the dual than in the DS-only condition.

Tests for linear trends were highly significant for all sequence lengths within both conditions (all ps $< .001$). Moreover, there were significant interactions between linear trends in the DS-only versus the dual conditions for all sequence lengths [for five digits, $F(1,23) = 8.13$, $p = .009$, seven digits, $F(1,23) = 14.91$, $p = .001$, and nine digits, $F(1,23) = 35.86$, $p < .001$]. In the RT-only condition, linear trends were significant for seven-digit sequences, $F(1,23) = 8.18$, $p = .009$, and nine-digit sequences, $F(1,23) = 4.75$, $p = .04$, but not for five-digit sequences.

Thus, as shown in Figure 3, TEPRs increased linearly with each digit to be remembered for all sequence lengths in both the DS-only and dual conditions, peaking at the word "go." Furthermore, the slope of this increase was significantly different between the DS-only and dual conditions for all sequence lengths, with the dual condition yielding shallower slopes. In contrast, TEPRs to these auditory stimuli *decreased* linearly within the RT-only condition for the seven- and nine-digit sequences, suggesting that participants did not allocate resources to the digits and followed instructions to not remember the digits in this condition.

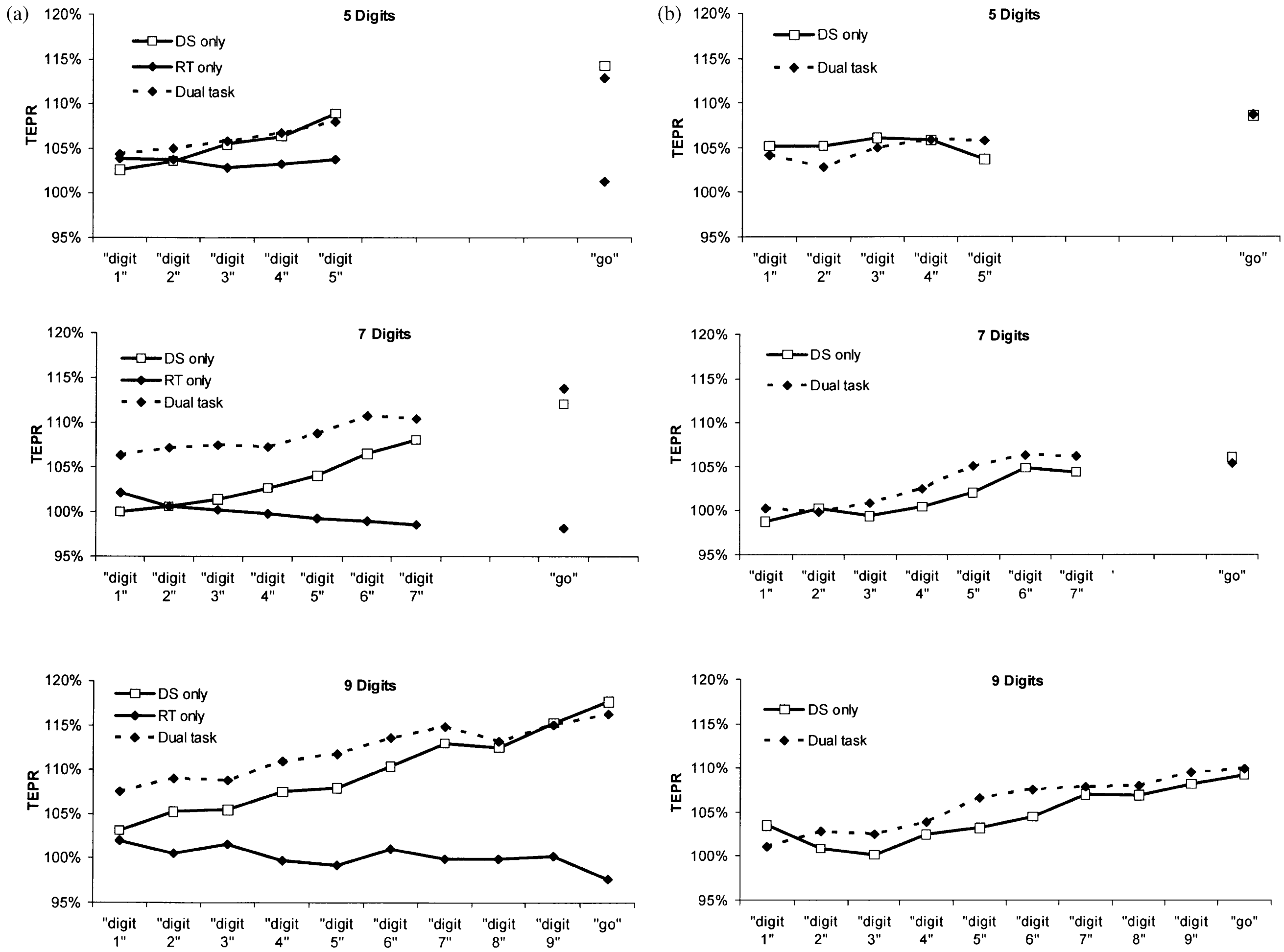

Figure 3. Task-evoked pupillary responses (percent increase over the no-task condition) to the auditory stimuli as a function of condition and sequence length in (a) Study 1 and (b) Study 2. DS: digit span. RT: response time. TEPR: task-evoked pupillary response.

Discussion

The goal of the study was to investigate allocation of attention in the dual-task paradigm. In the RT-only condition, participants were instructed to attend only to the visual stimuli and to ignore the auditory stimuli. Because there was no overt response to the auditory stimuli in this task, it was not possible to determine from behavioral findings alone whether participants were covertly attending to the digits. However, TEPRs to the auditory stimuli were either flat or decreased throughout the trial, suggesting that participants were following instructions and not trying to remember the digits.

Table 1. *Slope (Percent Increase in TEPR/Digit) and Linearity of the Functions Relating TEPR to Memory Load in the Single- and Dual-Task Conditions in Study 1*

	5 Digits	7 Digits	9 Digits
Slope			
RT only	– 0.3%	– 0.4%	– 0.4%
DS only	1.3%	1.4%	1.4%
Dual	1.0%	0.8%	0.8%
Linearity			
RT only	47%	93%	48%
DS only	90%	86%	97%
Dual	82%	86%	93%

