State of science: Mental workload in ergonomics

Mark S. Young[1*], Karel A. Brookhuis[2], Christopher D. Wickens[3] and Peter A. Hancock[4]

1 – School of Engineering and Design, Brunel University, Uxbridge, Middlesex UB8 3PH, UK

2 – Faculty of Behavioural and Social Science, University of Groningen, Grote Kruisstraat 2/1,

9712 TS Groningen, The Netherlands

3 – Alion Science Corporation, Micro Analysis and Design, 4949 Pearl East Circle, Suite 300, Boulder, CO 80301, USA

4 – Department of Psychology, University of Central Florida, Orlando, FL 32816, USA

* - corresponding author, email **m.young@brunel.ac.uk**

State of the science review: Mental workload

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Abstract

Mental workload (MWL) is one of the most widely used concepts in ergonomics and human factors (E/HF), and represents a topic of increasing importance. Since modern technology in many working environments imposes ever more cognitive demands upon operators while physical demands diminish, understanding how mental workload impinges on performance is increasingly critical. Yet MWL is also one of the most nebulous concepts, with numerous definitions and dimensions associated with it. Moreover, MWL research has had a tendency to focus on complex, often safety-critical systems (e.g., transport, process control). Here, we provide a general overview of the current state of affairs regarding the understanding, measurement, and application of MWL in the design of complex systems over the last three decades. We conclude by discussing contemporary challenges for applied research, such as the interaction between cognitive workload and physical workload, and the quantification of workload 'redlines' which specify when operators are approaching or exceeding their performance tolerances.

Practitioner summary

The study of workload in ergonomics has risen in popularity since the 1980s. Applied problems, particularly in transport, have taken centre stage in recent years. New developments in neuropsychological measurement techniques offer promise in quantifying both the interaction of physical and mental workload, as well as the elusive 'redline' performance limit for overload.

Keywords

Mental workload, attention, resources, measurement, applications

1. Context

Mental workload (MWL) is one of the most widely invoked concepts in ergonomics research and practice (Flemisch and Onken 2002; Loft et al. 2007; Parasuraman and Hancock 2001; Tsang and Vidulich 2006; Wickens 2008). System designers and managers invoke this notion when they ask questions such as: How busy is the operator? How complex are the tasks that the operator is required to perform? Can any additional tasks be handled above and beyond those that are already imposed? Will the operator be able to respond to unexpected events? How does the operator feel about the tasks being performed? Answers to these questions can be provided given that the mental workload of an existing system can be measured. The same is true for prospective design or the 'envisioned world' problem, where prospective MWL has to be modelled and/or estimated.

Mental workload has thus become a topic of increasing importance as modern technology imposes ever greater cognitive demands. The study of mental workload really became established within ergonomics during the 1980s, with the publication of major texts on the topic (e.g., Hancock and Meshkati 1988; Moray 1979). A search of Ergo-Abs (the Ergonomics Abstracts online database, which covers international books, journals and conference proceedings across a variety of ergonomics-related fields) over the last three decades (which reflects the vast majority of sources indexed in the database) shows that references to mental workload have increased more than threefold since the 1980s (see table 1).

INSERT TABLE 1 ABOUT HERE

A review of these search results indicates that the focus in the 1980s was much more on the measurement of mental workload, while the 1990s saw a shift towards theoretical developments as well as modelling efforts. Research in the 1990s was also concerned with the proliferation of automation, and a significant body of work was directed at the emergence of more advanced physiological metrics of workload. Finally, the first decade of the 21st century has seen the applied dimensions of mental workload research coming to the fore. Thus the general evolution of research in mental workload has progressed from trying to measure it, through trying to define it, to the real-world applications of it today.

Our paper seeks to present the contemporary state of the art in mental workload research across ergonomics. We broadly follow history's lead in the structure of our paper, by reviewing the areas of definition, measurement and application of mental workload. As well as distilling contemporary knowledge in each of these areas, we also discuss the challenges facing mental workload research now and in the future.

2. Concepts and Definitions

Mental workload is a peculiar concept that has intuitive appeal, but remains surprisingly difficult to define (see also situation awareness; Smith and Hancock 1995). Although numerous definitions have been offered, it is obvious that there is no universal agreement between these disparate statements. There are, however, commonalities among the various interpretations, which do help to shed light here.

An analogy is often made between mental and physical load, in that each expresses two components—stress (i.e., task demands) and strain (impact on the human; cf. Schlegel 1993). Even the international standard on mental workload (ISO 10075) is heavily dependent on the stress/strain analogy for its terminology. Demands (stress) can have multiple facets, such as time pressure or task complexity. There may also be different kinds of resources available, as in other team members, or technological support to cope with demand. Finally, the trade-off between stress and strain may have different effects on the human—as measured by the different objective (task performance, physiological) and subjective metrics which we have already described above (see e.g., Bevan and Macleod 1994).

Therefore, when we consider that stress is comprised of multiple demand factors, and strain itself shows multiple expressions depending on the resources available, explaining mental workload in terms of demand/resource balance offers an attractive and parsimonious approach to this otherwise multidimensional construct (and see Hancock and Warm 1989). Resources, in this arena of discussion, often refer to attentional resources (e.g., Wickens 1980, 2002a)—thus mental workload becomes a product of the resources available to meet task demands (Welford 1978). If demands begin to exceed capacity, skilled operators can either adjust their strategy to compensate, or else performance necessarily degrades. Such a view makes clear predictions about mental workload in any given situation, and observation of performance provides one reflection of mental workload. Resource models of workload are not without their drawbacks, though. For instance, they do not directly consider nonattentional factors, such as experience, or more slowly changing variation due to learning or the failure of capacity with age.

Augmenting the resource perspective, then, models can take into account the level of operator skill, and the extent to which cognitive processing is automatic (Schneider and Shiffrin, 1977). Automatic processing is associated with expert performance, and is characteristically fast, unconscious, and almost completely liberated from attentional resource constraints. The converse is controlled processing, and in the practical world these two elements lie on a continuum. From this view, mental workload in real world tasks is determined by the balance of automatic and controlled processing involved. This is consistent with the attentional resources approach, as automatic processing releases attentional resources for other tasks, with a resulting decrease in mental workload.

Thus, mental workload as a multidimensional construct, is determined by characteristics of the task (e.g. demands, performance), of the operator (e.g. skill, attention), and to a degree, the environmental context in which the performance occurs. In an attempt to bring each of these dimensions together and provide a global definition of mental workload, Young and Stanton (2005, ch. 39-1) have suggested that mental workload reflects 'the level of attentional resources required to meet both objective and subjective performance criteria, which may be mediated by task demands, external support, and past experience.' In this definition, attentional resources are assumed to have finite capacity, beyond which any further increases in demand become manifest in performance degradation. At the same time, the investment of resources is a voluntary and effortful process (Hancock and Warm 1989; Hockey 1997), so performance can be maintained at the cost of individual strain or vice-versa. Performance criteria can be imposed by external authorities, or may represent the internal goals of the individual (Hancock and Caird 1993). Examples of task demands are time pressure or complexity, as we have already seen, and support may be in the form of peer assistance or technological aids. Finally, past experience can influence mental workload via changes in skill or knowledge.

There is an abundance of knowledge about the factors which increase mental workload. For instance, elevation in perceived work required to achieve a goal, and decreased time available to complete that goal can both increase subjective workload. Furthermore, performance and workload are to some extent negatively correlated, such that performance failure is associated with higher perceived workload (Hancock 1989). On the other hand, there seems to be less certainty about the factors which can reduce mental workload. Performance feedback (Becker et al. 1995), and reducing the number of available decision options (Okada 1992), have both been associated with decreases in workload.

One of the reasons to study mental workload is to establish a relationship with operator performance (i.e., when workload is suboptimal leading to errors and incidents). Likely, workload is already suboptimal if performance is below par – below a required, wanted or imposed minimum level – even before any errors occur. Suboptimal workload can mean either overload or underload (Brookhuis and De Waard 2000). Overload occurs, for instance, when the operator is faced with more stimuli than (s)he is able to handle. Performance may well deteriorate seriously when the operator is distracted. Diverted attention is a major cause of collisions in motorized traffic, for instance (see Regan, Lee and Victor 2013). Humans are generally not good at devoting their attention to several sources of information at the same time, unless under special circumstances (e.g., during highly automated tasks such as driving). Dividing attention in itself leads to increases in workload as well. Conversely, too little stimulation leads to underload, at least in the long run, often then leading to drowsiness (Brookhuis et al. 2003; Hancock 2013). Compensatory effort may take care of performance decrements due to drowsiness up to a certain level. Underload through boredom, affecting the operator's capability to deal with the task demands, might be compensated for as well. If effort is exerted, be it computational or compensatory, mental workload will be increased. Effort is a voluntary process under control of the operator while mental workload is determined by the interaction of operator and task. As an alternative to exerting effort, the operator might decide to change the (sub)goals of the task (e.g., Sperandio, 1978; see also Brookhuis and De Waard 2000).

There is now a strong consensus that mental underload can be detrimental to performance just as it is to mental overload. Both can lead to performance degradation, attentional lapses, and errors (Wilson and Rajan 1995). Indeed, the current opinion is that there is an optimum range of mental workload which is associated with best performance (Hancock and Warm 1989; see also figure 1). This again raises the shibboleth of optimal state – the strain of underload or overload is caused by a mismatch between demands and capabilities (Csikszentmihalyi 1990; Yerkes and Dodson 1908). Excessive load can affect selective attention, leading to narrowed or inefficient sampling (Easterbrook 1959). Therefore, there is no direct guarantee that simply reducing mental workload improves performance, and in fact the opposite may be true.

