Multiple resources and performance prediction

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This paper describes the origins and history of multiple resource theory in accounting for differences in dual task interference. One particular application of the theory, the 4-dimensional multiple resources model, is described in detail, positing that there will be greater interference between two tasks to the extent that they share stages (perceptual/cognitive vs response) sensory modalities (auditory vs visual), codes (visual vs spatial) and channels of visual information (focal vs ambient). A computational rendering of this model is then presented. Examples are given of how the model predicts interference differences in operational environments. Finally, three challenges to the model are outlined regarding task demand coding, task allocation and visual resource competition.

1. Introduction

Driving along a crowded highway on a rainy evening, while trying to glance at the map and search the road side for the right turn off, the driver's cellular phone suddenly rings. The driver feels compelled to answer it and engage in conversation with the caller. Will the driver be successful? What is the likelihood that this added demand will seriously impair safety? Could a different interface on the phone make a difference? Suppose the map was presented in a head up location? Will the benefits of not having to look downward be offset by the clutter costs of trying to see two overlapping images? (Tufano 1997, Fadden *et al.* 1998.)

Multiple resource theory is a theory of multiple task performance typical of that carried out by the driver in the example above, that has both practical and theoretical implications. The practical implications stem from the predictions that the theory makes regarding the human operator's ability to perform in high workload multi-task environments, such as the automobile in heavy traffic, the aircraft pilot while landing, or the secretary in a busy office. These practical implications are often expressed in a particular instantiation of multiple resource theory, which we identify as a multiple resource *model*. In the applied context, the value of such models lies in their ability to predict *operationally meaningful* differences in performance in a multi-task setting, that result from changes (in the operator or in the task design) that can be easily coded by the analyst and the designer. In the theoretical context, the importance of the multiple resource concept lies in its ability to predict dual task interference levels between concurrently performed tasks, to be consistent with the neurophysiological mechanisms underlying task performance, and to account for variability in task interference that cannot easily be explained by simpler

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models of human information processing such as 'bottleneck' or 'filter' theory (Broadbent 1958, Welford 1967).

In both contexts, the distinction between 'multiple' and 'resources' is critical, and this distinction will remain an important theme throughout this article. The concept of 'resources' connotes something that is both *limited* and *allocatable* (i.e. can be distributed between tasks). The concept of 'multiple' connotes parallel, separate or relatively independent processing. Multiple resources formally defines the intersection between these two concepts, but each concept on its own has a great deal to contribute towards understanding time sharing (multiple task) performance.

Multiple resource theory, and its *performance* predictions are often closely related to two other concepts in engineering psychology: *attention*, and *workload*. Thus, it becomes important to highlight the distinctions between these, and the manner in which multiple resource theory is not exclusively a theory of attention nor of workload. On the one hand, despite the close relation between attention and dual task performance (as in 'successful divided attention' is involved in successful dual task performance), the two are far from synonymous. Attention also connotes awareness; and differences in multiple task performance (its success or its breakdowns) need have little to do with changes in awareness. On the other hand, as we shall see, the concept of workload is relatively closely aligned with the 'resources' aspect of multiple resource theory, but far less so with the 'multiple' aspect. An important distinction is that many workload issues are closely related to the *potential* to perform in high demand situations, and the various measures (many of which are unrelated to performance) that can be used to assess this potential, whereas multiple resources is directly related to the *actual* performance observed. Furthermore, workload concepts have recently been brought into play in 'underload' situations, where the concepts of task interference are less relevant (Young and Stanton 1997). However, the value of multiple-resources lies nearly entirely in its ability to account for performance in the 'overload' situation, where the operator is called on to perform two or more tasks at one time. In this regard, while multiple resource theory is sometimes called a workload theory, it is only in the sense that it predicts *performance* breakdowns in high workload circumstances.

In the following pages, we will first trace the origins and tenets of multiple resource theory, and then describe one particular version of the theory, the 4-dimensional multiple resource model proposed by Wickens (1980) and elaborated by Wickens and Hollands (2000). We demonstrate how this model can be implemented in a computational form, and conclude by describing some of its limitations and challenges.

2. History and origins

The origins of multiple resource theory can be traced, originally, to the concept of a 'single channel bottleneck' in human information processing, a bottleneck which limited the ability to perform two high speed tasks together as effectively as either could be performed alone (Craik 1948, Broadbent 1958, Welford 1967). Such a view was very prominent in the analysis of high-speed tasks (reaction time tasks in the psychologist's laboratory), and suggested that time was a very limited resource which *could not be shared* between tasks. Moray (1967) wrote a seminal article in which he described, instead of a non-sharable, non-divisible time resource, the concept that the human possessed a 'limited capacity central processor' that *could* be shared, to some extent, between tasks. Such a concept was captured elegantly in a model of attention proposed by Kahneman (1973), as well as in applied work by Rolfe (1973).

