EUROPEAN JOURNAL OF COGNITIVE PSYCHOLOGY
2006, 18 (4), 481–492

Integrative views on dual-task costs

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In this paper, we introduce a special issue about unique and shared mechanisms underlying the performance limitations observed in dual tasks. In particular, the relationship between task-switching costs, the attentional-blink effect, and the psychological refractory period effect is reviewed. These costs are traditionally attributed to fixed and unique capacity limitations for task set reconfiguration, target identification, and response selection, respectively. However, we argue that more global attentional processes play a role that cuts across these paradigms. This is reason for a more paradigm-independent approach to processing limitations in dual tasks.

Human cognitive performance is characterised by limitations on the amount of information that can be processed simultaneously, or nearly so. Processing limitations are clearly present when task processing requirements overlap (Wickens, 1983), but they are also observed with combinations of tasks that seem to overlap only in the requirement to select a response (Pashler, 1994). This raises the issue of where and why processing limitations arise.

This special issue addresses a number of current topics in dual-task performance. For example, are dual-task costs caused by structural or by

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This paper was written while the first author was supported by a fellowship from the Royal Netherlands Academy of Arts and Sciences.

http://www.psypress.com/ecp DOI: 10.1080/09541440500422675

functional processing limitations? Structural limitations refer to a fixed and hardwired limitation of perception of multiple stimuli, the storage of multiple memory items, or making multiple decisions. According to a functional view, the task goal, task context, task combination, and selected strategy can modulate considerably the amount of information that can be processed simultaneously.

Another, related topic is whether dual-task costs observed in different paradigms have shared or unique causes. Three paradigms that have been used extensively to study dual-task performance are the attentional-blink paradigm (AB; Raymond, Shapiro, & Arnell, 1992), the psychological refractory period paradigm (PRP; Telford, 1931; Welford, 1952), and the task-switching paradigm (TS; Jersild, 1927). Although these three paradigms do not comprise an exhaustive list, they represent three ways in which processing limitations become manifest that, on the surface, appear rather dissimilar. One of our aims in the current special issue was to bring together a number of contributions from researchers who had already previously crossed borders between paradigms and considered overarching explanations for these apparently disparate dual-task phenomena. The special issue reflects original empirical and theoretical work first presented at an expert meeting on the same topic.[1]

BACKGROUND

For cognitive psychology, processing limitations are a key to understanding the architecture of cognitive processing. A process without limitations is not likely to respond to experimental manipulations and therefore does not reveal its underlying structure. Therefore, experimental paradigms are initially developed to maximise dual-task costs. However, in reconsidering the processing architecture in a broader perspective, it is important to explore how processing limitations reflected in different paradigms may be interrelated. Yet, information-processing theories have long been developed for the explanation of paradigm-specific observations. It is only in the past decades that integrative views have begun to be formulated.

Integrative views carry two important improvements over paradigm-specific theories. First, the initial limited-capacity models of attention (e.g., Broadbent, 1958; Deutsch & Deutsch, 1963) were developed in strict isolation from the view of capacity limitations in memory maintenance (e.g., Miller, 1956). In current models of processing capacity, however, links

[1] The conference entitled "Unique and shared processing limitations in dual-task performance" was organised by Leiden University, May 13–15, 2004. The conference was supported by grants from NWO-ISW and the EPOS graduate research school.

between attention and temporary storage in memory are indispensable: Accurate responses in an attention task are strongly dependent on the ability to consolidate the information for later use (e.g., Baddeley, 2000; Chun & Potter, 1995; Jolicœur, 1998). Second, the importance of the goal representation for processing capacity has long been ignored in rather mechanistic processing models. Current models pertaining to processing capacity, however, almost all acknowledge that top-down processes modulate processing capacity (e.g., Hommel, Müsseler, Aschersleben, & Prinz, 2001; Logan & Gordon, 2001; Meyer & Kieras, 1997; Norman & Shallice, 1986).

A pioneering integrative view of processing limitations was the working-memory model of Baddeley (1986). It was one of the first models to suggest a link between capacity and executive function. The large number of studies that refer to Baddeley's work illustrates that a broader perspective yields innovative hypotheses. However, the majority of studies following Baddeley's working memory model still focus on how information is maintained in dedicated visuospatial and phonological systems. The model's suggestion that working memory combines storage capacity with processing capacity is still a largely unexplored territory.