In the complex, safety-critical systems where mental workload research is usually most pertinent and/or most pursued (such as aviation – e.g., Wickens 2002b; rail – e.g., Pickup, Wilson, Sharples et al. 2005; or driving – e.g., Young and Stanton 2004), both underload and overload are very real concerns. But whilst both low and high mental workload are undoubtedly basic precursors to errors, an exact relationship between mental workload and accident causation is not easily established, let alone measured in practice. Brookhuis and De Waard (2000) discriminated between underload and overload by referring to error sources, the former leading to reduced alertness and lowered attention, the latter to distraction, diverted attention and insufficient time for adequate information processing. They studied both underload and overload in relationship to driver impairment; however, the coupling to accident causation is not a direct one. Basic criteria for when impairment is below a certain acceptability threshold (i.e., leading to accidents) have been established (see Brookhuis et al. 2003). The relationship between accidents and mental workload (high or low) needs to be considered in conjunction with factors such as information overload, boredom, or fatigue. The traffic environment and traffic itself will only gain in complexity, at least for the time being, with the rapid growth in numbers of automobiles and telematics applications. Similar concerns can also be voiced regarding air traffic, along with health care demands given the ageing population. Since these are contemporary concerns for applied mental workload research, we return to review those applications in a wider set of operational contexts later in the paper.

3. Measurement

The multidimensional nature of mental workload is reflected in the variety of workload metrics available. In most areas of applied research into mental workload, we distinguish three categories of basic parameters: measures of task performance in the primary and/or the secondary task, subjective reports, and physiological metrics (see also Eggemeier and Wilson 1991; Brookhuis and De Waard 2000). The first, and by far the most used category of measures is based on techniques of direct registration of the operator's capability to perform the primary task at an acceptable level (i.e., with respect to an acceptably low error likelihood and concomitantly high level of efficiency). Using the field of psychological research into traffic behaviour as an example, these measures of task performance are directly related to vehicle handling (i.e., lateral and longitudinal vehicle control, such as steering and car following).

Monitoring attention to and workload from a primary task may be conducted by assessing performance on a secondary task. In any real-world dual task situation with a (genuine) secondary task, performance on the latter (in terms of errors and time) is closely associated with the spare capacity unused by the primary task. This has been shown to be the case for driving in various circumstances (De Waard and Brookhuis 1997).

A suitable tool to assess operators' workload from a primary task is the concurrent performance on a peripheral detection task (PDT). This has been observed and quite precisely determined during driving (Van Winsum, Martens and Herland 1999). The PDT is based on the premise that visual attention narrows as workload increases. Participants wear a headband with an LED light, which lights up randomly every 3–5 s. Participants are instructed to press a switch attached to their index finger as soon as they see the LED signal. As workload increases, the response time to, and the chance of missing a signal respectively increases. The workload is then measured through this monitoring of response times and the number of missed signals (see also Schaap et al., 2008, 2013).

Mental workload is a subjective state as well; people are able to express themselves in words or indications on scales in post-task responses (Zijlstra 1993). Well-known examples of self-reports have traditionally been rather complicated and time-consuming, such as the NASA-Task-Load-indeX (NASA-TLX, Hart and Staveland 1988), the Subjective Workload Assessment Technique (SWAT, Reid and Nygren 1988), and the simple and fast Rating Scale Mental Effort (RSME, Zijlstra 1993). Over the years, different researchers have sought to reduce the complexity of these scales and to reduce their administration time in order to improve validity and accuracy.

Physiological measures are a natural type of workload index since work demands physiological activity by definition. Suboptimal workload may also emerge from distortions in the operator's physiology, for instance when under stress or under low vigilance conditions (Hancock and Warm 1989), although other non-workload stressors (such as from the environment or sleep loss) can influence these indices. Whilst numerous physiological measures are now relatively easily measured in the operational environment, attention is less easily monitored in ambulant situations – but not impossible. For instance, promising data from eye movements and fixations, as well as eyelid positioning have become available lately (e.g., Mallis and Dinges 2004). Visual perception is crucial for drivers while concurrent execution of another visual task, such as in-vehicle looking at a cell phone, competes for visual attention with the primary driving task.

Both physical workload and mental workload are well known to have a clear impact on heart rate, heart rate variability and respiration (Mulder 1992). Mental workload can increase heart rate and decrease heart rate variability at the same time. De Waard (1996) showed that depending on how a situation develops, these differential measures are indicative of workload. Driving on an urban road with traffic, traffic signs and traffic lights leads to increased workload according to these measures (high heart rate, low variability), which immediately reverses when the driver stops if one of the lights turns red. Closely coupled to heart rate and also sensitive to workload is blood pressure (Rau 2004). Other measures of interest are the activity of the brain (De Waard and Brookhuis 1991; Brookhuis and De Waard 1993) and of certain facial muscles (Jessurun, Steyvers and Brookhuis, 1993; Hoogendoorn et al. 2010). Brookhuis and De Waard (2010) described how in driving simulator research, analysis of EEG by means of power density spectra might indicate driver state; for instance, low vigilance occurring in the course of time with increasing drowsiness or as a direct effect of loss of sleep. Mental (de)activation may be monitored by changing balance between brain activity regions. Beta activity (12-30 Hz) is predominant when the participant in the study is generally awake and alert, while the activity dropping to Alpha activity (8-12 Hz) indicates developing drowsiness, and going further down into the theta region (5-8 Hz) may even lead to falling asleep. Facial muscle activation has been found to be indicative of stress-inducing events and consequential exerted effort (Hoogendoorn et al. 2010), under various workload conditions. One of the problems with respect to the measurement of some of these physiological parameters, until not so long ago, was the troublesome procedure of applying electrodes and taking care to minimise noise to signal ratio. Modern integrated, wireless measurement facilities enable more easily accessible EEG-measurement.

Recently, with new information and communications technology, facilities of ambulant brain-computer interfaces (BCI, cf. Zander and Kothe 2011), and brain activity measurement systems such as near-infrared spectroscopy (NIRS) have enabled accessible non-invasive monitoring of operator brain functions in a variety of tasks (cf., Strangman et al. 2002). So far, these methods have been restricted to laboratory conditions, and the equipment is extremely expensive to purchase and use. But some researchers (e.g., Huppert et al. 2006) have demonstrated the feasibility of NIRS, and extensions in brain activity measurements may become increasingly accessible and affordable in the immediate future. Operator conditions in fixed positions such as operating motor vehicles, trains and airplanes are suitable for this next generation of MWL field studies.

Vidulich and Wickens (1986) observed that changes in subjective workload do not always parallel changes in task performance. If one measure reflects an increase in workload and another measure does not, then measures are said to dissociate (see also Hancock 1996; Yeh and Wickens 1988). Dissociation has usually been reported between self-reports and measures of performance, and sometimes between physiological and self-report measures (Myrtek et al. 1994). Often this is not a problem per se; on the contrary, this is a potentially very useful indication of the discrepancy between what people think or feel and how they objectively respond in practice. For this reason it is often useful to include more objective measures (such as the physiological indices outlined above) as a 'verum' to check on workload in such research (cf. Brookhuis and De Waard 1993), or criterion variables as Annett (2002) nominates them.

Dissociation of measures is put in a different perspective in the 'region model of operator performance, task demands and measurement of mental workload' (De Waard 1996). Thus increased mental workload does not have to affect performance, and not all measures have to be strongly correlated. Figure 1 shows an analogue representation that illustrates this principle. The x-axis depicts increasing resource demands of a task, while the y-axis represents the level of physiological activation, and the resultant task performance. In different regions, measures of performance and measures of MWL are actually expected to be decoupled (see Brookhuis and De Waard 2010). In the region on the left, increases in workload paradoxically lead to improvements in performance, as more resources are mobilized to meet the increasing demand. In the central region, workload changes while performance is at its best, and remains relatively constant. As a limited capacity or limited resource system, when demand exceeds supply, no further resources can be supplied. So, in the region on the right, increases in workload result in degradation of performance.

INSERT FIGURE 1 ABOUT HERE

Finding and using new ways of collecting information on workload requires the consideration of the global operating environment as the collective source of information. Integrating and filtering the relevant information from and for the operators in the centre of their dynamic operating environments with new methods is the challenge for the workload ergonomist in the coming years.

4. Applications

We have suggested here that the need to understand and measure mental workload has been very much driven by the applied concerns of the modern workplace. A review of trends in applied mental workload research over time supports this assumption, showing a much higher proportion of publications relating to applications in recent years.

Table 2 presents the number of hits in Ergo-Abs resulting from a decade-by-decade search of ‘mental workload’ in the publication title field, classified into broad application areas. There is an element of selectivity in this: the categorisation process being necessarily one of independent determination and based on the most obvious theme from the title and abstract of the publication and where the application was the main focus of the paper (as opposed to focusing on a workload metric albeit in a particular application). Furthermore, where there were obvious overlaps or duplications in publications (e.g., a report with several parts listed separately, or where the same article was published in separate media), these were not double-counted.

INSERT TABLE 2 ABOUT HERE

The result of this search shows that the first decade of the 21st century saw a total of 87 publications concerning MWL of mental workload. When taken in conjunction with the pattern of results observed in table 1, this represents some 46% of the total publications in the field. Compared to the 1990s (39%) and the 1980s (26%), this would seem to suggest a steady increase in focus on applications from the earliest publications on mental workload to the present. The same is true for absolute numbers of papers on mental workload applications, where the overriding trend is for a significant increase over the years.

In terms of thematic trends within the mental workload applications themselves, it is interesting to note the peak in software engineering and/or computer-aided design (CAD) in the 1980s, but the clear dominance of transport-related applications (e.g., air traffic control, aviation, driving and rail) from the 1990s onwards. Of these, driving stands out as a particular focus area especially in the last decade, although we should also note the rapid growth of mental workload research in the rail industry, reflecting the resurgence in ergonomics and human factors interest within this domain (e.g., Wilson and Norris 2005).

In the following sections, we briefly review the key themes of applied research in each decade. This is not intended to be an exhaustive review, but instead we look to provide a flavour of how the mental workload scene has evolved over time.