The general approach of all of these limited, but sharable, capacity models, which we can call 'resource models' is that task demand—the resources demanded by a task necessary to achieve a given level of performance—is not fixed. Rather, such models assume that mental resources from a limited source can be supplied (allocated) as necessary to meet the task demands defined jointly by the level of difficulty of the task and the level of performance required. Such resources that are left over (residual resources or 'spare capacity') can then be allocated to other tasks. Accordingly, if a task demands more resources, it will interfere more with a concurrent task. Tasks that demand no resources are said to be 'automated' (Fitts and Posner 1967, Schneider 1985). Tasks that demand the full allocation of resources to obtain maximum performance are said to be fully 'resource limited'. Tasks for which maximum performance can be obtained by only investing partial resources is said to be 'data limited' (Norman and Bobrow 1975). Such a continuum between heavily resource demanding tasks, and highly automated ones closely captures the knowledge-based, rule-based, skills-based behaviour continuum proposed by Rasmussen (1986), following on the heels of earlier conceptions of practice set forth by Fitts and Posner (1967).

During the decades of the 1960s and 1970s, there were numerous experiments that documented these tradeoffs between the primary task demand and secondary task performance (as well as other basic laboratory research that suggested that the single channel bottleneck was not as extreme in its limitations as first suggested, e.g. Keele 1973). Importantly, many of these experiments went further to identify converging operations that could characterize the notion of a 'resource demand'. These included measures such as subjective ratings, physiological indices of arousal (heart rate variability, pupil diameter and, more recently, cerebral blood flow) and, most importantly, some objectively definable *task characteristic* that could be posited, *a priori*, to influence resource demands. Example of such task characteristics are the bandwidth of information, the working memory load, or the skill level of the operator performing the task. The importance of all three of these converging operations (subjective, physiological and task-analytic), is that they keep the concepts of 'resource' and 'resource demand' from being totally circular ones in the prediction of dual task interference. That is, they avoid the circularity of saying that a task interferes more because of its higher resource demand, and its resource demand is inferred to be higher because of its greater interference. Resources can, thus, be defined as an 'energetics' concept (Kahneman 1973, Hockey *et al.* 1986) like mental effort, that can be characterized independently of its influence on dual task performance.

From the above discussion, the close association between the resource aspects of multiple resources, and the concept of mental workload (Moray 1979) should be evident: mental workload describes the relation between the (quantitative) demand for resources imposed by a task and the ability to supply those resources by the operator.

It should be noted also that investigators are often silent as to exactly what those 'resources' are. The original single channel model ascribes the limited resource to be time, as others have also more recently done (e.g. Hendy *et al.* 1997). Indeed, there are plenty of circumstances in which time can be viewed as not only a limited resource, but also the *only* limited resource that matters (Hendy *et al.* 1997). Yet, there are many other circumstances in which task difficulty can be expressed in ways that don't readily correlate with time demands (Carpenter *et al.* 1999). One can imagine, for example, a 'mindless' task that may occupy one's behavior 100% of the time, yet have little interference with many other tasks, and indeed have little demand characteristics (tapping one's fingers, walking or whistling, or listening to 'light' music are examples). If time demand were all that were responsible for task interference, then these tasks should interfere with others as much as heavily demanding tasks, like note-taking, passing a vehicle on a two-lane road, or rehearsing a telephone number. However, experience informs us that they do not.

3. Multiple resources

Subsequent to the development of a general resource model of task interference (i.e. the loss in performance levels of one or both tasks, as a function of their concurrent performance; Kahneman 1973), evidence emerged that a good bit of variance in dual task performance could *not* be attributed just to the difficulty (quantitative resource demand) of one or more component tasks, nor to the resource allocation policy between them (i.e. which task is 'favoured' and which is 'neglected'). Instead, evidence was provided that differences in the *qualitative* demands for information processing structures led to differences in time-sharing efficiency (e.g. Kantowitz and Knight 1976, Wickens 1976). Such structures thus behaved as if they were supported by separate (limited) resources. Time-sharing between two tasks was more efficient if the two utilized separate structures than if they utilized common structures (Kantowitz and Knight 1976, Wickens 1976, North 1977).

An obvious example of such a structural distinction is between the eyes (visual processing) and the ears (auditory processing). In many circumstances, dual task performance is poorer when two visual tasks must be time shared than in a configuration in which the equivalent information for one of the tasks is presented auditorally (e.g. Treisman and Davies 1973). To cite a more concrete example, the vehicle driver will have more success (at driving and comprehension) while listening to a set of instructions than while reading the same set (Parkes and Coleman 1990). That is, the eyes and ears behave as if they define multiple processing structures or 'resources'. Wickens (1980) performed a sort of meta analysis of a wide variety of multiple task experiments in which structural changes between task pairs had been compared, and found strong evidence that certain structural 'dichotomies' (like auditory vs visual processing), described in more detail below, behaved like separate resources.

It should be noted here that this aspect of multiplicity (to make parallel processing more feasible, and improve the level of multiple task performance) does not necessarily have to be linked to a 'resource' concept. However, in a classic article, Navon and Gopher (1979) laid out the clear intersection between the 'multiplicity' and the 'resource' (demand level) components, in the context of the economics theory of scarce resources. Their theory made explicit predictions about the different tradeoffs between two time-shared tasks, that result as a function of their degree of shared resources, their quantitative resource demands, and the allocation policy adopted by the performer regarding which task was favoured. In a parallel effort, as noted above, Wickens (1980) then identified the particular structural dimensions of human information processing that met the joint criteria of accounting for changes in time-sharing efficiency, and being associated with neurophysiological mechanisms which might define resources. This particular set of dimensions provided the basis for one particular multiple resource *model*, which is the focus of the remainder of the paper.