Oberauer and Göthe (2006 this issue) tested for dual-task interference between memory storage and memory updating in the visuospatial and numerical domain. While parallel processing was always associated with dual-task costs, the authors observed that memory storage as such was relatively insensitive to concurrent storage or concurrent processes. However, keeping memory items active for direct access dramatically raised the sensitivity to dual-task interference. This finding highlights the limitations to active memory maintenance.

The division between active and passive memory systems, in which only active memory systems induce capacity limitations, fits well with ideas of limited capacity for maintaining information. According to Luck and Vogel (1997), visual short-term memory can simultaneously keep features integrated for four different objects, regardless of the number of features involved. By this insight, Luck and Vogel clarified how storage limitations relate to selection requirements. The authors argued that capacity is not limited in the number of features that is activated, but in the concurrent integration of multiple objects. Their model has inspired study of the neural underpinnings of feature integration. Several studies suggest that short-term episodic storage of stimuli involves the synchronised firing of neurons that are responsible for representation of separate features (e.g., Engel, Roelfsema, Fries, Brecht, & Singer, 1997). It appears that interference arises if more than four patterns of synchronised activity need to be maintained, so the functional capacity for objects is limited to four items (Raffone & Wolters, 2001).

DUAL-TASK PERFORMANCE

In the typical AB paradigm, observers are not able to report a masked visual target that is presented up to 500 ms after a previous target as part of a rapid serial visual presentation (RSVP) stream. The AB is mostly reported with visual stimuli, but this does not imply that the AB is a modality-specific phenomenon. Dell'Acqua, Jolicœur, Sessa, and Turatto (2006 this issue) show that tactile stimuli are reported with less accuracy if a preceding stimulus has to be reported than if the preceding stimulus can be ignored, and Duncan, Martens, and Ward (1997) and Arnell and Jolicœur (1999) reported an AB effect within the auditory modality. Evidence for between-modality AB effects has been mixed, however. For example, Duncan et al. found no AB effect if two targets were presented in different modalities, whereas Arnell and Jolicœur found between-modality interference that was as strong as within-modality interference. Perhaps cross-modal AB occurs as a result of interactions between central processing of the first target and the extent to which processing in the other modality requires central control and/or consolidation mechanisms. Experimental paradigms may differ in the degree to which central mechanisms are required for the control and integration of information coming into the cognitive system via a particular input modality (see Potter, Chun, Banks, & Muckenhoupt, 1998, for another view involving interactions between the AB and task switching).

Regardless of whether the AB is a modality-specific or supramodal effect, it reflects an inability to complete multiple tasks in limited time. The mere presentation of a stimulus prior to a target is not enough to induce an AB (Raymond et al., 1992): The AB seems to be due to specific processes following stimulus presentation. Furthermore, another critical factor is not whether another task is present prior to the target, but whether the subject's attention is captured. Jolicœur, Sessa, Dell'Acqua, and Robitaille (2006 this issue) show that the mere presentation of a stimulus, which the subject is trying to ignore, can produce a strong AB effect if that stimulus captures attention by virtue of top-down control settings (Folk, Remington, & Johnston, 1992).

In the PRP paradigm, the latency of a choice response increases with a decrease of the interval between the current and the previous stimulus. This result, known as the PRP effect, is usually taken to imply that processes of the second task are postponed or slowed by requirements of the first task (Navon & Miller, 2002; Pashler, 1994; Tombu & Jolicœur, 2003). Pashler's (1994) bottleneck model holds a class of central processes responsible for the PRP effect, with response selection as the most ubiquitous bottleneck process. Other processes that have been considered to have bottleneck properties are mental rotation (Ruthruff, Miller, & Lachman, 1995) and memory retrieval (Carrier & Pashler, 1995). However, others (Logan &

Schulkind, 2000; van Selst & Jolicœur, 1994) have shown signs of parallel execution for these demanding processes.

As the existence of an all-or-none bottleneck in central cognitive processes has been challenged by several PRP studies, there is reason to describe capacity allocation as a continuous process (Navon & Miller, 2002; Tombu & Jolicœur, 2002). Capacity for parallel execution of central cognitive processes is limited, and in the PRP task participants tend to allocate most capacity to the first task, but this does not imply that processing on the second task stands still.