4.1 1980s

Studies of mental workload in CAD applications were led by Jarvenpaa and colleagues (Jarvenpaa 1986; Jarvenpaa and Teikari 1987a; 1987b), who focused in particular on the strain associated with designing printed circuit boards, amongst other CAD tasks. Also, Hayashi (1988; Hayashi and Kosugo 1987) examined the mental workload of software engineers in programming tasks. Across each of these early studies, there was a focus on understanding the variations in workload across different stages of the task, as well as the interaction with operator skill level. There was less evidence, though, of deriving potential solutions or recommendations for task design from these studies.

The other key theme in the 1980s was on adaptive interfaces. Hancock and Chignell (1988) considered the underlying dimensions of workload in putting forward proposals for an adaptive system, with the aim of maintaining optimal load on the user. Other work from the same authors (Hancock and Chignell 1987; Loewenthal, Chignell and Hancock 1985) discussed the ability of intelligent interfaces to respond to peaks in mental workload and provide appropriate assistance, with implications for mental workload assessment techniques. Similarly, Nowakowski (1987) was also concerned with on-line mental workload assessment for a knowledge-based adaptive system, with a particular focus on individual differences between users. Although the apparent concern is more with overload than underload, it is clear that issues of optimising workload and defining workload 'redlines' or thresholds have occupied researchers since some of the earliest work in this field.

4.2 1990s

The stand-out application areas in the 1990s were associated with the two themes of aviation and driving. Aviation research featured, for example, the work of Svensson and colleagues (Svensson 1997; Svensson and Angelborg-Thanderz 1995; Svensson, Angelborg-Thanderz and Sjoberg 1993; Svensson et al. 1997), whose investigations focused on issues of information complexity and pilot situation awareness in relation to mental workload, particularly in combat aircraft. Other aviation research examined the impact of automation (Masalonis, Duley and Parasuraman 1999), communication format (Sirevaag et al. 1993), and instrument scanning strategy (Hameluck 1990; Itoh et al. 1990). In addition, one paper (Lassiter et al. 1996) investigated the interaction between age and expertise on pilot mental workload.

In driving research, the frequently appearing names are those of Young and Stanton (1997a, 1997b, 1997c, 1998) and Zeitlin (1993, 1995, 1998). Young and Stanton's research very much focused on the emerging interests in vehicle automation, with particular concern for mental underload. One of their reports (Young and Stanton 1998) also looked at the interaction between driver skill and vehicle automation. Meanwhile, Zeitlin's research was primarily concerned with measurement of driver mental workload with a view to understanding the different determinants of workload – such as road type, weather, or traffic conditions. Other research into driving mental workload investigated the impact of in-car tasks (Jordan and Johnson 1993), age differences (Baldwin and Schieber 1995), the effects of experience on attention patterns (Unema and Rotting 1990), and the performance of specific driving manoeuvres (Hancock et al. 1990).

On the topic of transport, it is worth elaborating on two further reports in the rail domain, in anticipation of the increased prominence of this field that was to come in the following decade. Both Lenior and Gobel (1997) and MacDonald (1999) looked at train controllers' (i.e., signallers') workload in relation to their area of coverage, as well as in terms of any effects of automation on their task. The ultimate concern here was, of course, the safety of the railway network. Elsewhere, papers on occupational stress specifically investigated the role of mental workload in job design and long-term health implications (e.g., Aoyama and Umemura 1991; Klonowicz 1995), and in the same field, other researchers investigated the role of office automation (Jarvenpaa 1990) and adaptive job design to improve job satisfaction (Cook and Salvendy 1999).

4.3 2000s

Research concerning driving far outstrips mental workload applications in all other fields in the most recent decade, with a much wider pool of researchers now involved. Although Young and Stanton (2004, 2007) continued to work on vehicle automation, there is now also substantive research into age differences (Makishita and Matsunaga 2008; Schlorholtz and Schieber 2006; Wu and Liu 2006), in-vehicle tasks (Lansdown, Brook-Carter and Kersloot 2004), mobile phone use (Tokunaga et al. 2001; Tornros and Bolling 2006), driver support systems (Brookhuis et al. 2009) and adaptive interfaces (Piechulla et al. 2003; Uchiyama et al. 2002). There is also interest in public transport and truck drivers (e.g., Simoes et al. 2005b; Ward et al. 2006), as well as private car drivers. Outside of this list of specific driving tasks and activities, there continues to be a substantial body of literature addressing issues of understanding and measurement of driver mental workload (e.g., Baldwin and Coyne 2003; Hao et al. 2007; Horrey et al. 2006; Kuriyagawa and Kageyama 2003; Lei, Welke and Roetting 2009; Makishita and Matsunaga 2005; Recarte and Nunes 2003; Schwalm, Keinath and Zimmer 2008).

As well as these diverse applications, mental workload has also been used to assess the critical levels of driver distraction from numerous vehicle-born and hand-held devices (see Regan, Lee and Young 2009). Here, mental workload is used as an indicative measure but has proved its use, being influential in rule-setting and legal considerations in many countries, such as the widespread bans on hand-held mobile phone use. One of the major problems of an adequate adaptive vehicle control system is to detect and assess inadequate driving by the driver; when and why performance drops 'below the red line', or where and what exactly this red line is (see Brookhuis, De Waard and Fairclough 2003). The system functions should not be limited to vehicle tracking patterns in relation to the infrastructure, but should include characteristics of the driver as well (Brookhuis and De Waard 2002). The way a driver behaves relative to the constantly changing situation at hand is crucial. Mental workload and its assessment remains central to the theme of intelligent vehicles as various innovations penetrate into the everyday fleet of vehicles, on the ground, in the sea, and in the air.

The increase in rail research is due in no small part to the significant contributions from Wilson, Pickup and their colleagues (Pickup and Wilson 2007; Pickup, Wilson and Clarke 2003; Pickup, Wilson, Nichols and Smith 2005; Pickup, Wilson, Sharples et al., 2005; Wilson et al. 2005). As with previous research, the focus is very much on signaller mental workload and the work of this group has been directed towards modelling and assessment of signaller workload, based on the identified fundamental theoretical underpinnings. Other published research in this area is also concerned with signaller workload (MacDonald 2001; Mussgnug, Neumann and Landau 2000), while Simoes and colleagues (Simoes et al. 2005a, 2007) were interested in train driver workload as well, from the perspective of longer-term stress and fatigue.

The other growth area for application in the 2000s was air traffic control. Here, the concerns are for the measurement of the growing volumes of traffic (Loft et al. 2007), adverse weather conditions (Weikert and Naslund 2006), implications of free flight (Nunes and Matthews 2002) and automated support (Low 2003; Metzger and

Parasuraman 2005). Furthermore, fundamental concerns of traffic on controller workload are evident (e.g., Averty et al. 2004), akin to the research on railway signallers.

4.4 Summary and Observations

The predominance of transport applications amongst mental workload research over the last two decades cannot be ignored. From aviation and ATC in the 1990s, to driving and rail in the 2000s, this to some extent reflects wider human factors concerns in these fields, such as their safety criticality, as well as the general march of both technology and the associated penetration of automation. Although we have categorised automation separately as supervisory control here, it should be recognised that there are numerous works examining automation and adaptive systems within these other domains, even from the earliest papers on mental workload applications (e.g., Hancock and Chignell 1987). Indeed, the particular problem of automation almost merits separate treatment, such is the attention it has attracted in recent years. For instance, glass cockpits in commercial aircraft have relieved workload in some areas, such as reduced display clutter, and more automated flight procedures. However, the same systems have increased workload in other areas, such as more decision options in any given situation (Hilburn 1997), and confusion with respect to operating modes (Ferris, Sarter and Wickens 2010, Sarter and Woods 1995). The problem with some automation is that it reduces workload when demand is low but problematically increases workload when demand is high. This tendency is evident when the automation is 'dumb and dutiful' as Wiener (1989) cast it. This argues for much greater context awareness in the design of automation as well as implementation of adaptive automation. Moreover, such automation is not restricted to transport, as we have seen similar papers addressing job design and office automation.

Another theme emerging from this review surrounds the impacts of skill (or experience) and age on mental workload, which can, more generally, be related to the still unsolved puzzle of individual differences (see Damos 1988; Szalma 2009). With current political and economic concerns regarding the develop world's ageing population, it is reasonable to assume that this area in particular will attract considerable effort in the coming decade. In anticipating other trends for current and future research, the increasing realisation about the importance of ergonomics in patient safety and health care (Grundgeiger et al. 2010; Morrow, North and Wickens 2006) will undoubtedly see more evaluations of applications in the medical arena than the handful in the last two decades. Finally, although not directly considered a workload issue, there has been a heavy focus over the last 15 years on the issue of interruption management (e.g, Trafton and Monk 2007; Wickens, Santamaria and Sebok 2013). The connection obviously results because an interruption almost always means that the person is already performing some ongoing task, at or near the red-line of workload; and so at issue is how the person handles these two tasks, now above the red line.

5. Current / future issues and challenges

We conclude our assessment of the state of understanding on the issue of mental workload assessment firstly by setting this concern within the larger social framework. Since the currency of modern work has changed so radically, the first juxtaposition we explore are the contrasts and commonalties of physical and cognitive work. It was the requirements of the industrial revolution that accelerated the formal measurement of physical action and when Taylor (among others) conceived of the advantages of the disembodied mastery of skills alongside of its piecemeal reintegration, the recording and indexing of physical actions was elevated to a high art. The artisan became a machine in what remains a highly contentious line of work evolution. Whilst work was primarily composed of physical demand the issue of measurement was largely dealt with in wider scientific endeavours. After all, the measurement of physical work is founded on the science of physics and physics is a mature science. Notwithstanding the progress reported here, the measurement of mental work is founded on the science of psychology and comparatively speaking, psychology is an immature, if more difficult, science.