4. The four-dimensional multiple resource model

The multiple resource model proposes that there are four important categorical and dichotomous dimensions that account for variance in time-sharing performance. That is, each dimension has two discrete 'levels'. All other things being equal (i.e. equal resource demand or single task difficulty), two tasks that both demand one level of a given dimension (e.g. two tasks demanding visual perception) will interfere with each other more than two tasks that demand separate levels on the dimension (e.g. one visual, one auditory task). The four dimensions, shown schematically in figure 1, and described in greater detail in the following pages, are processing *stages*, perceptual *modalities*, visual *channels*, and processing *codes*. Consistent with the theoretical context of multiple resources, all of these dichotomies can be associated with distinct physiological mechanisms.

4.1. *Stages*

The resources used for perceptual activities and for cognitive activities, e.g. involving working memory, appear to be the same, and those resources are functionally separate from those underlying the selection and execution of responses (figure 2). Evidence for this dichotomy is provided when the difficulty of responding in a task is varied and this manipulation does not affect performance of a concurrent task whose demands are more perceptual and cognitive in nature or, conversely, when increases in perceptual cognitive difficulty do not much influence the performance of a concurrent task whose demands are primarily response-related.

This stage dichotomy can be supported by physiological evidence. In a series of experiments by Isreal *et al.* (1980a, b), the amplitude of the P300 component of an evoked brain potential elicited by a series of counted tones is assumed to reflect the

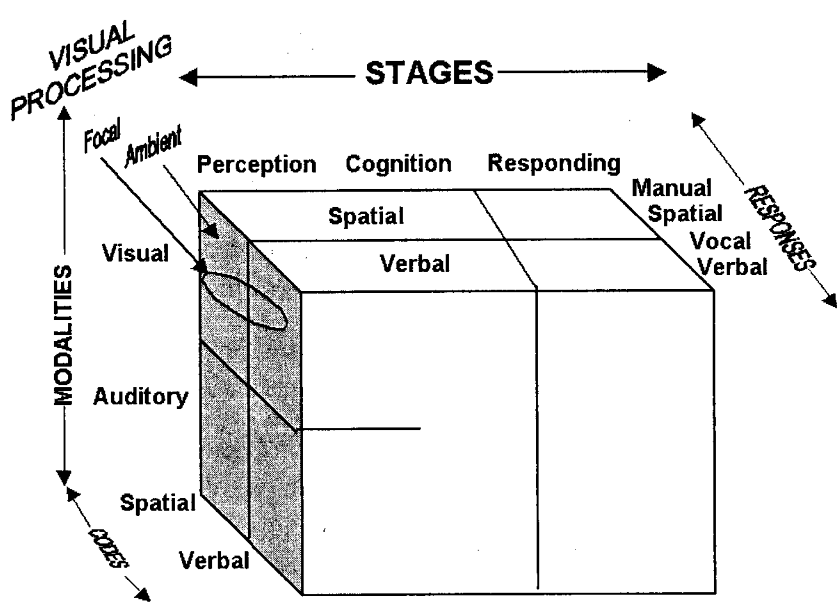

Figure 1. Three-dimensional representation of the structure of multiple resources. The fourth dimension (visual processing) is nested within visual resources.

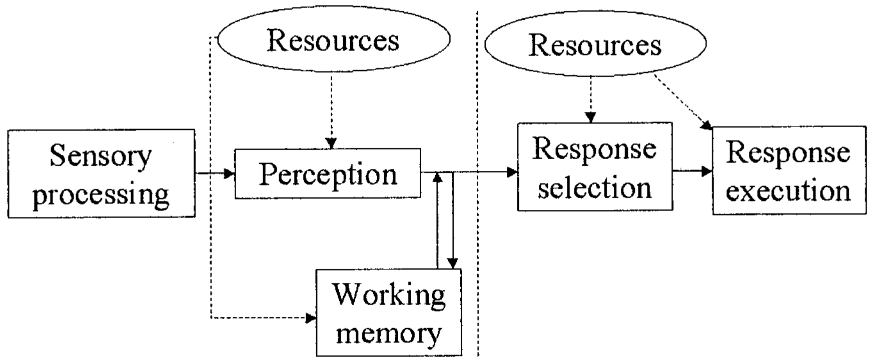

Figure 2. Representation of two resources, supplying the different stages of information processing. Sensory processing, the operation of the peripheral visual and auditory systems, is assumed to be relatively resource-free (after Wickens and Hollands 2000).

investment of perceptual and cognitive processing resources, since the P300 can be elicited without requiring any overt responses. The experiments revealed that the P300 is not sensitive to response-related manipulations of tracking difficulty but *is* influenced by manipulations of display load. Shallice *et al.* (1985) examined dual-task performance on a series of tasks involving speech recognition (perception) and production (response) and concluded that the resources underlying these two processes are somewhat separate. It is important that the stage dichotomy can be associated with different brain structures. That is, speech and motor activity tend to be controlled by frontal regions in the brain (forward of the central sulcus), while perceptual and language comprehension activity tends to be posterior of the central sulcus.

As an operational example of separate stage-defined resources, we would predict that the added requirement for an air traffic controller to acknowledge vocally or manually each change in aircraft state (a response demand) would not disrupt his or her ability to maintain an accurate mental picture of the airspace (a perceptual-cognitive demand).