In the TS paradigm, responses to a stimulus are slower if the task for the current stimulus differs from the task for the previous stimulus. The costs of task switching are attributed to the processes involved in retrieving the goal for the upcoming task from memory and adjusting the input and output settings accordingly (Allport, Styles, & Hsieh, 1994; Rogers & Monsell, 1995; Rubinstein, Meyer, & Evans, 2001). More specifically, switch costs seem to arise from multiple sources. There are costs of mixed versus pure task blocks (Kray, Li, & Lindenberger, 2002), which are independent of the reaction time costs of task switch trials relative to task repetition trials. Some costs can be reduced by advance preparation, whereas part of the switch costs remains after a long preparation interval. Substantial costs even appear if the task is repeated but the task cue changes (Logan & Bundesen, 2003), which suggests that interruption of a task sequence as such may be enough to trigger a delay on the next response (cf. Gopher, Armony, & Greenshpan, 2000). With regard to the explanation of TS costs, there is an ongoing debate about the relative importance of proactive interference from an old task (Allport et al., 1994) and the mere costs of reconfiguring the task set (de Jong, 2000; Meiran, 1996, 2000; Rogers & Monsell, 1995).

INTEGRATIVE VIEWS

Several authors have considered overlapping mechanisms behind the reduced accuracy of target recall in the AB paradigm, and the delay of the response in the PRP paradigm. Jolicœur (1998; Jolicœur & Dell'Acqua, 1999) explored the differences between the two paradigms by adding to the AB paradigm the requirement to make an immediate and speeded response, just as in the PRP paradigm. Jolicœur (1998) found that the accuracy of an unspeeded response to the second target in an RSVP stream was sensitive to the relative speed of the first response, and that the AB effect was larger if a speeded than if a delayed response was required in the first task. This led Jolicœur to suggest a model in which short-term consolidation of the second stimulus is postponed by central processes of the first task. Because targets in the AB paradigm are masked, postponing consolidation sometimes leads to a failure to retrieve the target identity. This model is closely related to current models for the delayed response on the PRP paradigm, in which postponement of central processes of the second task is reflected in a longer reaction time. Furthermore, this model predicts that, under some conditions, strong cross-modal interference should occur if the first task requires a speeded response, which was confirmed in a number of experiments (e.g., Jolicœur, 1999; Jolicœur, Dell'Acqua, & Crebolder, 2000).

Arnell and Duncan (2002) also considered the relationship between mechanisms underlying the AB and the PRP effect. Because they observed differential interference between tasks with stimuli from the same versus different modalities, they concluded that, in addition to the processing limitation that is shared by AB and PRP performance, the typical AB paradigm with two visual stimuli may reflect processing limitations that are specific to this modality. A similar conclusion was drawn in a study of Wong (2002).

The idea that limited processing resources may be one of the sources of the AB is contradicted by a recent study of Olivers and Nieuwenhuis (2005). They instructed subjects to listen to an audio track, or think about holidays, while simultaneously performing the AB task. Surprisingly, both distraction conditions resulted in smaller ABs than the control condition in which subjects were not performing an additional task. One of the explanations that Olivers and Nieuwenhuis considered is that performance on the AB is not optimal if there is a strong focus on the first target, and that some degree of distraction during the processing of the first target benefits the recall of the second target. An apparently opposite result was obtained by Akyürek and Hommel (2006 this issue), who found that the size of the AB was insensitive to variations of a concurrent load of working memory. The memory load only had an overall performance penalty. This finding suggests that the processes that are responsible for the AB do not tap into the same resources as short-term memory maintenance. Nonetheless, the data of Olivers and Nieuwenhuis are reason to consider limitations arising from the capacity-allocation policy for concurrent tasks. A more diffuse attentional state that is beneficial to performance in the attentional blink task may be accomplished only by active concurrent processes such as listening to music, and not by memory maintenance as such.

Under the assumption that the PRP effect reflects a limitation for time-limited execution of demanding processes, an interesting question is whether and how the AB fits in it. Jolicœur (1998) suggested that short-term consolidation for the second target is deferred both in the AB and the PRP paradigm. To the extent that the consolidation concerns the identity of the response, it is a process closely related to response selection. According to Hommel et al. (2001), decision making involves the domains of perception as well as action. They argued that a decision involves the binding of stimulus, task, and response features into an event file. Similar to consolidation, event coding entails the formation of an episodic trace in memory (cf. Akyürek & Hommel, 2006 this issue). Hommel et al. have shown that active event files can interfere with the formation of new event files with overlapping features. Their model suggests that the bottleneck may be not a structural limitation for response selection (Pashler, 1994), but a functional limitation for episodic encoding.

Another functional model of PRP performance was developed by Meyer and Kieras (1997), who attributed the PRP effect to strategic settings in executive control that keep processes such as response selection from being executed in parallel. Meyer and Kieras (1999) have argued that participants are well able to perform a dual-task without costs if only a set of requirements is met, such as sufficient training and the absence of overlap. Logan and Gordon (2001) attributed the PRP effect even more explicitly to control requirements. They explained the PRP effect with the costs of switching between tasks, such that the costs increase if there are more parameters to reconfigure.