Indeed, the contribution of physical demands to mental workload is often neglected in applied research, despite numerous implicit and explicit acknowledgements of its influence. We have already discussed the oft-quoted analogy between mental and physical load, in that mental workload characterises the demands of tasks imposed on the limited information processing capacity of the brain, in much the same way that physical workload characterized the energy demands upon the muscles. More formally, ISO 10075 is not alone in considering physical load itself to be a component of mental workload—seminal metrics for quantifying mental workload (e.g., the NASA-TLX; Hart and Staveland 1988) include physical workload in their dimensions. Earlier, we discussed the impacts of both physical and mental workload on physiological metrics such as heart rate, heart rate variability and respiration (Mulder 1992). But where physical workload should normally be kept low, we now know that mental workload should not be minimized, but instead be optimised in order to achieve best performance (Wilson and Rajan 1995). Indeed, more recent research has explored the interaction between physical and mental workload across some of these metrics, espousing the idea that light physical activity could actually compensate for the deficits imposed by mental underload (Basahel, Young and Ajovalasit 2010).

5.1 Defining underload and overload – The elusive redline

The challenge of assessing and measuring mental work naturally derives on the one hand from a fundamental theoretical concern for an understanding of cognition. Computing the cost of neurocognitive operations certainly challenges our understanding of actions within the brain. Thus, mental workload assessment lies very much within both the cognitive revolution of psychology and is also encompassed by the more recent neurophysiological revolution in neuroscience.

However, alongside these evident scientific concerns, the need to assess mental work is also very much fuelled by the ever-present practical necessity to measure mental activity and allocate tasks in the modern electronic workplace. Earlier in the paper, we reviewed research from the 1980s promising workload-based adaptive automation. Some 25 years later, that promise is yet to be fulfilled. But that applied challenge is still present – perhaps more than ever before, with the proliferation of technology in all aspects of our lives. And maybe, armed with the new knowledge from all of these theoretical developments, we are on the cusp of answering the challenge. In other words, how much work can an individual cope with?

In any resource-limited system, the most relevant measure of demand is specified relative to the supply of available resources. We have seen this relationship conceptualised already in figure 1, but if we now consider the y-axis as representing resource supply, then when demands exceed supply, further demand increases will lead to further performance decrements. The break point on the performance curve is sometimes referred to as the 'redline' of workload (Hart and Wickens 2010; Wickens and Tsang 2014; or given its fuzziness, a 'red zone'), and is marked in figure 2. Importantly, as we describe below, the redline divides two regions of the supply demand space. The region at the left can be called the 'reserve capacity' region. That to the right can be labelled the 'overload region.' The two regions have different implications for workload theory, prediction and assessment, as well as the kinds of concerns of ergonomists.

INSERT FIGURE 2 ABOUT HERE

Both ergonomists and designers are interested in predicting when demand exceeds supply and performance declines as a result, in understanding and modelling the task overload management strategies used (e.g., task shedding; Wickens et al. 2013), as well as in applying different remedies when this overload condition occurs. When this performance decrement results because of multi-tasking overload, models such as the multiple resource model (Wickens, 2002a, 2005, 2008) can offer a framework for design or task changes that will reduce the demand and resulting decrement on performance. This may include using separate, rather than common resources; it may include reducing the resource demands of the task (e.g., by reducing working memory load, or automating parts of the task), extensive training to expertise, re-assigning some of the tasks to another operator, or changing procedures in such a way that previously concurrent tasks can now be performed sequentially. These latter solutions also derive from any resource model (single or multiple).

The multiple resource model is a useful tool for predicting what can be done to lower the multi-task resource demand, and this reduction can be quantified by computational models (e.g., Horrey and Wickens 2003; Wickens 2005; Wickens et al. 2011). Hence such models can be used to predict the relative workload (e.g., workload reduction) of different design alternatives. Multiple resource models will also predict the reduction in performance decrement achieved by operator training via developing automaticity of one or more of the component tasks, but such models cannot predict how much training is required to move demands below the redline. In the same way, the computational models of multiple resources are not yet able to predict the level of resource demand and resource competition that is at the redline (such that further increases will degrade performance, and decreases will not improve it). That is, such models do not well predict the absolute workload.

Increasing demands can also be imposed by increasing the difficulty of a single task (rather than multitasking) as when the working memory load is increased, the relational complexity of a cognitive task is increased (Boag et al. 2006; Halford et al. 1998), or the bandwidth of a tracking task is increased (driving along a winding road at faster and faster speeds), or the number of aircraft that a controller needs to supervise in his/her sector rises (Ayaz et al. 2012).

In these cases, where a particular variable can be counted (e.g., number of chunks, number of variable interactions, number of turns/second or number of aircraft, respectively), it is straightforward to predict relative workload (more is higher) and in many cases, data have provided a reasonable approximation to a redline. For example we have noted the redline for working memory at roughly seven chunks of information. For relational complexity it is roughly three interacting relations between cognitive variables (Halford et al 1998). For tracking bandwidth, it is roughly one cycle per second.

Several variables can moderate these count ‘constants’, effectively moving the redline to the left or right along the x-axis of figure 2. In the case of the air traffic controller, for example, the degree of uncertainty in trajectory, as well as the complexity of the airspace, greatly affect the number of aircraft that can be adequately supervised (Cummings and Mitchell 2007).

One of the most important count variables, which can be employed in either single or multi-task circumstances is time: simple time line analysis computes the ratio of time required to time available (Parks and Boucek 1989). More specifically, time line analysis will enable the system designer to profile the workload that operators encounter during a typical mission, such as landing an aircraft or starting up a power-generating plant (Kirwan and Ainsworth 1992). In a simplified but readily usable version, it assumes that workload is proportional to the ratio of the time occupied performing tasks to total time available. If one is busy with some measurable task(s) for 100 percent of a time interval, workload is 100 percent during that interval. This may be defined as a 'redline'. Thus, the workload of a mission would be computed by drawing lines representing different activities, of length proportional to their duration. The total length of the lines would be summed and then divided by the total time (Parks and Boucek 1989). In this way the workload encountered by or predicted for different members of a team (e.g., pilot and copilot) may be compared and tasks reallocated if there is a great imbalance. Furthermore, epochs of peak workload or work overload, in which load is calculated as greater than 100 percent, can be identified as potential bottlenecks.

Importantly, time-line analysis is equally applicable to the overload region (TR/TA >1) and the reserve capacity region (TR/TA <1). In the latter it can be used equally well in workload predictive models (if tables are available to look up the time required to perform different tasks) and workload assessment, if observers can carefully record operator activity (including non-observable cognitive tasks). Whilst the 100% level may be initially set as the redline, observations by Parks and Boucek (1989) suggest instead that it is the 80% level where errors in performance begin to occur (and this is reflected in figures 1 and 2, where performance starts to fall away as demands approach the upper limit of resources, not just when demands exceed resources).

The important general point to be made here is that for both single and multi-task demands in the overload region above the redline, simple measures of performance are adequate to measure 'workload', and models of multi-task performance, or single task count variables can predict workload increases (performance decreases), or relative workload above the redline. Count variables can be used to predict absolute workload values, both above and below the redline, but multi-task interference models cannot easily do so at the current stage of their maturity.

Whilst defining thresholds for overload might be difficult, doing the same for underload is approaching the impossible for the time being. The theoretical underload redline does exist and is illustrated on figure 2, but identifying or quantifying it remains elusive. A key part of this problem is that a widely accepted theory of underload does not yet exist – and if we cannot describe a concept, we will certainly struggle to quantify it.

The classic resource model implies that in the lower two regions, the operator has ample supply to meet those demands. Almost by definition, when supply exceeds demand, performance should remain perfect. But we know this is not the case; underload is just as bad for performance as overload, and leads to the classic inverted-U curve as illustrated in the figures.

The ‘problem’ with underload, then, is that it does not neatly fit into a traditional demand-resource equation: why should an excess of resources result in poor performance? Various arguments have been put forward, which are not necessarily mutually exclusive. Young and Stanton’s research into vehicle automation led them to propose a theory whereby attentional resources shrink in situations of low workload, thus leading to problems when demands suddenly increase (see Young and Stanton 2002). Alternatively, low demands could be misperceived by the operator, leading to a mismatch in terms of effort invested to perform the task (Matthews and Desmond 1997). Effort is voluntary and is related to resource investment, so this could be compatible with Young and Stanton’s (2002) idea.

We note that the issues of underload and overload are joined in a single application when the challenge of workload transitions is faced, particularly with highly automated systems such as nuclear or process control, or the modern flight deck (Huey and Wickens 1993; Sebok et al. 2012). Here, very low workload is often coupled with fatigue and sleep-disruption induced complacency, leading to a lack of vigilance. Then the sudden unexpected failure rapidly throws the operator into a highly stressful fault diagnosis and failure management mode, well above the redline, in such a way that the prior loss of situation awareness has rendered them unprepared.

Earlier in this paper, we reviewed more recent research relating the underload performance decrement to levels of physiological activation, again relating this to the core premise of available resources. This is reflected (albeit with some artistic licence) in figure 2, as resource supply (based on activation and/or effort) at first lags behind task demands in the underload region, then exceeds it until resources start to asymptote towards the upper capacity limit, and we reach overload. The redlines of both overload and overload coincide with the points where the demand and resource lines cross over; performance degrades in both regions of underload and overload when demands exceed resources. Whilst this notion offers a neat hypothetical explanation of underload and overload, it still does not let us quantify or predict these redlines in an applied setting.

Once again, it is the latest research in neuroscience that perhaps offers the most promise in terms of defining thresholds for underload (and, potentially, overload). It has been suggested (Perrey, Thedon and Rupp 2010) that metrics of brain oxygenation could essentially represent a quantitative measure of attentional resources. If this is the case, then the possibility of objectively quantifying the demand-resource relationship – opening the door for definitive redlines to be established at both ends of the performance curve – could be within reach.