In the DS-only condition, participants were instructed to attend only to the auditory stimuli and to ignore the visual stimuli. Both the behavioral and the psychophysiological data indicated that participants were trying to remember the digits in this condition. That is, DS accuracy decreased linearly as a function of sequence length and TEPRs increased linearly with each digit to be remembered across each sequence length. Thus, participants appeared to exert more mental effort with each increase in memory load within sequences, even in conditions in which behavioral performance was at ceiling level (i.e., five-item sequences).

In the dual condition, participants were instructed to divide their attention between the DS and simple RT tasks and to give equal priority to both. Compared to the single-task conditions, DS accuracy suffered only slightly in the dual condition, but RTs were significantly slower. Thus, it appeared that participants gave higher priority to the DS than to the RT task during the dual condition. The verbal comments of some of the participants after the completion of the experimental session were consistent with this explanation.

As shown in Figure 3, TEPRs to the auditory stimuli in the dual condition were higher than TEPRs in the DS-only condition from the start. However, TEPRs during the dual condition increased more slowly as a function of memory load. Thus, participants appeared to have allocated more resources to the DS task during the dual- than during the single-task condition.

A limitation of Study 1 was that we had to conduct post hoc manipulations of the TEPR data to control for differences in absolute pupillary diameters between the single- and dual-task conditions. These differences in diameter may have resulted from the blocked structure of the paradigm. Participants may have anticipated that the dual condition would be more demanding and thus recruited more resources from the beginning. Although previous studies had shown that TEPRs are independent of absolute pupillary diameter, we wished to demonstrate more directly that this was the case in the current study as well. Thus, before discussing the implications of the findings for allocation of attention, we conducted a second study to rule out the possibility that condition differences in TEPRs were due to differences in absolute pupillary diameter.

STUDY 2

In Study 2, we attempted to equalize absolute diameters between the DS-only and dual conditions by presenting the first four digits without additional visual stimuli. Thus, the two conditions were identical until Digit 4, when the visual stimuli were added. After Digit 4, the DS-only and dual conditions were identical to those in Study 1. Because the results of Study 1 were fairly clear for the RT-only condition, we eliminated this condition in Study 2.

