GOLDEN ANNIVERSARY SPECIAL ISSUE

Multiple Resources and Mental Workload

Christopher D. Wickens, University of Illinois, Champaign, Illinois

Objective: The objective is to lay out the rationale for multiple resource theory and the particular 4-D multiple resource model, as well as to show how the model is useful both as a design tool and as a means of predicting multitask workload overload. **Background:** I describe the discoveries and developments regarding multiple resource theory that have emerged over the past 50 years that contribute to performance and workload prediction. **Method:** The article presents a history of the multiple resource concept, a computational version of the multiple resource model applied to multitask driving simulation data, and the relation of multiple resources to workload. **Results:** Research revealed the importance of the four dimensions in accounting for task interference and the association of resources with brain structure. Multiple resource models yielded high correlations between model predictions and data. Lower correlations also identified the existence of additional resources. **Conclusion:** The model was shown to be partially relevant to the concept of mental workload, with greatest relevance to performance breakdowns related to dual-task overload. Future challenges are identified. **Application:** The most important application of the multiple resource model is to recommend design changes when conditions of multitask resource overload exist.

HISTORY AND MULTIPLE RESOURCE MODEL DEVELOPMENT

Multitasking is prevalent in our society. Issues such as the dangers of using cell phones while driving call for understanding the extent to which such dual-task performance will lead to decreases in time-sharing ability. Multiple resource theory is one approach to this understanding. The concept of multiple resources in attention was spawned, in my mind, from two seeds. First, Kahneman's (1973) influential book on attention inspired me as a graduate student, with concise theory-based writing and a model in which human performance is supported by a general pool of mental "effort" or undifferentiated resources (although this model was actually proposed earlier in a short chapter by Moray, 1967; see also Kalsbeek & Sykes, 1967). The concept of graduated effort stood in marked contrast to the then existing all-or-none single-channel bottleneck view of attention (Broadbent, 1971; Welford, 1967). Kahneman's model emphasized the demand of task for these limited resources, the lack of availability of resources for concurrent tasks, and the suffering of performance of the latter as a consequence. However, in the final chapter, Kahneman makes note of the other sources of "structural interference," which could not be accounted for by a pure resource demand or "undifferentiated capacity" model.

Second, there was by this time a growing body of multitasking studies, some in the experimental literature (e.g., Bahrick, Noble, & Fitts, 1954; Bahrick & Shelly, 1958; Briggs, Peters, & Fisher, 1972) and during the 1960s. These contributed to the creation of the study of "divided attention" in performance as a discipline. Two such studies explicitly cast their results within a framework of multiple resources, postulating that all tasks did not compete for a single undifferentiated "pool" of demand-sensitive resources (Kantowitz & Knight, 1976; Wickens, 1976).

Shortly after this, and stimulated by the parallel work of North and Gopher (1976; North, 1977), I embarked on a series of studies to examine the costs and benefits of the newly emerging technology of voice recognition and synthesis, particularly as applied within the multitask environment

Address correspondence to Christopher D. Wickens, Alion Science Corporation, Micro Analysis and Design, 4949 Pearl East Circle, Suite 300, Boulder, CO 80301; cwickens@alionscience.com. ***HUMAN FACTORS,*** Vol. 50, No. 3, June 2008, pp. 449–455. DOI 10.1518/001872008X288394.

of the aircraft cockpit. In interpreting the results of studies in this area, along with the collective implications of the growing body of multitask studies referred to earlier, I created, for a chapter in *Attention & Performance VIII,* a sort of meta-analysis. In this analysis, I tried to account for the variance in time-sharing efficiency revealed across over 50 different studies by two characteristics: (a) the extent to which time-shared tasks used the same versus different processing structures and (b) the extent to which "difficulty insensitivity" was expressed when the two tasks used different structures. Difficulty insensitivity occurs when an increase in the difficulty of one task fails to degrade the performance of a concurrent one.

Out of these two analyses emerged a fairly coherent picture that "defined" separate resources in terms of a set of three dichotomies of information processing, now quite familiar to many readers and expressed (because of their three dimensions) in the "cube" shown in Figure 1.

- The *stages of processing* dimension indicates that perceptual and cognitive (e.g., working memory) tasks use different resources from those underlying the selection and execution of action (Isreal, Chesney, Wickens, & Donchin, 1980).
- The *codes of processing* dimension indicates that spatial activity uses different resources than does verbal/linguistic activity, a dichotomy expressed in perception, working memory (Baddeley, 1986), and action (e.g., speech vs. manual control; Liu & Wickens, 1992; Wickens & Liu, 1988).
- The *modalities* dimension (nested within perception and not manifest within cognition or response) indicates that auditory perception uses different resources than does visual perception.