6. Summary and conclusions

In this paper, we have reviewed the fundamental nature of mental workload, its historical development in the field of ergonomics, and addressed contemporary challenges for research and applications. The field has developed from tackling the thorny issue of defining the concept, through the development of metrics of mental workload, to the more recent focus on applied research, which in turn reflects the technological and societal concerns of our times.

We would certainly not wish to claim that progress in measurement or definition has ended; mental workload looks to be just as nebulous a concept today as it did three decades ago, and researchers continue to debate over definitions to this day. In measurement, new neuropsychological techniques are emerging as strong contenders for finally ascertaining the physiological correlates of mental demand. These metrics suggest a resolution of the physical vs. mental workload question, and perhaps even augur the potential to quantify workload and those redlines of performance. These are thus indeed exciting times.

Nevertheless, it is reasonable to suggest that the applied problems will assume even greater prominence as we move forward. This is particularly the case as technology progresses in areas such as transportation, which has already dominated the mental workload scene in recent years. It also reflects and further emphasises the role of mental work over physical work in the modern workplace. To quote Hancock (2009), 'within two generations, the currency of modern work has gone from joules to bytes and it promises no future return.'

7. References

Annett, J. 2002. "Subjective rating scales: science or art?" *Ergonomics* 45: 966-987.

Aoyama, T., and M. Umemura. 1991. "An Examination of the Mental Workload of Design Work in Offices." In *Towards Human Work: Solutions to Problems in Occupational Health and Safety*, edited by M. Kumashiro and E.D. Megaw, 243-249. London: Taylor & Francis, London.

Averty, P., C. Collet, A. Dittmar, S. Athenes, and E. Vernet-Maury. 2004. "Mental Workload in Air Traffic Control: An Index Constructed from Field Tests." *Aviation, Space, and Environmental Medicine* 75(4): 333-341.

Ayaz, H., P. A. Shewokis, S. Bunce. K. Izzetoglu, B. Willems, and B. Onaral. 2012. "Optical brain monitoring for operator training and mental workload assessment." *NeuroImage* 59: 36–47.

Baldwin, C. L., and J. T. Coyne. 2003. "Mental Workload as a Function of Traffic Density: Comparison of Physiological, Behavioral, and Subjective Indices." In *Proceedings of the 2nd International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design*, edited by D.V.

McGehee, J.D. Lee, M. Rizzo, M. Raby and L. Boyle, 19-24. Iowa City: University of Iowa.
Baldwin, C. L., and F. Schieber. 1995. “Dual Task Assessment of Age Differences in Mental Workload with Implications for Driving.” In *Designing for the Global Village. Proceedings of the Human Factors and Ergonomics Society 39th Annual Meeting, Volume 1*, 167-171. Santa Monica, CA: The Human Factors and Ergonomics Society.
Basahel, A. M., M. S. Young, and M. Ajovalasit. 2010. “Effects of interaction between physical and mental workload on human performance.” In *Contemporary Ergonomics and Human Factors 2010*, edited by M. Anderson, 598-601. London: Taylor & Francis.
Becker, A. B., J. S. Warm, W. N. Dember, and P. A. Hancock. 1995. “Effects of jet engine noise and performance feedback on perceived workload in a monitoring task.” *International Journal of Aviation Psychology* 5(1): 49-62.
Bevan, N. and M. Macleod. 1994. “Usability measurement in context.” *Behaviour and Information Technology* 13: 132-145.
Boag, C., A. Neal, S. Loft, and G. Halford. 2006. “An analysis of relational complexity in an air traffic control conflict detection task.” *Ergonomics* 14: 1508-1526.
Branton, P. 1979. “Investigations into the skills of train driving.” *Ergonomics* 22: 155-164.
Brookhuis, K.A., and D. De Waard. 1993. “The use of psychophysiology to assess driver status.” *Ergonomics* 36: 1099-1110.
Brookhuis, K.A., and D. De Waard. 2000. “Assessment of drivers’ workload: performance, subjective and physiological indices.” In *Stress, Workload and Fatigue*, edited by P.A. Hancock and P.A. Desmond, 321-333. New Jersey: Lawrence Erlbaum.
Brookhuis, K.A., and D. De Waard, D. 2002. “On the assessment of (mental) workload and other subjective qualifications.” *Ergonomics* 45: 1026-1030.
Brookhuis, K.A., D. De Waard, and S. H. Fairclough. 2003. “Criteria for driver impairment.” *Ergonomics* 46: 433-445.

Brookhuis, K.A., and D. De Waard. 2010. "Measuring physiology in simulators." In *Handbook of driving simulation for engineering, medicine and psychology*, edited by D. Fisher, J.D. Lee, J.K. Caird, and M. Rizzo, 233-241. London: Taylor and Francis.
Brookhuis, K. A., C. J.G. Van Driel, T. Hof, B. Van Arem, and M. Hoedemaeker. 2009. "Driving with a Congestion Assistant: Mental Workload and Acceptance." *Applied Ergonomics* 40(6): 1019-1025.
Cook, J. R., and G. Salvendy. 1999. "Job Enrichment and Mental Workload in Computer-Based Work: Implications for Adaptive Job Design." *International Journal of Industrial Ergonomics* 24(1): 13-23.
Csikszentmihalyi, M. 1990. *Flow: The Psychology of Optimal Experience*. New York: Harper.
Cummings, M., and P. Mitchell. 2007. "Predicting Controller Capacity in Supervisory Control of Multiple UAVs." *IEEE Transactions on Systems, Man and Cybernetics, Part A: Systems and Humans* 38(2): 451-460.
Damos, D. L., 1988. "Individual differences in subjective estimates of workload." In *Human Mental Workload,* edited by P. A. Hancock and N. Meshkati, 231-237. Amsterdam: North-Holland.
Easterbrook, J. A. 1959. "The effect of emotion on cue utilization and the organization of behaviour." *Psychological Review* 66(3): 183-201.
Eggemeier, F.T., and G. F. Wilson. 1991. "Performance-based and subjective assessment of workload in multi-task environments." In *Multiple-Task Performance*, edited by D.L. Damos, 217- 278. London: Taylor and Francis.
Ferris, T., C. D. Wickens, and N. Sarter. 2010. "Cockpit automation: still struggling to catch up." In *Human Factors in Aviation (2nd edition)*, edited by E. Salas, T. Allard, and D. Maurino, 479-502. New York: Elsevier.
Flemisch, F. O., and R. Onken. 2002. "Open a window to the cognitive work process! Pointillist analysis of man-machine interaction." *Cognition, Technology and Work* 4(3): 160-170.

Grundgeiger, T., P. M. Sanderson, B. Venkatesh, and H. MacDougall. 2010. “Interruption management in the intensive care unit: Predicting resumption times and assessing distributed support.” *Journal of Experimental Psychology: Applied* 16(4): 317–334.

Halford, G., W. Wilson, and S. Philips. 1998. “Processing capacity defined by relational complexity.” *Behavioral and Brain Sciences* 21: 803–831.

Hameluck, D. 1990. “Mental Models, Mental Workload, and Instrument Scanning in Flight.” In *Countdown to the 21st Century. Proceedings of the Human Factors Society 34th Annual Meeting, Volume 1,* 76-80. Santa Monica, CA: The Human Factors Society.

Hancock, P. A. 1989. “The effect of performance failure and task demand on the perception of mental workload.” *Applied Ergonomics* 20: 197-205.

Hancock, P. A. 1996. “Effect of control order, augmented feedback, input device and practice on tracking performance and perceived workload.” *Ergonomics* 39: 1146-1162

Hancock, P. A. 2009. *Mind, machine and morality*. Chichester: Ashgate.

Hancock, P. A. 2013. “In search of vigilance: The problem of iatrogenically created psychological phenomenon.” *American Psychologist*, 68(2): 97-109.

Hancock, P. A., and J. K. Caird. 1993. “Experimental evaluation of a model of mental workload.” *Human Factors*, 35(3): 413-429.

Hancock, P. A., and M. H. Chignell. 1987. “Adaptive control in human-machine systems.” In *Human Factors Psychology,* edited by P. A. Hancock, 305-345. Amsterdam: North-Holland.

Hancock, P., and M. Chignell. 1988. “Mental Workload Dynamics in Adaptive Interface Design.” *IEEE Transactions on Systems, Man, and Cybernetics* 18(4): 647-658.

Hancock, P. A., and N. Meshkati, eds. 1988. *Human Mental Workload*. Amsterdam: North-Holland.

Hancock, P. A. and J. S. Warm. 1989. “A dynamic model of stress and sustained attention.” *Human Factors* 31: 519-537.

Hancock, P. A., G. Wulf, D. Thom, and P. Fassnacht. 1990. "Driver workload during differing driving maneuvers." *Accident Analysis and Prevention* 22: 281-290.
Hao, X., Z. Wang, F. Yang, Y. Wang, Y. Guo, and K. Zhang. 2007. "The Effect of Traffic on Situation Awareness and Mental Workload: Simulator-Based Study." In *HCI International 2007. Proceedings of the 12th International Conference on Human-Computer Interaction*, available in CD-ROM Format, 9-9. Heidelberg, Germany: Springer.
Hart, S.G., and L. E. Staveland. 1988. "Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research." In *Human Mental Workload*, edited by P. A. Hancock and N. Meshkati, 239-250. Amsterdam: North Holland.
Hart, S. G., and C. D. Wickens. 2010. "Cognitive Workload." In *NASA Human Systems Integration Handbook*, Chapter 6.
Hayashi, Y. 1988. "A Study on Mental Workload of Software Engineers. (2) Work Analysis on the Design Process." *Journal of Science of Labour* 64(6): 257-267.
Hayashi, Y., and R. Kosugo. 1987. "A Study of the Mental Workload of Software Engineers." *Journal of Science of Labour* 63(7): 351-359.
Hilburn, B. 1997. "Dynamic decision aiding: the impact of adaptive automation on mental workload." In *Engineering Psychology and Cognitive Ergonomics*, edited by D. Harris, 193-200. Aldershot: Ashgate.
Hockey, G. R. J. 1997. "Compensatory control in the regulation of human performance under stress and high workload: A cognitive-energetical framework." *Biological Psychology* 45: 73-93.
Hoogendoorn, R.G., S. P. Hoogendoorn, K. A. Brookhuis, and W. Daamen. 2010. "Psychological elements in car-following models: mental workload in case of incidents in the other driving lane." *Procedia Engineering* 3: 87-99.
Horrey, W. J., D. J. Simons, E. G. Buschmann, and K. M. Zinter. 2006. "Assessing Interference from Mental Workload Using a Naturalistic Simulated Driving Task: A Pilot Study." In *Proceedings of the Human Factors and Ergonomics Society*

50th Annual Meeting, available in CD-ROM Format, 2003-2007. Santa Monica, CA: Human Factors and Ergonomics Society.