As shown in figure 2, the stage dichotomy of the multiple resource model also predicts that there will be substantial interference between resource-demanding perceptual tasks and cognitive tasks involving working memory to store or transform information (Liu and Wickens 1992). Even though these define different stages of information processing, they are supported by common resources. For example, visual search coupled with mental rotation, or speech comprehension coupled with verbal rehearsal, both provide examples of operations at different stages (perceptual and cognitive) that will compete for common stage-defined resources, and will thus be likely to interfere.

4.2. *Perceptual modalities*

It is apparent that we can sometimes divide attention between the eye and ear better than between two auditory channels or two visual channels. That is, cross-modal time-sharing is better than intra-modal time-sharing. As examples, Wickens *et al.* (1983) found advantages to cross-modal over intra-modal displays in both a laboratory tracking experiment and in a fairly complex flight simulation. Parkes and Coleman (1990) found that discrete route guidance was better presented auditorily than visually while subjects were concurrently driving a simulated vehicle (driving has heavy visual attention demands). Wickens (1980) reviews several other studies that report similar cross-modal advantages.

The relative advantage of cross-modal (auditory-visual or AV) over intra-modal (VV and AA) time-sharing may not, however, really be the result of separate perceptual resources within the brain, but rather the result of the peripheral factors that place the two intra-modal conditions (VV and AA) at a disadvantage. Thus, two competing visual channels (VV), if they are far enough apart, will require visual scanning between them—an added cost. If they are too close together they may impose confusion and masking, just as two auditory messages (AA) may mask one another if they occupy nearby or overlapping temporal frequencies. The degree to which peripheral rather than central factors are responsible for the examples of better cross-modal time-sharing (AV better than AA or VV) remains uncertain and, when visual scanning is carefully controlled, cross-modal displays do not always produce better time-sharing (Wickens and Liu 1988). However, in most real world settings, visual scanning is enough of a factor that dual-task interference can be reduced by off-loading some information channels from the visual to the auditory modality (Seagull *et al.* 2001). Furthermore, simultaneous auditory messages are sufficiently hard to process that an advantage can usually be gained by displaying one of them visually (Rollins and Hendricks 1980).

The issue of whether the advantage of separating auditory and visual displays is entirely a sensory phenomenon, related to visual scanning and auditory masking in the intra-modality case, or whether there are separate auditory and visual resources within perception, is one that remains unresolved. It is clear that some experiments which have carefully controlled these peripheral factors *have* found cross-modal advantages (see Wickens 1980, 1984 for a review). However, it is equally clear that there may be some non-resource factors that may offset a separate-resource advantage, in particular the attention-capture or 'pre-emptive' characteristics of auditory information (Wickens and Liu 1988, Spence and Driver 2001, Helleberg and Wickens 2002).

4.3. *Visual channels*

In addition to the distinction between auditory and visual modalities of processing, there is good evidence that two aspects of visual processing, referred to as *focal* and *ambient* vision, appear to define separate resources in the sense of (a) supporting efficient time-sharing, (b) being characterized by qualitatively different brain structures, and (c) being associated with qualitatively different types of information processing (Leibowitz *et al.* 1982, Weinstein and Wickens 1992, Previc 1998). Focal vision, which is nearly always *foveal*, is required for fine detail and pattern recognition (e.g. reading text, identifying small objects). In contrast, ambient vision heavily (but not exclusively) involves peripheral vision, and is used for sensing orientation and ego motion (the direction and speed with which one moves through the environment). When we successfully walk down a corridor while reading a book, we are exploiting the parallel processing or multiple resource capabilities of focal and ambient vision, just as we are when keeping the car moving forward in the centre of the lane (ambient vision) while reading a road sign , glancing at the rear view mirror or recognizing a hazardous object in the middle of the road (focal vision). Aircraft designers have considered several ways of exploiting ambient vision to provide guidance and alerting information to pilots, while their focal vision is heavily loaded by perceiving specific channels of displayed instrument information (Stokes *et al.* 1990, Liggett *et al.* 1999).

It is appropriate to ask whether the successful time sharing of focal and ambient visual tasks results because ambient vision uses separate resources, or because it uses *no resources* at all; that is, processing from ambient vision may be said to be 'pre-attentive' or automated. At the present time, insufficient data exist to answer this question, as few researchers have attempted to examine dual task performance of two ambient tasks. One study (Weinstein and Wickens 1992), however, did suggest that the second (pre-attentive/automatic) explanation offered above may in fact be the more correct one.

4.4. *Processing codes*

This dimension defines the distinction between analogue/spatial processes and categorical/symbolic (usually linguistic or verbal) processes. Data from multiple task studies (Wickens 1980) indicate that spatial and verbal processes, or *codes*, whether functioning in perception, working memory or response, depend on separate resources, and that this separation can often be associated with the two cerebral hemispheres (Polson and Friedman 1988). See also Paivio (1971), Baddeley (1986) and Logie (1995) for parallel views on the important distinctions between spatial and verbal working memory or cognitive operations.

The separation of spatial and verbal resources seemingly accounts for the relatively high degree of efficiency with which manual and vocal responses can be time-shared, assuming that manual responses are usually spatial in nature (tracking, steering, joystick or mouse movement) and vocal ones are usually verbal (speaking). In this regard, investigations by McLeod (1977), Wickens (1980), Wickens *et al.* (1983), Tsang and Wickens (1988), Vidulich (1988), Wickens and Liu (1988), Martin (1989), and Sarno and Wickens (1995) have shown that continuous manual tracking and a discrete verbal task are time-shared more efficiently when the discrete task employs vocal as opposed to manual response mechanisms. Also consistent is the finding that discrete manual responses using the non-tracking hand appear to interrupt the continuous flow of the manual tracking response, whereas discrete vocal responses leave this flow untouched (Wickens and Liu 1988).