Based on the results of Study 1, the key predictions were that: (a) the absolute diameter of the pupil during the 1 s before the presentation of the first digit would not differ between the DS-only and dual conditions, (b) TEPRs to the digit sequences would increase linearly with each digit to be remembered within both the DS-only and dual conditions for each sequence length, and (c) the slope of the TEPR increase as a function of memory load would differ between the DS only and dual conditions only after Digit 4.

Method

Participants

Participants were 11 healthy adults (3 men, 8 women). They ranged in age from 19 to 24 ($M = 20.62$, $SD = 1.63$), and consisted of 9 Caucasian, 1 African American, and 1 Asian-American individuals. All participants were recruited, screened, and compensated in the same way for Study 2 as for Study 1.

Apparatus

Stimulus presentation, recording of manual responses, and eye tracking procedures were the same for Study 2 as for Study 1 except for one change. The computer monitor used to present the stimuli was larger (53 cm diagonal) for reasons unrelated to this study.

Procedure

All participants were administered three conditions: no-task, DS-only, and dual-task. All participants were informed from the beginning that the visual stimuli would appear after the fourth digit in all conditions. The tasks were similar to those in Study 1 with two exceptions. In the no-task condition, only 6 trials were used instead of 12, both to reduce the duration of the task and because data from Study 1 suggested that we could obtain reliable data from only 6 trials in this condition. In all conditions, the visual stimuli did not appear until Digit 4 of the DS task. As in Study 1, the no-task condition was always presented first. The order of the other two conditions was counterbalanced. All other aspects of the procedure were identical to Study 1. As in Study 1, participants were instructed to perform only the DS task in the DS-only condition and both tasks at the same time in the dual condition once the visual stimuli began to appear. The time to complete all three conditions was approximately 20 min.

Dependent Variables

The dependent variables in Study 2 were the same as for Study 1. TEPRs used in these analyses were defined in the same way as in Study 1.

Results

Data were analyzed in the same way as in Study 1. Independent-samples t tests were used to compare the DS-only and dual conditions of participants who were administered DS-only before versus after the dual condition. Tests on DS accuracy showed an effect of order, $t(9) = 3.24$, $p = .01$, with 1.4% better performance when the DS-only condition was presented first. Thus, the data of all participants were collapsed regardless of administration order.

Behavioral Analyses

First, we tested if DS accuracy differed between the DS-only and dual conditions. As shown in Figure 2, DS accuracy was at ceiling level for the five-item sequences ($M = 95\%$, $SD = 7\%$) and decreased to 76% ($SD = 24\%$) for the seven-digit sequences and 62% ($SD = 17\%$) for the nine-item sequences. As shown in Figure 2, the DS accuracy results were similar between Studies 1 and 2. However, as the dual task in Study 2 did not start until the fourth digit, DS accuracy differed less between the DS-only and dual conditions than in Study 1. A repeated measures 2 (condition) × 3 (sequence) ANOVA showed no effect of condition. As expected, there was a large effect of sequence length, $F(2,20) = 28.93$, $p < .001$, but no Condition × Sequence interaction.

The effect size of the difference in DS accuracy between the DS-only and the dual conditions was 0.33 in Study 1 and 0.14 in Study 2 (where the requirement to divide attention did not commence until the presentation of Digit 4 on each trial).

As shown in Figure 2, manual RTs were slower in Study 2 than in Study 1. This difference is probably attributable to the fact that Study 2 did not include an RT-only condition and contained fewer stimuli to respond to in the dual condition than Study 1. Hence, participants were less practiced at this task than in Study 1.

Psychophysiological Analyses

First, we tested if the experimental manipulation was successful in equalizing the absolute diameter of the pupil between the DS-only and dual conditions during the 1 s before the presentation of the first digit. Absolute pupillary diameters in the three conditions as a function of sequence length are displayed in Figure 4. *T* tests comparing average pupil dilation 1 s before the first digit in the two conditions were not significant for five and seven digits ($ps > .19$), but reached significance for nine digits, $t(10) = 2.50$, $p = .03$. However, as inspection of Figure 4 shows, the absolute diameter of the pupil was in fact smaller in the dual than in the DS-only condition for nine-digit sequences. Therefore, we conducted the subsequent analyses with TEPRs standardized in the same manner as in Study 1.