Although switch costs may contribute to the observed size of the PRP effect, they do not seem to be the only source. Band and van Nes (2006 this issue) demonstrated that a full-blown PRP effect occurred on trials in which no task switch was required (except for a change between two nonoverlapping response sets). Furthermore, the costs of a task switch were additive to the effect of the interval between stimuli, which implies that task switching did not start before the bottleneck processes of the first task had finished (cf. Lien, Schweickert, & Proctor, 2003).

In contrast with the PRP effect, which seems to exist independently of task switches, several studies suggest that the AB effect is modulated by task switches (Juola, Botella, & Palacios, 2004; Potter et al., 1998). Kawahara, Zuvic, Enns, and DiLollo (2003) observed an AB effect in a task without masking, and a task switch between the first and second target was a necessary condition for the occurrence of such an AB.

Task switches do not only modulate stimulus processing, there is also an opposite effect. Waszak, Hommel, and Allport (2003) have shown that switch costs could be substantially enhanced by giving one or two training trials with a different task at the beginning of the experimental session. They argued that episodic memory traces build up during each trial and that these traces bias towards processing subsequent stimuli in the same way. This type of priming effects is strongest if the task contains a large number of stimuli that have a very distinguishable meaning, such as pictures of objects. Although it remains to be seen whether priming effects play a substantial role in TS experiments with a small set of abstract stimuli, the study of Waszak et al. shows that switch costs do not stem purely from deliberate application of a task cue for reconfiguring the task set. They are modulated by task history.

The importance of the task history for TS costs is confirmed by studies that focus on sequential effects. Manifestations of stimulus–response binding that seems to occur after a single trial turn out to have longer lasting effects. Pösse, Waszak, and Hommel (2006 this issue) observed that an encounter with a specific stimulus–response pair affected performance even two task switches and three trials later. While this already reflects some degree of extended storage, Waszak et al. (2003) observed that stimulus–task binding, induced by one or two trials with the same combination of stimulus and task, affected TS costs on trials with the same stimulus several blocks later in the session.

Priming effects can go in two directions: A task set can be relatively active on repetition trials, and relatively suppressed shortly after that task was replaced through a task switch (Mayr & Keele, 2000). Inhibition of a no-longer relevant task may lead to enhanced switch costs on tasks that have recently become no longer immediately relevant compared with tasks that have become no longer immediately relevant longer ago. Philipp and Koch (2006 this issue) present data suggesting independent activation of the new task and suppression of the old task. The authors observed support for top-down modulation of the inhibition process in response to the presence versus absence of task repetitions.

Finally, the context of a task is defined by the way higher order task organisation is imposed. For example, Lien and Ruthruff (2004) were able to remove switch costs by promoting the grouping of series of tasks. Luria, Meiran, and Dekel-Cohen (2006 this issue) have investigated the costs of switching between two response series with the same onset. Does the switch in response order affect the onset of the series, or the timing of the first differential response in the series? Their results show that the latter is the case: The final tuning of subtask order control is performed during the execution of the subtask that most distinguishes the orders.

CONCLUDING REMARKS

This special issue shows that capacity limitations in working memory, attention, and cognitive control are often presented as independent phenomena. Although the paradigms discussed in this issue do not cover the entire field of research on processing capacity limitations, it is clear that a small number of processes can be shown to play an important role in the causes of a variety of dual-task costs. In particular the time-critical consolidation of intermediate processing results qualifies as a common denominator in the AB effect, TS costs, and the PRP effect. Of course some caution is required after this claim: By saying that there is a common denominator we do not want to argue against other sources of dual costs, and thus we do not claim that such a common denominator is the only cause of dual-task costs. Finally, the hypothesis that only a limited number of objects can be consolidated within a given time window (Luck & Vogel, 1997) illustrates that functional processes in task performance can inflict capacity limitations that mimic structural limitations. It is clear that structural properties of the nervous system impose important processing limitations at every level of processing ranging from acuity in sensory systems, the number of effectors available for interaction with the external world, to more cognitive limitations, such as limits on how many independent representations can be maintained in an active state in visual short-term memory. Nonetheless, there is mounting evidence that such structural limitations cannot explain the entire range of dual-task costs, and several studies in this issue show that functional and representational issues also contribute in important ways to performance.

PrEview proof published online 24 February 2006

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