An important practical implication of the processing codes distinction is the ability to predict when it might or might not be advantageous to employ voice vs manual control. As noted by Brooks (1968) and confirmed in a more applied context by Wickens and Liu (1988), manual control may disrupt performance in a task environment imposing demands on spatial working memory (e.g. driving), whereas voice control may disrupt performance of tasks with heavy verbal demands (or be disrupted by those tasks, depending on resource allocation policy). Thus, for example, the model predicts the potential dangers of manual dialing of cellular phones, given the visual, spatial and manual demands of vehicle driving, and it suggests the considerable benefits to be gained from voice dialing (Goodman *et al.* 1999). The code dichotomy also accounts for the greater disruption of background music when it has words, in the typical office environment, in which verbal processing is heavily employed (Martin *et al.* 1988).

Figure 1 presents the four dimensions of the model in a graphical form. Each line boundary in the 3-D cube separates the two categorical levels of each dimension (i.e. separate resources). The figure shows how the distinction between verbal and spatial codes is preserved across all stages of processing, the way in which the distinction between auditory and visual processing is defined at perception, but not within cognitive or response processing, and the way in which the distinction between ambient and focal vision is 'nested' only within the visual resources.

5. Model design applications

The most important applications of the multiple resource model are to predict the level of *performance* of two or more time shared tasks. Stated in other terms, the model is used to predict the level of disruption or interference between two tasks when they must be time-shared. That is, the model is most applicable in the high demand multi-task environment, typical of the vehicle driver, overworked secretary, or commander in an emergency operations mode. In this context, the model can be employed either in a more informal intuitive fashion, or in a more formal computational fashion.

In the informal use, the model can serve to guide designers in making decisions such as those described above: when is it better to use voice control than manual control, to use auditory rather than visual displays, or to use spatial graphic, rather than verbal material (e.g. maps vs route lists for delivering navigational instructions). In employing multiple resource theory to guide such dichotomous categorical design decisions, it is of course important to bear in mind the other consequences of switching from one resource category to another, such as, for example, the fact that a visual–spatial map may be a more compatible means of delivering geographical information than via words. Such a difference would show up in single task performance. Furthermore, because incompatible mappings are more difficult to process, these mappings would influence the quantitative resource demand of the single task and, hence, the amount of dual task interference (Wickens *et al.* 1983, 1984).

More formally, the model can be rendered in such as way as to *compute* the amount of interference predicted between two tasks, as a function of the competition of those tasks for shared resources across the entire array presented in figure 1, and it is this computational aspect of the model that we will describe in some detail (see also North and Riley 1989, Sarno and Wickens 1995).

In presenting the model in its computational form, it is important to consider the *value added* by the multiple resources concept, above the more simple models of task interference, based upon task timeline analysis (e.g. Parks and Boucek 1989, Kirwan and Ainsworth 1992, Hendy *et al.* 1997). In some applications, the value added is not terribly large. Thus, we consider first the pure time-line model. The simple time-line model of task interference identifies the periods in which two (or more) tasks must be performed concurrently, and identifies this as an 'overload' period. 'Workload' can, thus, be defined as the ratio of:

Time required (to perform tasks)/time available.

When this ratio exceeds 1.0 within a specified time interval, then 'overload' has occurred and, according to a strict single channel model, performance of one or the other task must decline below its single task baseline level (or performance of one must be delayed until the other has been completed).

Such a model is quite adequate for predicting or assessing levels of experienced workload (time busy) when the ratio is considerably less than 1.0. The difference between a ratio of 0.30 and 0.80 is a very meaningful one, in deciding for example that the operator with a 0.30 ratio is more able to assume an added task than is the operator with a 0.80 ratio. Furthermore, when all tasks demand a single non-sharable resource, the ratio can be very meaningful. An example of a non-sharable resource is the voice for speaking. It is meaningful to speak of the air traffic controller as having, say, an 80% communications load, if 80% of her time is spent speaking (or listening). In many circumstances, focal vision can be defined as a non-sharable resource, so that workload here can be related to the time during which the eye is scanning a particular area of interest (Wickens *et al.* 2002). As an example, the timeline model is found to predict performance well in a purely visual air traffic control simulation (Hendy *et al.* 1997).

The major limitation with this simple form of task analysis, however, is that it assumes (computationally) that all tasks are alike, insofar as overload prediction is concerned. As the two components of multiple resource theory would suggest, this is not the case. First, tasks vary in their resource demands in ways not accounted for by time. Thus, it is reasonable to say that solving two simultaneous and difficult arithmetic problems is an 'overload', but that monitoring two closely spaced visual channels for infrequent events is not. Correspondingly, driving on an icy highway in turbulent cross winds while conversing, is at or near overload, whereas driving on a smooth highway in light cross winds while conversing is well below the 'overload' state in which task interference would be predicted.