The second goal of the study was to test if TEPRs to the auditory stimuli would increase linearly as a function of memory load within the DS-only and dual conditions for each sequence length. As shown in Figure 4, this prediction was supported (except for the five-digit sequences of the DS-only condition), replicating the results of Study 1. The linear trend was significant in the DS-only condition for seven digits, $F(1,10) = 16.23$, $p = .002$, and nine digits, $F(1,10) = 31.26$, $p < .001$. The linear trend was also significant in the dual condition for five digits, $F(1,10) = 8.00$, $p = .018$, seven digits, $F(1,10) = 18.66$, $p = .002$, and nine digits, $F(1,10) = 96.28$, $p < .001$.

To test if the slope of the increase in TEPRs as a function of memory load would be steeper in the dual than in the DS-only condition, we analyzed TEPRs to Digits 3, 4, and 5 with the average TEPR of Digits 3, 4, and 5 across sequence lengths as the dependent variable. We expected a Condition (DS only vs. dual) $\times$ Digit interaction between Digits 4 and 5 (when the visual stimuli were added), but not between Digits 3 and 4 (when no visual stimuli were present). Two repeated measures 2 (condition) $\times$ 2 (digit) ANOVAs confirmed these predictions. There

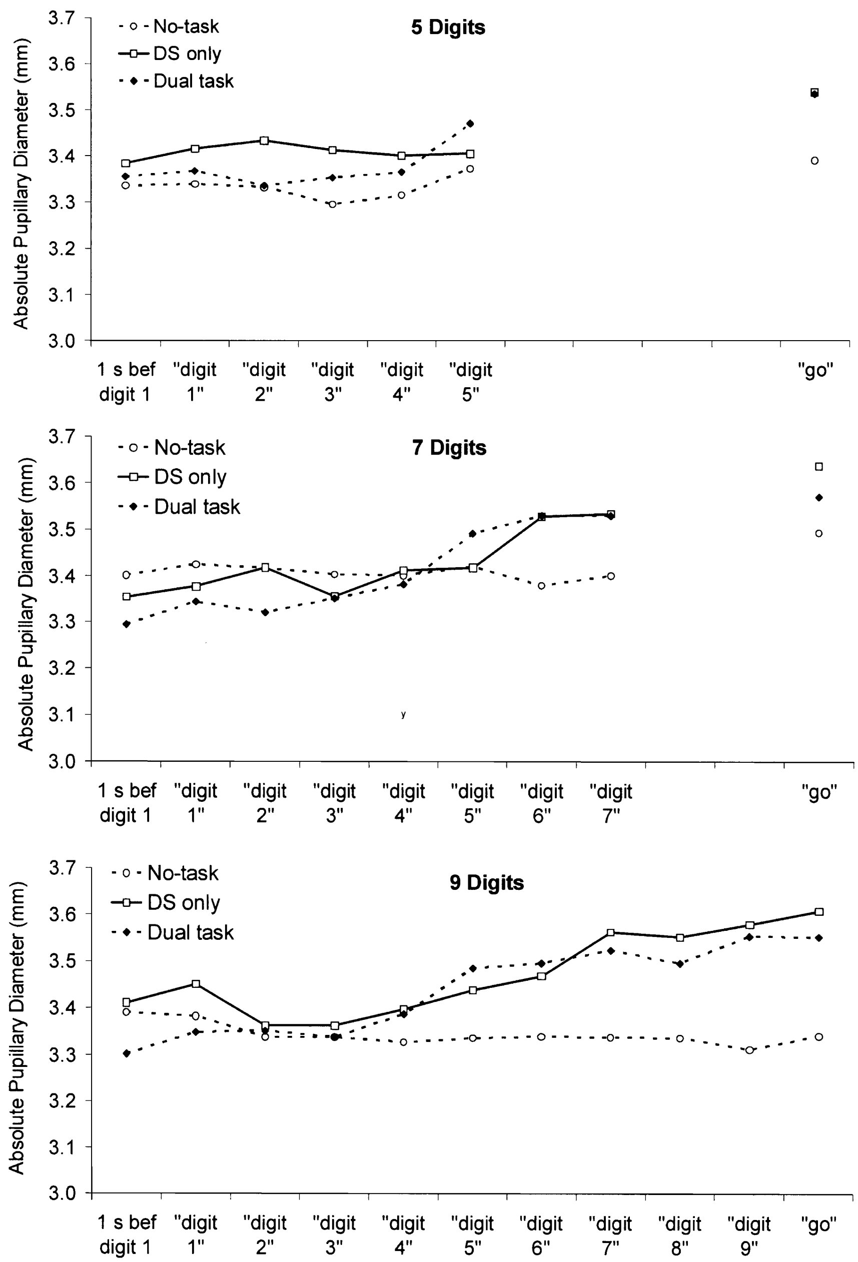

Figure 4. Pupillary diameters (in millimeters) in Study 2 as a function of condition and sequence length. DS: digit span. RT: response time.

was no Digit × Condition interaction between Digits 3 and 4, but a significant interaction between Digits 4 and 5, $F(1,10) = 23.18$, $p = .001$. A follow-up t test showed that the difference between Digits 4 and 5 was greater in the dual than in the DS-only condition, $t(10) = 4.82$, $p = .001$.

Discussion

The behavioral results showed that in the dual condition, the additional load imposed by the RT task did not lead to a significant deterioration in DS accuracy. As in Study 1, TEPRs to the digits were highly sensitive to task demands and increased linearly with increases in memory load in both the DS-only and dual conditions.

The goals of Study 2 were to equalize absolute pupillary diameter before the first digit between the DS-only and dual conditions and to test if we could still replicate the results of Study 1. In general, both goals were accomplished. In Study 2, absolute pupillary diameter before the first digit was similar between the DS only and dual conditions or even smaller in the dual condition. Yet, when the RT task was imposed on the DS task after the fourth digit in the dual condition, the slope of the TEPRs diverged between the DS-only and dual conditions.

Given that there were only 11 participants in Study 2 and only four trials for each sequence length in both studies (and only two trials per sequence length in the no-task condition in Study 2), these results indicate that the TEPR effects observed in these two studies are quite robust.