Thus, *to the extent that two tasks use different levels along each of the three dimensions, time-sharing will be better.* Note that this assertion does not imply that perfect time-sharing will emerge whenever different resources are used for two tasks. For example, time-sharing an auditory and visual task will still compete for common perceptual resources (and may also compete for common code-defined resources if, say, both are linguistic, involving speech perception and reading).

- To these three dimensions was later added a fourth: *visual channels,* distinguishing between focal and ambient vision (Leibowitz & Post, 1982; Previc, 1998), a nested dimension within visual resources. Focal vision, primarily (but not exclusively) foveal, supports object recognition and, in particular, high acuity perception such as that involved in reading text and recognizing symbols. Ambient vision, distributed across the entire visual field and (unlike focal vision) preserving its competency in peripheral vision, is responsible for perception of orientation and movement, for tasks such as those supporting walking upright in targeted directions or lane keeping on the highway (Horrey, Wickens, & Consalus, 2006).

Concurrent with the identification of the first three dimensions, Navon and Gopher (1979) developed an elegant mathematical theory of multiple resources that predicts the consequences to

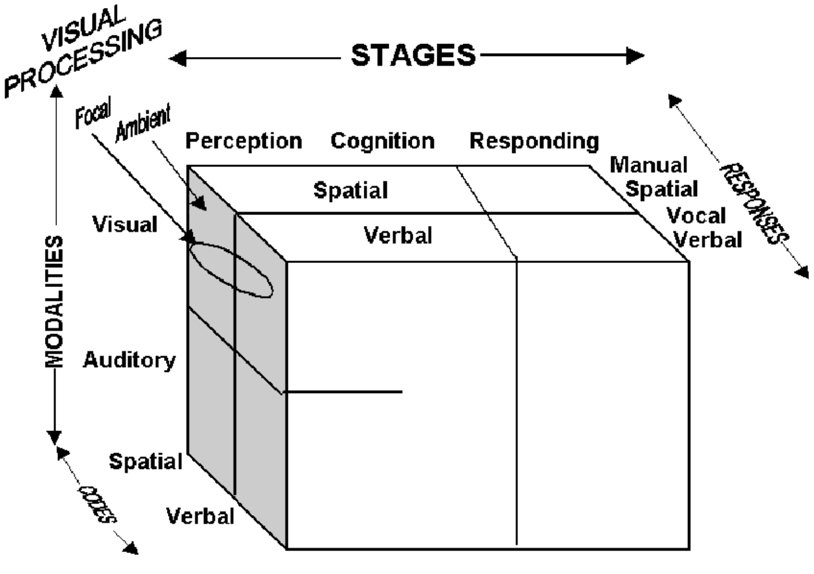

Figure 1. The 4-D multiple resource model.

concurrent task performance of the resource allocation policy between the tasks, their demand for limited resources (task difficulty), and their demand for common versus distinct resources (e.g., resource overlap). After these authors integrated their theory with my postulation of the identity of the three (later four) specific resource dimensions, this one particular version of the multiple resource model emerged (Wickens, 1980, 1984).

The rationale for defining these four dimensions is based strongly on the confluence and joint satisfaction of two criteria. First, the four dimensions defining the model should have *neurophysiological plausibility,* in the sense that the dichotomies have parallels in brain anatomy. In the 3-D + 1 model, they certainly do: (a) Perceptual-cognitive activity is associated with neural activity posterior to the central sulcis of the brain, whereas motor and action-oriented activity is anterior. (b) A well-established line of research associates the processing of spatial and verbal material, respectively, with the right and left cerebral hemispheres of most individuals. Recently work by Just and colleagues (Just et al., 2001; Just, Carpenter, & Miyaki, 2003) has directly associated activity in these areas, as assessed by functional magnetic resonance imaging (fMRI) analysis, with dual-task processing and resource demand. (c) Auditory and visual processes are distinctly associated with auditory and visual cortices, respectively. (d) Focal and ambient vision are supported by ventral and dorsal visual pathways, respectively (Previc, 1998).

The second criterion emerged from my human factors orientation. I felt it important that the dimensions of the model coincide with relatively straightforward decisions that a designer could make in configuring a task or work space to support multitask activities: Should one use keyboard or voice? Spoken words, tones, or text? Graphs or digits? Can one ask people to control while engaged in visual search or memory rehearsal? These two criteria, neurophysiological plausibility and design decisions, appeared to be fairly well satisfied in the proposed cube model. Furthermore, with a few qualifications described at the end of this article, the model has appeared to stand the test of time in its ability to account for three decades of dual-task research and to support design decisions (see Wickens, 2002, for a recent summary).