Secondly, any two tasks to be time-shared can vary in their qualitative resource demands, having a great impact on their mutual interference. To cite again the driving task, driving while reading provides a lot of interference (above the 'overload' level), whereas driving while listening to the identical message, will often be well below the overload threshold, even though both of these circumstances occupy the same amount of time in a time-line analysis. Because both of these conditions (varying quantitative and qualitative resource demand) often prevail in complex, high demand environments, computational models must extend beyond simple time line analysis to incorporate multiple resource assumptions in predicting which configurations will be more likely to predict overload.

6. A computational multiple resource model

The computational multiple resource models appear to have their greatest value in predicting the relative differences in task interference between different task configurations. A typical model will possess the following three features:

(1) Each task can be represented as a vector of its resource demands, both at a qualitative level (which resources) and a quantitative level (how many resources). For example, the task of vehicle control in automobile driving may be represented as demanding:

visual – spatial-ambient + manual resources.

(2) The amount of load within each of these resources will be task-dependent. For example, visual/spatial resource demands will increase on dimly illuminated highways at night, whereas manual resource demands will increase on icy roads. Both will increase as vehicle speed increases, as long as some manoeuvring is required.

(3) The model computes a loss of performance on one or both tasks from its single task level by a formula that penalizes performance to the extent that: (a) the total demand on both tasks is high, and (b) both tasks compete for

overlapping resources (common levels on one of the dichotomous dimensions) within the four dimensions of the multiple resource model (or within the dimensions of whatever other model is selected).

(4) The extent to which one or the other of the two tasks loses performance can be established by an allocation policy. If both tasks have equal priority, each task will share equally in the performance decrement.

In order to accomplish these operations computationally, a typical model (e.g. Sarno and Wickens 1995) incorporates the following components:

(1) A *task analysis shell*, in which task demand levels can be input at different resources on each task, i.e. constructing the resource vector. Note that simple default values can be easily assumed (e.g. 1 for some demand on a resource, 0 for no demand). In this case, the 'multiple' aspect of multiple resources becomes more important than the 'resource' aspect.

(2) A *conflict matrix*, in which the amount of conflict, between resource pairs across tasks, is determined. This is the heart and soul of the 'multiple' aspect of the model. Conveniently, it may be assumed that if two tasks cannot share a resource, the conflict value is 1.0 (e.g. two tasks simultaneously demanding voice resources). If two tasks can perfectly share the resources in question, then the value is 0. A convenient heuristic may then be to assume that the amount of conflict is proportional to the number of shared resources within the 4-D model, shown in figure 2. Figure 3 provides an example of a typical conflict matrix involving the three primary dimensions of resource competition shown in figure 1: stages, codes and modalities. It does not include the focal-ambient distinction, although it could be elaborated to do so. The

Task A Resources

		Perceptual				Cognitive		Response	
		VS	VV	AS	AV	CS	CV	RS	RV
	VS	0.8	0.6	0.6	0.4	0.7	0.5	0.4	0.2
	VV		0.8	0.4	0.6	0.5	0.7	0.2	0.4
	AS			0.8	0.4	0.7	0.5	0.4	0.2
Task B	AV			0	.8	0.5	0.7	0.2	0.4
Resources	CS			0		.8	0.6	0.6	0.4
	CV						0.8	0.4	0.6
	RS							0.8	0.6
	RV							0.6	1.0

Figure 3. A typical 'conflict matrix' based upon the three primary dimensions of the multiple resource model. The resources demanded by each task are listed across the rows and down the columns. A and V in the first position = Auditory and ~~Verbal~~ Visual. V and S in the second position = Visual and Spatial. C = cognitive, R = Response. This version of the model does not incorporate the focal-ambient vision dichotomy.

numbers within each cell of figure 3 are derived as follows. First, every channel pair has a baseline conflict value of 0.2, a fundamental 'cost of concurrence' or general capacity for which all tasks compete in a time sharing situation. This might be considered the role of an 'executive processor' (Rogers and Monsell 1995). Secondly, each added dimension of overlapping resources increments the conflict value by 0.2. This can be readily seen by comparing any two adjacent cells (e.g. within the perceptual channels in the upper left hand corner). Thirdly, since cognitive resources do not involve the A-V modality distinction, their conflict with perceptual resources (that do involve this distinction) is defined as an average value between sharing and separate modality resources. (Hence, the odd numbers within the cognitive cells.) While intuition informs us that values along the negative diagonal will be higher than those off of the diagonal, it is not the case that all such values on the negative diagonal will be 1.0. For example, unlike voice responses (which cannot be shared and, hence, deserve a conflict value of 1.0), two tasks may feasibly share the visual spatial channel—not perfectly—but still with a conflict value much less than 1.0. In the matrix example shown, two manual responses show high (0.8), but not impossible conflict (consider turning the steering wheel while activating radio buttons, or sipping a drink. These are possible to perform, but not without considerable mutual interference). Finally, it is, therefore, important in certain circumstances to adjust the particular conflict values given the physical separation of the interfaces for the two channels. Thus, for example, the value on the visual-spatial perception channel will be lowered, if the two visual sources are close together, and increased to the extent that they are widely separated, particularly if they both demand focal processing for their performance. Note that the adjustment of conflict values should *not* be based on differences in single task demands, since these were captured by the single task analysis shell.