In conclusion, the results of Study 2 indicate that the results of Study 1 could not be attributed to condition differences in absolute diameter at the beginning of the trials.

General Discussion

The goal of this study was to assess allocation of attention in the dual-task paradigm using a combination of behavioral and psychophysiological measures. The results of both Study 1 and Study 2 were consistent with the hypothesis that TEPRs can be used to distinguish mental effort from behavioral performance. In both studies, there was minimal or no decline in DS accuracy from the single to the dual condition. However, as expected, RTs in Study 1 were slower in the dual than in the single-task condition.

On the RT-only task, TEPRs to the auditory stimuli either did not change or decreased with each digit presented, suggesting that participants were following instructions to try not to remember the digits. In contrast, as in previous studies, TEPRs increased with memory load on the DS task in both the DS only and dual conditions in both Study 1 and Study 2. In addition, we found that TEPRs were higher in the dual than in the DS-only condition at the beginning of the trials in Study 1 (where task demands between conditions differed from the beginning) but only after the Digit 4 in Study 2 (when task demands between conditions diverged). However, the rate of increase in TEPRs with each increase in memory load was slower. Thus, trying to maintain the same level of behavioral performance on the DS task during the dual condition seemed to have come at the cost of slower RTs on the simple RT task and increased physiological arousal in response to the working memory demands of the DS task.

These results provide also support for Kahneman's (1973) thesis that during the dual-task paradigm, physiological and behavioral measures provide "independent indices of the momentary effort investigated in the primary task" (p. 22). Indeed, these two types of measures seem to capture the distinction between effectiveness and efficiency of performance. "Effectiveness is a measure of the quality of performance, while efficiency is the relation between the quality of performance and the effort invested in it" (Kahneman, 1973, p. 181). As Kahneman and others before him have noted, the two measures are not always directly related. In previous studies of the dual-task paradigm, efficiency has generally been estimated from behavioral performance on the secondary task. The current study suggests that TEPRs can also help distinguish between these two aspects of performance. Thus, in our version of the dual-task paradigm, participants appeared to have been less efficient but almost as effective on the DS task during the dual than during the single-task condition.