Horrey, W. J., and C. D. Wickens. 2003. "Multiple resource modeling of task interference in vehicle control, hazard awareness and in-vehicle task performance." In *Proceedings of the Second International Driving Symposium on Human Factors in Driver Assessment, Training, and Vehicle Design*, 7-12. Iowa City: University of Iowa.

Huey, F.M., and C. D. Wickens. 1993. *Workload transition: Implications for individual and team performance*. Washington, DC: National Academy Press.

Huppert, T.J., R. D. Hoge, S. G. Diamond, M. A. Franceschini, and D. A. Boas. 2006. "A temporal comparison of BOLD, ASL, and NIRS hemodynamic responses to motor stimuli in adult humans." *NeuroImage* 29: 368–382.

ISO 10075: 2000. *Ergonomic principles related to mental work-load*. Brussels: CEN.

Itoh, Y., Y. Hayashi, I. Tsukui, and S. Saito. 1990. "The ergonomic evaluation of eye movement and mental workload in aircraft pilots." *Ergonomics* 33: 719-733.

Jarvenpaa, E. 1986. "Mental Workload in CAD-Work: Computer Aided Design of Printed Circuit Boards as an Example." In *Psychological Aspects of the Technological and Organizational Change in Work*, edited by L. Norros and M. Vartiainen, 107-112. Helsinki: Finnish Psychological Society.

Jarvenpaa, E. 1990. "Mental Workload in Different Phases of the Implementation of New Technology: The Implementation of Office Automation as an Example." In *Proceedings of the International Ergonomics Association Conference on Human Factors in Design for Manufacturability and Process Planning*, 159-163.

Jarvenpaa, E., and V. Teikari. 1987a. "Mental Workload in Simple and Complicated Computer Aided Design." In *Social, Ergonomic and Stress Aspects of Work with Computers*, edited by G. Salvendy, S. L. Sauter and J. J. Hurrell, 271-276. Amsterdam: Elsevier.

Jarvenpaa, E., and V. Teikari. 1987b. "On Mental Workload and the Level of Skills in Computer Aided Design of Printed Circuit Boards." In *The Technological Change and Work Psychology*, edited by V. Teikari and M. Vartiainen, 107-113. Helsinki: Finnish Psychological Society.

Jessurun, M., F. J. J. M. Steyvers, and K. A. Brookhuis. 1993. "Perception, activation and driving behaviour during a ride on a motorway." In *Vision in Vehicles IV*, edited by A. G. Gale, I. D. Brown, C. M. Haslegrave, H. W. Kruysse, and S. P. Taylor, 335-337. Amsterdam: Elsevier.

Jordan, P. W., and G. I. Johnson. 1993. "Exploring Mental Workload via TLX: The Case of Operating a Car Stereo whilst Driving." In *Vision in Vehicles IV*, edited by A. G. Gale, I. D. Brown, C. M. Haslegrave, H. W. Kruysse and S. P. Taylor, 255-262. Amsterdam: Elsevier.

Kirwan, B. and L. Ainsworth. 1992. *A Guide to Task Analysis*. London: Taylor and Francis.

Klonowicz, T. 1995. "Mental Workload and Health: A Latent Threat." *International Journal of Occupational Safety and Ergonomics* 1(2): 130-135.

Kuriyagawa, Y., and I. Kageyama. 2003. "A Study on the Evaluation Model of Mental Workload for Drivers." In *Ergonomics in the Digital Age. Proceedings of the XVth Triennial Congress of the International Ergonomics Association and the 7th Joint Conference of the Ergonomics Society of Korea and the Japan Ergonomics Society*.

Lansdown, T. C., N. Brook-Carter, and T. Kersloot. 2004. "Distraction from Multiple In-Vehicle Secondary Tasks: Vehicle Performance and Mental Workload Implications." *Ergonomics* 47(1): 91-104.

Lassiter, D. L., D. G. Morrow, G. E. Hinson, M. Miller, and D. Z. Hambrick. 1996. "Expertise and Age Effects on Pilot Mental Workload in a Simulated Aviation Task." In *Human Centered Technology - Key to the Future. Proceedings of the Human Factors and Ergonomics Society 40th Annual Meeting, Volume 1*, 133-137. Santa Monica, CA: The Human Factors and Ergonomics Society.

Lei, S., S. Welke, and M. Roetting. 2009. “Represenation of Driver's Mental Workload in EEG Data.” In *Human Factors, Security and Safety*, edited by D. de Waard, J. Godthelp, F. Kooi and K. Brookhuis, 285-294. Maastricht, The Netherlands: Shaker Publishing.

Lenior, T. M. J., and M. P. Gobel. 1997. “Predicting Mental Workload for Train Traffic Control Tasks.” In *From Experience to Innovation - IEA '97. Proceedings of the 13th Triennial Congress of the International Ergonomics Association*, edited by P. Seppala, T. Luopajarvi, C.H. Nygard and M. Mattila, 358-360. Finnish Institut.

Loewenthal, A., M. Chignell, and P. Hancock. 1985. “Use of Mental Workload Measures in Interface Design.” In *IEEE 1985 Proceedings of the International Conference on Cybernetics and Society*, 624-626. New York: IEEE.

Loft, S., P. Sanderson, A. Neal, and M. Mooij. 2007. “Modeling and Predicting Mental Workload in En Route Air Traffic Control: Critical Review and Broader Implications.” *Human Factors* 49(3): 376-399.

Low, I. 2003. “Assessment of the Impact on Mental Workload from Advanced Air Traffic Management Systems: A Diagnostic Tool.” In *Ergonomics in the Digital Age. Proceedings of the XVth Triennial Congress of the International Ergonomics Association and the 7th Joint Conference of the Ergonomics Society of Korea and the Japan Ergonomics Society*.

MacDonald, W. A. 1999. “Train Controller Interface Design: Factors Influencing Mental Workload.” In *People in Control*, 31-36. London: Institution of Electrical Engineers.

MacDonald, W. 2001. “Train Controllers, Interface Design and Mental Workload.” In *People in Control: Human Factors in Control Room Design*, edited by J. Noyes and M. Bransby, 239-258. London: Institution of Electrical Engineers.

Makishita, H., and K. Matsunaga. 2005. “Influence of Mental Workload on Reaction Time while Driving a Car.” *Japanese Journal of Ergonomics* 41(4): 228-236.

Makishita, H., and K. Matsunaga. 2008. “Differences of Drivers' Reaction Times According to Age and Mental Workload.” *Accident Analysis and Prevention* 40(2): 567-575.
Mallis, M. M., and D. F. Dinges. 2004. “Monitoring alertness by eyelid closure.” In *Handbook of Ergonomics and Human Factors Methods,* edited by N. Stanton, A. Hedge, H. W. Hendrick, K. A. Brookhuis and E. Salas. London: Taylor and Francis.
Masalonis, A. J., J. A. Duley, and R. Parasuraman. 1999. “Effects of Manual and Autopilot Control on Mental Workload and Vigilance during Simulated General Aviation Flight.” *Transportation Human Factors* 1(2): 187-200.
Matthews, G., and P. A. Desmond. 1997. “Underload and performance impairment: evidence from studies of stress and simulated driving.” In *Engineering Psychology and Cognitive Ergonomics*, edited by D. Harris, 355-361. Aldershot: Ashgate.
Metzger, U., and R. Parasuraman. 2005. “Automation in Future Air Traffic Management: Effects of Decision Aid Reliability on Controller Performance and Mental Workload.” *Human Factors* 47(1): 35-49.
Moray, N. E. 1979. *Mental Workload: Its Theory and Measurement*. New York: Plenum Press.
Morrow, D.G., R. North, and C. D. Wickens. 2006. “Reducing and mitigating human error in medicine.” *Reviews of Human Factors and Ergonomics* 1(1): 254-296.
Mulder, L. J. M. 1992. “Measurement and analysis methods of heart rate and respiration for use in applied environments.” *Biological Psychology* 34: 205-236.
Mussgnug, J., M. Neumann, and K. Landau. 2000. “Quantifying Mental Workload of Operators in Future Control-Centres of the Deutsche Bahn AG.” In *Ergonomics for the New Millennium. Proceedings of the XIVth Triennial Congress of the International Ergonomics Association and 44th Annual Meeting of the Human Factors and Ergonomics Society*, 527-529.
Myrtek, M., E. Deutschmann-Janicke, H. Strohmaier, W. Zimmermann, S. Lawerenz, G. Brügner, and W. Müller. 1994.