Alternative multiple resource models have been proposed. Two have been grounded most prominently in the hemispheric laterality framework described earlier. Polson and Friedman (1988) focused exclusively on this dimension, whereas Boles (Boles, 2002; Boles, Bursk, Phillips, & Perdelwitz, 2007; Boles & Law, 1998), using factor analysis, has further differentiated auditory and visual processing within each hemisphere into subprocesses such as spatial positional, spatial quantitative, auditory linguistic, and auditory emotional resources. In this manner, 14 separate perceptual resources emerge (and 17 overall). This structure also has been evaluated in dual-task paradigms, revealing that task pairs with a greater degree of resource overlap suffer greater dual-task decrements. With the proliferation of more resources, it becomes more difficult to precisely associate each with brain locations (and therefore gain full neurophysiological plausibility; Wickens, 2007), but fMRI technology offers promise that such association might be forthcoming.

Both EPIC (Kieras, 2007; Meyer & Kieras, 1997) and a model of threaded cognition (Salvucci & Taatgen, 2008) invoke multiple resource constructs within perceptual modalities to account for dual-task interference patterns. Finally, single-channel bottleneck theory (Pashler, 1998) represents a version of multiple resource theory (although not cast in those terms), based primarily on the stage dimension. Here response selection depends on a very limited supply of resources, forcing essentially on sequential processing with high time demand tasks, whereas perceptual-cognitive resources are limited but more available. As noted by Wickens and Hollands (2000), such multiple resource assumptions are quite consistent with data from the double-stimulation paradigm (Pashler, 1989, 1998).

A COMPUTATIONAL MODEL

We have recently developed a relatively simple computational model of multiple resources, following a more elaborate version described and validated in Sarno and Wickens (1995). This simple model (Horrey & Wickens, 2003; Wickens, 2002, 2005; Wickens, Dixon, & Ambinder, 2006) predicts total interference between a time-shared pair of tasks to be the sum of two components, a demand component (resource demand) and a multiple resource conflict component (degree to which overlapping resources are required). Each of these components can range in ordinal values from 0 to 4, providing a simple, intuitive, and bounded scale.

For the demand component, each task is specified as being automated (D = 0), easy (D = 1), or difficult (D = 2), independently of which resources may be demanded (e.g., perception vs. response, auditory vs. visual). Hence, the total task demand can range from 0 (two automated tasks) to 4 (two difficult tasks).

For the resource conflict component, the two tasks are compared in the extent to which they share demands on common levels of each of the four dimensions of the 3-D + 1 multiple resource model, 0, 1, 2, 3, or 4. From the sum of these two components, a total interference component can be produced ranging from 0 to 8. This is a simplified version of the kind of computation that goes into predicting multitask workload, in software packages such as IMPRINT© (Laughery, LeBiere, & Archer, 2006) or MIDAS (Booher & Minninger, 2003; Gore & Jarvis, 2005). Of course, the simple prediction of the total interference between tasks does not inform the modeler as to which task suffers when there is interference, and hence added use must be made of a third, resource allocation component of the multiple resource model, which can express, for example, the extent to which driving versus cell phone conversation suffers when the two compete for multiple resources. This issue is discussed later.

Although the validation of a more elaborate version of this computational model is described in Sarno and Wickens (1995) and in Wickens et al. (2006) in studies demonstrating the importance of invoking multiple rather than single resource models, a third validation has been described (Horrey & Wickens, 2003). The experimental data, reported in Horrey and Wickens (2004), were those collected in a high-fidelity driving simulator, as drivers drove on roadways of three differing demands (varying traffic and curvature) while engaging in concurrent tasks delivered in different modalities (auditory, visual head up, and head down). A slightly modified (but conceptually equivalent) version of the multiple resource formula was imposed on the task interference data created by these nine conditions of the 3 × 3 design for the three tasks of lane keeping, responding to unexpected hazards, and performing the in-vehicle task. For each task, the dual-task interference score was assessed by subtracting the single-task (baseline) performance measure. The analysis revealed great success in predicting both hazard response (98% of variance accounted for by the model) and in-vehicle task performance (92%). However, the model did not predict differences in lane-keeping performance well at all for two reasons: (a) separate ambient and focal vision channels which were not included in that version of the model. Thus, for example, it is the ambient vision of the upper visual field that allows the driver to glance downward and still keep the car headed forward in the lane center (Horrey et al., 2006). (b) Drivers protected lane keeping from interference (treated it as the primary task), hence protecting it from variance in interference caused by structural differences in task resource competition. This clearly demonstrates the resource allocation effect.

Before I conclude this section on multiple resource model prediction, it is important to emphasize that the primary value of such a model is predicting relative differences in multitasking between different conditions or interfaces. Such a model is not designed to make *absolute* predictions of performance – that is, generate a predicted multitask performance level that can be designated as acceptable or unacceptable. This issue as related to workload will be addressed later.

MULTIPLE RESOURCES AND WORKLOAD

Multiple resource theory and mental workload are two related concepts that are often confused. They overlap but are distinct. To distinguish them, remember that the multiple resource model architecture consists of three components related to demand, resource overlap, and allocation policy. The concept of mental workload relates most strongly to the first of these, characterizing the demand imposed by tasks on the human's limited mental resources, whether considered as single or multiple (Moray, 1979).