(3) A *computational formula* typically consists of two components corresponding to the two components of multiple resources. One penalizes the task pair for its total resource demand value. This penalty may be set to be directly proportional to the sum (across two tasks) of the average (within each task) resource demand value. The assumption underlying this component is identical for a single and a multiple resource model: that is, the amount of interference increases with the difficulty (resource demands) of one or both of the time-shared tasks. The second component penalizes a task pair according to the degree of conflict between tasks on resource pairs with non-zero loadings on both tasks. That is, when there is a non-zero entry in both the row and column associated with a cell, then that cell actively computes a conflict, proportional to its value. This second component can be set equal to the sum of the 'active' cell conflict values across the full matrix.

(4) A *task interference value* will be provided as an output. As the sum of the two components (resource demand and conflict), such a value can be appropriately apportioned to one task or the other, depending on the prioritization scheme.

(5) A *time line analysis* may be applied in circumstances when the particular combination of tasks will be time-dependent. Indeed, sometimes it is possible to approximate the demand level of each task by the time during which a

task is performed (Sarno and Wickens 1995, Hendy *et al.* 1997). In this case, the model, while emphasizing the 'multiple' aspect of multiple resources, de-emphasizes the 'resource' aspect (i.e. it de-emphasizes the quantitative aspects).

7. An example

To provide a very simple example of such a computation, let us consider the model shown in figure 4 which postulates only two resources: perceptual cognitive (PC) vs response (R).

Consistent with the original multiple resource model, this matrix shows greater conflict within a stage (the negative diagonal) than across stages (the positive diagonal). Furthermore, consistent with single channel bottleneck models of processing, it portrays the inability to respond to two tasks at once (1.0), and the greater capacity to time-share the perceptual–cognitive aspects of a pair of tasks (0.80).

Now consider three tasks. Task A involves pure, demanding monitoring, so its vector of demands across the two resources will be [2,0]. Task B involves standard information transmission (e.g. a tracking task) involving perception and response [1,1]. Task C is also a tracking task, but has an incompatible control, so that control movement must be reversed from the expected direction in order to correct an error. Because display–control compatibility is found to influence the difficulty of response selection (Wickens and Hollands 2000), its demands are [1,2]. Table 1 shows the predicted interference patterns resulting from the two components of the formula (total demand and resource conflict), across the six possible dual task combinations reflected by the different two-way combinations of the three tasks, A, B and C. The demand component is computed by summing the average demand, across all resources, within a task (and summing over both tasks). The conflict component is computed by summing the conflict matrix components of all cells that are demanded by both tasks.

	PC	R
PC	.80	.30
R	.30	1.00

Figure 4. A simplified conflict matrix.

Table 1. Predicted total interference values (right column) resulting from six task combinations. The two contributing components from demand (task) difficulty and resource conflict are shown in the two columns to the left.

Task	Demand component	Conflict component	Total interference
AA	$1+1=2$	$0.8+0+0+0=0.8$	2.8
BB	$1+1=2$	$0.8+1+0.3+0.3=2.4$	4.4
CC	$1.5+1.5=3$	$0.8+1+0.3+0.3=2.4$	5.4
AB	$1+1=2$	$0.8+0+0.3+0=1.1$	3.1
AC	$1+1.5=2.5$	$0.8+0+0.3+0=1.1$	3.6
BC	$1+1.5=2.5$	$0.8+1+0.3+0.3=2.4$	4.9

7.1. *Implementing the matrix*

In implementing a matrix and its computational formula, a few important issues should be born in mind. First, the computation of conflicts should only be carried out between tasks, and not between resources within a given task. It is a reasonable simplifying assumption that the latter conflict is nil. That is, since most tasks accomplish information processing activities in sequence within the task, concurrent performance of resources within a task is not required. (There may be some obvious exceptions to this, such as the task of note-taking in lecture, when writing may interfere with speech understanding. However, the added complexities of the model to handle such exceptions do not appear to be worth the added variance that it may account for in these few circumstances.)

Secondly, caution should be placed on interpreting the precise meaning of a single numerical output. The value of the model is realized instead in the comparison between the outputs with different configurations (e.g. changing input or output modalities, or making processing at a particular stage more difficult). For example, its value is realized in predicting the *relative* ease of time-sharing across the six rows of table 1. Thirdly, the analyst should not be too concerned about establishing precise levels of demand values. As noted above, in many circumstances, simply using the values of 0 and 1 is adequate to account for important variance in task interference, and three-level coding (0, 1, 2) is adequate in most circumstances. Fourthly, if the analyst is uncertain as to how a particular aspect of task difficulty affects different resources within a task, it may be assumed that it effects all resources equally. In the example shown in table 1, doubling the difficulty of task B could be assumed to change a [1,1] to a [2,2]. Fifthly, note that in deriving the conflict values within the cells, the example shown in table 1 derives the same values independent of the demand values within a row or column, so long as both are non-zero. It is indeed possible that this conflict matrix value could be multiplied by the sum of the demand values across the two tasks, within a row-column pair. However, such an approach would overly weight the contribution of task demand to total interference, since these demand values have already entered into the first component of the formula.

Finally, a note should be added regarding the default 0.2 conflict value added to all cells. We described this above as a ‘cost of concurrence’ or penalty of executive control, and there is indeed ample evidence in the literature that time-sharing of any two tasks must involve some resource-demanding overload (Navon and Gopher 1979).