The distinction between effectiveness and efficiency of performance has been elaborated recently by resource theorists such as Hockey (1997). Building on Kahneman's model, Hockey argues that analyses of task performance need to take into account not only task demands but also trade-offs among the individual's goals, motivation, strategies, and the amount of mental effort he or she chooses to spend to accomplish those goals. According to Hockey, it is these trade-offs that lead to adaptive and maladaptive ways of functioning in the face of stressors. For instance, when faced with a difficult task, such as having to divide attention between two tasks, individuals can intensify their mental effort to maintain an acceptable level of behavioral performance. However, this strategy runs the risk of increased anxiety and fatigue, reflected in elevated catecholamine and cortisol levels. Alternatively, individuals with lower frustration tolerance may lower their goals or adopt less sophisticated strategies that demand less effort, but at the cost of impaired behavioral performance, feelings of helplessness, and higher adrenocortical activity. Hockey adds that the ability to monitor goals and behavioral performance and to adjust level of effort accordingly are also important in coping effectively with stressors such as task difficulty.

TEPRs can be a powerful tool in revealing the hidden costs of performance, testing hypotheses about performance/cost trade-offs, and examining the dynamic allocation of attention in the face of difficult tasks. The current study extends Kahneman's previous studies of the dual-task paradigm by employing a new pair of tasks and, more importantly, by directly comparing TEPRs between the single- and dual-task conditions. Future studies of TEPRs in the dual-task paradigm can be used to map out performance/cost functions across individuals and groups (e.g., developmental and clinical populations) and to test if strategic choices about attention allocation are made at different points of this curve in different groups of participants (cf. Schumacher et al., 1999). These studies could also help estimate resource costs of different strategies for different individuals and groups, and test hypotheses about differences in the ability to monitor performance and regulate arousal level as performance begins to decline. TEPR studies would also be suitable for investigating the effects of low versus high arousal (e.g., from fatigue, drowsiness, stress, caffeine, or medications) on allocation of attention. Finally, Sanders (1997) notes that in dual-task situations, secondary tasks can sometimes recruit resources even when participants are instructed to ignore them. In the current study, TEPRs to the digits did not differ between the no-task and the RT-only conditions, suggesting that the "concurrence cost" of the secondary DS task in this condition was minimal. Future studies could investigate further the effects of different pairings of tasks on the extent of "concurrence costs" of secondary tasks in the dual-task paradigm.

A limitation of the current study is that participants were instructed to emphasize performance on the two tasks equally in the dual-task condition. Nevertheless, they appeared to have tried to maintain accuracy on the DS task at the expense of speed on the RT task. This discrepancy can be attributed to the fact that it is difficult to divide attention equally between two tasks that differ to a great extent in difficulty. In future studies using this paradigm, it would be advisable to instruct participants to try to maintain the same level of accuracy on the DS task in the dual condition as in the DS-only condition.

Another limitation of the study was that we did not ascertain if participants were using the same strategies to remember the digits during the single and dual conditions. Visual inspection of the TEPR data of individual subjects revealed some heterogeneity in the shapes of the TEPR functions, suggesting that behavioral performance probably resulted from an interaction among type of strategy used (e.g., simple rehearsal vs. chunking), individual differences in the cost of the strategy in terms of mental effort, as well as individual differences in memory span. In future studies, it may be advisable to instruct participants to use similar strategies or to manipulate the temporal delay between digits to facilitate the use of certain strategies. In addition, because the auditory and visual stimuli had to be presented in temporal proximity to each other, it was difficult to tease apart the effects of the visual stimuli on TEPRs independent of the effects of the auditory stimuli. Other pairings of tasks in which TEPRs to the secondary task can be measured independently would increase the utility of this method for investigating divided attention.

Top-down control over attention allocation in situations involving multiple tasks is a complex and dynamic process, and investigating these processes requires the use of multiple methods. TEPRs can contribute to this effort by enabling researchers to operationalize the construct of resources and to assess the integrity of cortical-reticular interactions regulating level of arousal in accordance with task demands (cf. Heilman, Watson, Valenstein, & Goldberg, 1987). Studies of dual-task performance that use a combination of behavioral, psychophysiological, and neuroimaging methods can have theoretical and practical implications for understanding how we learn to divide our attention efficiently across multiple tasks and how this ability may break down in pathological conditions.

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