“Physical, mental, emotional, and subjective workload components in train drivers.” *Ergonomics* 37: 1195-1203.
Nowakowski, M. 1987. “Personalized Recognition of Mental Workload in the Human-Computer System.” In *Social, Ergonomic and Stress Aspects of Work with Computers*, edited by G. Salvendy, S. L. Sauter and J. J. Hurrell, 75-82. Amsterdam: Elsevier.
Nunes, A., and M. L. Matthews. 2002. “Predictive Aids in Air Traffic Control: Situation Awareness and Mental Workload Implications.” In *Human Factors in Transportation, Communication, Health, and the Workplace*, edited by D. de Waard, K. A. Brookhuis, J. Moraal and A. Toffetti, 209-211. Maastricht, The Netherlands: Shaker Publishing.
Okada, Y. 1992. “Human characteristics at multi-variable control when the operator changes over the plant-lines.” *Ergonomics* 35: 513-523.
Parasuraman, R., and P. A. Hancock. 2001. “Adaptive control of mental workload.” In *Stress, Workload and Fatigue*, edited by P. A. Hancock and P. A. Desmond, 305-320. Mahwah, NJ: Lawrence Erlbaum.
Parks, D. L., and G. P. Boucek Jr. 1989. “Workload prediction, diagnosis, and continuing challenges.” In *Applications of Human Performance Models to System Design*, edited by G. R. McMillan, D. Beevis, E. Salas, M. H. Strub, R. Sutton and L. Van Breda, 47–64. New York: Plenum.
Perrey, S., T. Thedon, and T. Rupp. 2010. “NIRS in ergonomics: its application in industry for promotion of health and human performance at work.” *International Journal of Industrial Ergonomics* 40(2): 185-189.
Pickup, L., and J. R. Wilson. 2007. “Mental Workload Assessment and the Development of the Operational Demand Evaluation Checklist (ODEC) for Signallers.” In *People and Rail Systems: Human Factors at the Heart of the Railway*, edited by J. Wilson, B. Norris, T Clarke and A. Mills, 215-223. Aldershot: Ashgate.
Pickup, L., J. Wilson, and T. Clarke. 2003. “Mental Workload of the Railway Signaller.” In *Contemporary Ergonomics 2003*, edited by P.T. McCabe, 397-402. London: Taylor & Francis.

Pickup, L., J. R. Wilson, S. Nichols, and S. Smith. 2005. "A Conceptual Framework of Mental Workload and the Development of a Self-Reporting Integrated Workload Scale for Railway Signallers." In *Rail Human Factors: Supporting the Integrated Railway*, edited by J. R. Wilson, B. Norris, T. Clarke and A. Mills, 319-329. Aldershot: Ashgate.

Pickup, L., J. R. Wilson, S. Sharples, B. Norris, T. Clarke, and M. S. Young. 2005. "Fundamental examination of mental workload in the rail industry." *Theoretical Issues in Ergonomics Science* 6(6): 463-482.

Piechulla, W., C. Mayser, H. Gehrke, and W. Konig. 2003. "Reducing Drivers' Mental Workload by Means of an Adaptive Man-Machine Interface." *Transportation Research Part F: Traffic Psychology and Behaviour* 6(4): 233-248.

Rau, R. 2004. "Ambulatory assessment of blood pressure to evaluate work load." In *Handbook of Ergonomics and Human Factors Methods*, edited by N. Stanton, A. Hedge, H. W. Hendrick, K. A. Brookhuis, and E. Salas. London: Taylor and Francis.

Recarte, M. A., and L. M. Nunes. 2003. "Mental Workload while Driving: Effects on Visual Search, Discrimination, and Decision Making." *Journal of Experimental Psychology: Applied* 9(2): 119-137.

Regan, M. A., J. D. Lee, and T. W. Victor, eds. 2013. *Driver Distraction and Inattention: Advances in Research and Countermeasures, Volume 1*. Farnham: Ashgate.

Regan, M. A., J. D. Lee and K. L. Young, eds. 2009. *Driver Distraction: Theory, Effects and Mitigation*. Boca Raton, FL: CRC Press.

Reid, G. B. and T. E. Nygren. 1988. "The subjective workload assessment technique: a scaling procedure for measuring mental workload. In Human Mental Workload, edited by P. A. Hancock and N. Meshkati. Amsterdam: North-Holland.

Sarter, N. B., and D. D. Woods. 1995. "How in the world did we ever get into that mode? Mode error and awareness in supervisory control." *Human Factors* 37(1): 5-19.

Schaap, T.W., A. R. A. Van der Horst, B. Van Arem, and K. A. Brookhuis. 2008. "Drivers' reactions to sudden braking by lead

car under varying workload conditions; towards a driver support system.” *IET Intelligent Transport Systems* 2: 249–257.
Schaap, T.W., A. R. A. Van der Horst, B. Van Arem, and K. A. Brookhuis. 2013. “The relationship between driver distraction and mental workload.” In *Driver Distraction and Inattention: Advances in Research and Countermeasures, Volume 1,* edited by M. A. Regan, J. D. Lee and T. W. Viktor, 63-80. Farnham: Ashgate.
Schlegel, R. E. 1993. “Driver mental workload.” In *Automotive Ergonomics*, edited by B. Peacock and W. Karwowski, 359-382. London: Taylor & Francis.
Schlorholtz, B. J., and F. Schieber. 2006. “Assessment of Age Differences in Mental Workload While Driving Using Verbal versus Visual-Spatial Subsidiary Tasks.” In *Proceedings of the Human Factors and Ergonomics Society 50th Annual Meeting*, available in CD-ROM Format, 2378-2382. Santa Monica, CA: Human Factors and Ergonomics Society.
Schneider, W., and R. M. Shiffrin. 1977. “Controlled and automatic human information processing: 1. Detection, search, and attention. *Psychological Review* 84: 1-66.
Schwalm, M., A. Keinath, and H. D. Zimmer. 2008. “Pupillometry as a Method for Measuring Mental Workload within a Simulated Driving Task.” In *Human Factors for Assistance and Automation*, edited by D. de Waard, F. Flemisch, B. Lorenz, H. Oberheid, and K. Brookhuis, 75-87. Maastricht, The Netherlands: Shaker Publishing.
Sebok, A., C. Wickens, N. Sarter, S. Quesada, C. Socash, and B. Anthony. 2012. “The Automation Design Advisor Tool (ADAT): Development and validation of a model-based tool to support flight deck automation design for nextgen operations.” *Human Factors and Ergonomics in Manufacturing and Service Industries* 22(5): 378-394.
Simoes, A., J. Carvalhais, P. Ferreira, J. Correia, J., and M. Lourenco. 2005a. “Research on Fatigue and Mental Workload of Railway Drivers and Traffic Controllers.” In *Proceedings of the Second European Conference on Rail Human Factors*.

Simoes, A., J. Carvalhais, P. Ferreira, J. Correia, and M. Lourenco. 2005b. “Research on Mental Workload of Truck and Bus Drivers on Long Distance Routes.”
Simoes, A., J. Carvalhais, P. Ferreira, J. Correia, and M. Lourenco. 2007. “Research on Fatigue and Mental Workload of Railway Drivers and Traffic Controllers.” In *People and Rail Systems: Human Factors at the Heart of the Railway*, edited by J. Wilson, B. Norris, T Clarke and A. Mills, 553-563. Aldershot: Ashgate.
Sirevaag, E. J., A. F. Kramer, C. D. Wickens, M. Reisweber, D. L. Strayer, and J. F Grenell. 1993. “Assessment of Pilot Performance and Mental Workload in Rotary Wing Aircraft.” *Ergonomics* 36(9): 1121-1140.
Smith, K., and P. A. Hancock. 1995. “Situation awareness is adaptive, externally directed consciousness. *Human Factors* 37(1): 137-148.
Sperandio, A. 1978. “The regulation of working methods as a function of workload among air traffic controllers.” *Ergonomics* 21: 367-390.
Stanton, N. A., and M. S. Young. 1999. *A guide to methodology in ergonomics: Designing for human use*. London: Taylor and Francis.
Strangman, G., J. P. Culver, J. H. Thompson, and D. A. Boas. 2002. “A quantitative comparison of simultaneous BOLD fMRI and NIRS recordings during functional brain activation.” *NeuroImage* 17: 719-731.
Svensson, E. 1997. “Pilot Mental Workload and Situational Awareness - Psychological Models of the Pilot.” In *Decision Making under Stress: Emerging Themes and Applications*, edited by R. Flin, E. Salas, M. Strub and L. Martin, 261-267. Aldershot: Ashgate.
Svensson, E., and M. Angelborg-Thanderz. 1995. “Mental Workload and Performance in Combat Aircraft: Systems Evaluation.” In *Human Factors in Aviation Operations*, edited by R. Fuller, N. Johnston and N. McDonald, 313-318. Aldershot: Ashgate.
Svensson, E., M. Angelborg-Thanderz, and L. Sjoberg. 1993. “Mission Challenge, Mental Workload and Performance in