7.2. *Value added*

While several different users have implemented various forms of the multiple resource computation to make workload/performance predictions (e.g. Aldrich *et al.* 1989, North and Riley 1989), only one study appears to have specifically examined different components of the model, to assess the predictive ‘value added’ by making different assumptions. In this study, Sarno and Wickens (1995) asked pilots to perform a simulated flight task (visual-spatial manual), while they performed a cognitive side task that could vary in its input modality (visual-auditory), its central processing/cognitive code (verbal spatial), its response code (speech-manual) and its difficulty (easy hard). Task interference measures (decrements in tracking from single task tracking performance as a measure of ‘overload’) were collected across the 16 conditions thus created, by combining factorially the four different experimental variations of the side task, and these interference measures were then correlated with predictions from computational models that made more or less sophisticated assumptions about demand and resources. These different models included those that other investigators had proposed, assuming different structures of multiple resources (e.g. Aldrich *et al.* 1989, North and Riley 1989). Most importantly, Sarno and Wickens (1995) results revealed that a pure time line model predicted very little of the variance between the different conditions. In contrast, a variety of the multiple resource models tested accounted for between 60–70% of the variance in task interference.

The analysis of alternative versions of the model carried out by Sarno and Wickens (1995) also suggested that important predictive capabilities of the model were lost, if the 'multiple' assumptions of the multiple resource concept were abandoned (i.e. in favour of a single resource model). However, less predictability was lost when the 'resource' (i.e. demand level coding) aspect of the model was abandoned, and replaced by the simple assumption that 'more difficult' tasks simply occupied greater time on the time line. Such a finding is consistent with the conclusion offered by Hendy *et al.* (1997), that many aspects of task difficulty can be adequately represented by task time requirements. However, we suggest caution in abandoning the assumptions that demand level accounts for variance beyond time requirements, particularly in light of the fact that (a) demand coding *did* account for some variance in Sarno and Wickens' (1995) study, and (b) in many other environments, prominent differences in demand cannot easily be accounted for by task time, as described above.

8. Conclusions and cautions

In conclusion, the techniques for implementing multiple resource predictions of dual task interference are both intuitive and plausible. Furthermore, ample empirical evidence exists to support both the 'resources' aspect (more difficult tasks create greater interference) and the 'multiple' aspect (structurally similar tasks interfere more). Insufficient research exists, however, to fully understand how these two aspects work together, when heterogeneous, real world tasks are combined, the data of Sarno and Wickens (1995) and a few other studies notwithstanding. Future research must seek the balance between model parsimony, which will force simplifying assumptions (e.g. uniform demand coding) and performance variance accounted for by the model. Indeed, the issue of demand coding of individual tasks remains one of the real sticking points of such a model. Where does the analyst get the 'baseline' values of task components? In this regard, it is noteworthy that some researchers have sought to develop a quantitative scale of demand for different molecular tasks (Aldrich *et al.* 1989), and this scale has become available in software tools for making multiple resource predictions of task interference (IMPRINT; Microanalysis and Design). However, such values themselves may be highly task specific, require confirmation, and of course will be influenced by the practice level (automaticity) of the performer.

A second challenge to the model is the need to better accommodate the concept of resource allocation, i.e. the distribution of resources between two time-shared tasks (whatever their conflict level may be). Of particular concern are the phenomena that we may characterize under the general labels of 'preemption' and 'engagement'. These are circumstances in which one task demands or attracts so much attention to itself that any benefits that might otherwise have been realized by its separate resources are eliminated, as full attention is given to that task; as a consequence, the concurrent task is essentially 'dropped' altogether. Two examples may be identified here. In one laboratory simulation study, Strayer and Johnston (2002) found that cellular phone conversations were so 'engaging', that drivers totally neglected aspects of the concurrent driving task, even though the two tasks were quite (but not totally) separate in their resource demands. In aviation simulation studies, Helleberg and Wickens (2000) and Latorella (1998) found that auditory as contrasted with visual delivery of a side task, performed concurrently with a visual flight task, would indeed compete for fewer resources, but could also interrupt the visual flight task entirely. This interruption resulted as the pilot turns momentarily to deal with the incoming auditory message, a finding consistent with the review of basic research in auditory-visual time-sharing (Wickens and Liu 1988). Such discrete interruption of the ongoing flight task is much less likely to take place when the message is delivered visually. Thus, it will be important to understand the conditions in which preemption, or other intrinsic characteristics that lead to pronounced allocation effects, override, or at least offset, many of the benefits offered by resource separation.

A third challenge concerns visual scanning. In most visual environments, it will be necessary to offer specific guidance on setting conflict matrix values between visual focal sources as a function of their separation (and this will also include visually guided manual activity such as making keyboard entries). Some assistance in this endeavour may be offered by models of focal information acquisition (Wickens 1993, 2000, Previc 1998, 2000) which make the qualitative distinction between (a) two channels both in *foveal* (not focal) vision ($<4°$ visual angle), (b) two channels both within the 'eye field' (4–30°) for which saccadic eye movements, but not head movements, are required, and (c) two channels within the 'head field' ($>30°$). Using these distinctions, implementation of the conflict matrix could boost the cell value of visual interference between focal channels by a constant (0.10) weighting, for each of these three levels of separation.

In conclusion, despite the absence of much empirical validation of the computational multiple resource model, there are many instances in which the human operator is carrying out 'performance' (including non-observable cognitive activity) of two or more tasks at once. Basic psychology and neurophysiology must identify the characteristics of human information processing that make such endeavours more, or less, successful. The analysis and prediction of human productivity and safety in high workload environments requires models to predict such differences.

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