Importantly, this demand can be conceptually associated with one of two "regions" of task demand level (Wickens & Hollands, 2000). The first is one in which the demand is less than the capacity of resources available (i.e., there is "residual capacity" unused in task performance). This is the ideal state because it means that the worker will have some resources available should unexpected circumstances be imposed. The second region is one in which the demand exceeds the capacity, and, as with any economic system (Navon & Gopher, 1979), performance will break down. Sometimes the distinction between these regions is referred to as a “red line” of workload (Grier, 2008).

Task demand, varying along this continuum, can result from either single-task demand (e.g., driving progressively faster on a winding road imposes progressively more resource demand, until lane keeping begins to fail) or dual-task demand. In characterizing single-task demand, the “multiple” aspect of multiple resource theory has little relevance. Furthermore, whether one is doing one or two tasks in the “residual capacity” region, multiple resource theory is not fully germane. Only in the region where overload is imposed by multiple tasks does multiple resource theory make an important contribution to mental workload by predicting how much performance will fail once overload has been reached (i.e., the size of dual-task decrements). Here multiple resource theory can of course also provide guidance as to how redesign can restore performance to the residual capacity region.

This distinction between regions is critical because most measures of workload are designed as much for the residual capacity region as for the overload region, if not more so (Gawron, 2008; Tsang & Vidulich, 2006). Secondary tasks are explicitly designed to probe “residual capacity” not used for a primary task; physiological and subjective measures operate across the entire range of both regions (and do not generally distinguish which resources, within the multiple resource framework, are used). Thus, the greatest value of such measures is to ensure that task demands can remain within the residual capacity region. Importantly, some models, such as IMPRINT© (Laughery et al., 2006) or MIDAS (Gore & Jarvis, 2005) do have a mental workload component, with task competition based on multiple resource theory and with workload channels defined to correspond to the dimensions in Figure 1. However, this component is really intended to predict performance decrements in the overload region as a result of multitask requirements, which, as we saw, represents only one portion of the workload concept. Such models have been employed in important design decisions regarding workload and crew size (Booher & Minninger, 2003).

FUTURE CHALLENGES FOR MULTIPLE RESOURCES

Although the multiple resource model has been able to account for a good deal of variance in time-sharing efficiency when heterogeneous tasks are imposed (Horrey & Wickens, 2003; Liu & Wickens, 1992; Sarno & Wickens, 1995; Wickens & Colcombe, 2007; Wickens, Goh, Helleberg, Horrey, & Talleur, 2003; Wickens, Sandry, & Vidulich, 1983), both the theory and the model remain challenged by a number of issues. These include the following:

- Adding another level to the modalities dimension, related to tactile input (Boles et al., 2007)
- The fact that other mechanisms, unrelated to resources, also account for variance in dual-task performance. In particular, these relate to confusion between task elements (e.g., the problems of time-sharing a perception and working memory task both using digits; Hirst & Kalmar, 1987) and cooperation between elements (e.g., dual-task processing supported by different dimensions of a single object; Duncan, 1979; Wickens & Hollands, 2000).
- The inability to characterize resource demand on a single scale, on which the “red line” distinguishing the reserve capacity from the overload region can be placed (Hart & Wickens, 1990; Grier, 2008)
- Understanding what drives the allocation policy. In the laboratory, this often can be driven by primary and secondary task instructions (Tsang, 2006), but in the real world, phenomena such as unwanted diversion of attention to interruptions (Trafton & Monk, 2008), “cognitive tunneling” (Wickens & Alexander, in press), and auditory preemption (Horrey & Wickens, 2004; Wickens & Colcombe, 2007; Wickens, Dixon, & Seppelt, 2005) often operate in ways that are clearly at odds with optimal allocation, as witnessed by the safety compromise of driving while using a cell phone (Strayer & Drews, 2007). Such findings are consistent with recent developments that allocation policy is a function closely related to that of the *central executive,* a construct well established to account for differences in time-sharing efficiency (Engle, 2002; Monsell, 2003; Wickens & McCarley, 2008), as well as to identifiable prefrontal brain regions (Kramer & Parasuraman, 2007).

Such challenges await the allocation of research resources to the interested human factors investigator.

ACKNOWLEDGMENTS

I thank Dr. Bill Horrey and Dr. David Boles for their comments on this manuscript.

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Christopher D. Wickens is a senior scientist at Alion Science Corporation, Micro Analysis & Design Operations, Boulder, Colorado, and professor emeritus at the University of Illinois at Urbana-Champaign. He received his Ph.D. in psychology from the University of Michigan in 1974.

Date received: September 7, 2007
Date accepted: February 26, 2008