Military Aviation." *Aviation, Space & Environmental Medicine* 64(11): 985-991.
Svensson, E., M. Angelborg-Thanderz, L. Sjoberg, L., and S. Olsson. 1997. "Information complexity - mental workload and performance in combat aircraft." *Ergonomics* 40(3): 362-380.
Szalma, J. L. 2009. "Individual differences in performance, workload, and stress in sustained attention: Optimism and pessimism." *Personality and Individual Differences* 47: 444-451.
Tokunaga, R. A., A. Shimojo, T. Hagiwara, S. Kagaya, and K. E. Uchida. 2001. "Effects of Cellular Telephone Use While Driving Based on Objective and Subjective Mental Workload Assessment." In *Proceedings of the International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design*, edited by D.V. McGehee, J.D. Lee, M. Rizzo, K. Holeton and T. Lopes, 112-117. Iowa City: University of Iowa.
Tornros, J., and A. Bolling. 2006. "Mobile Phone Use - Effects of Conversation on Mental Workload and Driving Speed in Rural and Urban Environments." *Transportation Research Part F: Traffic Psychology and Behaviour* 9(4): 298-306.
Trafton, J. G., and C. Monk. 2007. "Dealing with interruptions." *Reviews of Human Factors and Ergonomics* 3(1): 111-126.
Tsang, P., and M. A. Vidulich. 2006. "Mental workload and situation awareness." In *Handbook of Human Factors and Ergonomics*, edited by G. Salvendy, 243-268. Hoboken, NJ: Wiley.
Uchiyama, Y., S. I. Kojima, T. Hongo, R. Terashima, and T. Wakita. 2002. "Voice Information System Adapted to Driver's Mental Workload." In *Bridging Fundamentals and New Opportunities. Proceedings of the 46th Annual Meeting of the Human Factors and Ergonomics Society*, 1871-1875. Santa Monica, CA: Human Factors and Ergonomics Society.
Unema, P., and M. Rotting. 1990. "Differences in Eye Movements and Mental Workload between Experienced and Inexperienced Motor-Vehicle Drivers." In *Visual Search*, edited by D. Brogan, 193-202. London: Taylor & Francis.
Van Winsum, W., M. Martens, and L. Herland. 1999. *The effects of speech versus tactile driver support messages on workload,*

driver behaviour and user acceptance. Report TM–01–D009, TNO Human Factors Research Institute, Soesterberg, The Netherlands.
Vidulich, M. A., and C. D. Wickens. 1986. "Causes of dissociation between subjective workload measures and performance; Caveats for the use of subjective assessments." *Applied Ergonomics* 17: 291-296.
Waard, D. de 1996. "The measurement of drivers' mental workload." PhD Thesis. Haren, The Netherlands: Traffic Research Centre, University of Groningen.
Waard, D. de and K. A. Brookhuis. 1991. "Assessing driver status: a demonstration experiment on the road." *Accident Analysis and Prevention* 23: 297-307.
Waard, D. de and K. A. Brookhuis. 1997. "On the measurement of driver mental workload." In *Traffic and Transport Psychology*, edited by J.A. Rothengatter and E. Carbonell, 161-173. Amsterdam: Elsevier.
Ward, N. J., C. Shankwitz, A. Gorgestani, M. Donath, D. De Waard, and E. R. Boer. 2006. "An Evaluation of a Lane Support System for Bus Rapid Transit on Narrow Shoulders and the Relation to Bus Driver Mental Workload." *Ergonomics* 49(9): 832-859.
Weikert, C., and J. Naslund. 2006. "Task Analysis, Subjective Mental Workload and Incidents in Airport Tower Air Traffic Control during Adverse Weather Conditions." In *Developments in Human Factors in Transportation, Design, and Evaluation*, edited by D. de Waard, K. A. Brookhuis and A. Toffetti, 153-155. Maastricht, The Netherlands: Shaker Publishing.
Welford, A. T. 1978. "Mental work-load as a function of demand, capacity, strategy and skill." *Ergonomics* 21: 151-167.
Wickens, C. D. 1980. "The structure of attentional resources." In *Attention and Performance VIII*, edited by R. Nickerson, 239-257. Hillsdale, NJ: Erlbaum.
Wickens, C. D. 2002a. "Multiple resources and performance prediction." *Theoretical Issues in Ergonomics Science* 3: 159–177.

Wickens, C. D. 2002b. “Situation awareness and workload in aviation.” *Current Directions in Psychological Science* 11(4): 128–133.
Wickens, C. D. 2005. “Multiple resource time sharing models.” In *Handbook of Human Factors and Ergonomics Methods*, edited by N. Stanton, A. Hedge, K. Brookhuis, E. Salas, and H. Hendrick, 40.1–40.7. Boca Raton, FL: CRC Press.
Wickens, C. D. 2008. “Multiple resources and mental workload.” *Human Factors* 50(3): 449-455.
Wickens, C., T. Bagnall, M. Gosakan, and B. Walters. 2011 “Modeling single pilot control of multiple UAVs.” In *Proceedings of the 16th International Symposium on Aviation Psychology*, edited by M. Vidulich and P. Tsang, available in CD-ROM format. Dayton Ohio: Wright State University.
Wickens, C. D., A. Santamaria, and A. Sebok. 2013. “A computational model of task overload management and task switching.” In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* 57(1): 763-767. Santa Monica, CA: Human Factors and Ergonomics Society.
Wickens, C. D., and P. Tsang. 2014. “Workload.” In *Handbook of Human-Systems Integration*, edited by F. Durso, in press. Washington, DC: American Psychological Association.
Wiener, E. L. 1989. *Human factors of advanced technology (“glass cockpit”) transport aircraft.* (National Aeronautics and Space Administration [NASA] Contractor Rep. No. 177528). Moffett Field, CA: NASA-Ames Research Center.
Wilson, J. R., L. Pickup, B. J. Norris, S. Nichols, and L. Mitchell. 2005. “Understanding of Mental Workload in the Railways.” In *Rail Human Factors: Supporting the Integrated Railway*, edited by J. R. Wilson, B. Norris, T. Clarke and A. Mills, 309-318. Aldershot: Ashgate.
Wilson, J. R., and B. J. Norris. 2005. “Rail human factors: Past, present and future.” *Applied Ergonomics* 36: 649-660.
Wilson, J. R., and J. A. Rajan. 1995. “Human-machine interfaces for systems control.” In *Evaluation of Human Work: A Practical Ergonomics Methodology*, edited by J. R. Wilson and E. N. Corlett, 357-405. London: Taylor & Francis.

Wu, C., and Y. Liu. 2006. "Queuing Network Modeling of Age Differences in Driver Mental Workload and Performance." In *Proceedings of the Human Factors and Ergonomics Society 50th Annual Meeting*, available in CD-ROM Format, 190-194. Santa Monica, CA: Human Factors and Ergonomics Society.

Yeh, Y. Y., and C. D. Wickens. 1988. "Dissociation of performance and subjective measures of workload. *Human Factors* 30: 111-120.

Yerkes, R. M., and J. D. Dodson. 1908. "The relation of strength of stimulus to rapidity of habit formation." *Journal of Comparative Neurological Psychology* 18: 459-482.

Young, M. S., and N. A. Stanton. 1997a. "Automotive automation: Effects, problems and implications for driver mental workload." In *Engineering Psychology and Cognitive Ergonomics: Vol. 1 - Transportation Systems*, edited by D. Harris, 347-354. Aldershot: Ashgate.

Young, M. S., and N. A. Stanton. 1997b. "Automotive automation: Investigating the impact on drivers' mental workload." *International Journal of Cognitive Ergonomics* 1(4); 325-336.

Young, M., and N. Stanton. 1997c. "Taking the load off: Investigating the effects of vehicle automation on driver mental workload". In *Contemporary Ergonomics 1997*, edited by S. Robertson, 98-103. London: Taylor & Francis.

Young, M., and N. Stanton. 1998. "What's skill got to do with it? Vehicle automation and driver mental workload." In *Contemporary Ergonomics 1998*, edited by M. A. Hanson, 436-440. London: Taylor & Francis.

Young, M. S., and N. A. Stanton. 2002. "Malleable Attentional Resources Theory: A new explanation for the effects of mental underload on performance." *Human Factors* 44(3): 365-375.

Young, M. S., and N. A. Stanton. 2004. "Taking the load off: investigations of how adaptive cruise control affects mental workload." *Ergonomics* 47(9): 1014-1035.

Young, M. S., and N. A. Stanton. 2005. "Mental workload." In *Handbook of Human Factors and Ergonomics Methods*, edited by N. A. Stanton, A. Hedge, K. Brookhuis, E. Salas, and H. W. Hendrick, Ch. 39. London: Taylor & Francis.

Young, M. S., and N. A. Stanton. 2007. "What's skill got to do with it? Vehicle automation and driver mental workload." *Ergonomics* 50(8): 1324-1339.

Zander, T. O., and C. Kothe. 2011. "Towards passive brain-computer interfaces: applying brain-computer interface technology to human-machine systems in general." *Journal of Neural Engineering* 8.

Zeitlin, L. R. 1993. "Subsidiary Task Measures of Driver Mental Workload: A Long-Term Field Study." In *Driver Performance: Measurement and Modeling, IVHS, Information Systems, and Simulation*, by the Transportation Research Board, National Research Council, Washington, D.C. National Academy Press, Washington, D.C., Transportation Research Record No.1403, 23-27.

Zeitlin, L. R. 1995. "Estimates of driver mental workload: A long-term field trial of two subsidiary tasks." *Human Factors* 37(3): 611-621.

Zeitlin, L. R. 1998. "Micromodel for Objective Estimation of Driver Mental Workload from Task Data." In *Driver and Vehicle Modeling*, by the Transportation Research Board, National Research Council, Washington, D.C., Transportation Research Record No.1631, 28-34.

Zijlstra, F.R.H. 1993. "Efficiency in work behavior. A design approach for modern tools." PhD thesis, Delft University of Technology. Delft, The Netherlands: Delft University Press.

List of table and figure captions

Table 1: Number of hits in the Ergo-Abs database resulting from a decade-by-decade search for the terms ‘mental workload’ (MWL), ‘physical workload’ (PWL), and ‘workload’ (WL)

Table 2: Number of papers resulting from a decade-by-decade title search of ‘mental workload’ on the Ergo-Abs database, categorised into broad application areas.
Table notes: [1] Includes supervisory control
[2] Includes blind travellers’ pedestrian wayfinding, and road traffic control

Figure 1. The relationship between activation level, workload (task demands) and performance (adapted from Brookhuis and De Waard 2010).

Figure 2: The supply-demand relationship associated with mental workload and performance, highlighting the redlines of overload and underload

	MWL	PWL	WL
1980s	58	7	260
1990s	140	47	563
2000s	191	55	662

Table 1: Number of hits in the Ergo-Abs database resulting from a decade-by-decade search for the terms ‘mental workload’ (MWL), ‘physical workload’ (PWL), and ‘workload’ (WL)

	1980s	1990s	2000s	**Total**
Maritime	1			**1**
Software engineering / CAD	6	1		**7**
Adaptive interfaces	3	1	2	**6**
ATC	1	6	10	**17**
Aviation	1	10	8	**19**
HCI / interface design	1	8	4	**13**
Job design / occupational	1	6	8	**15**
Driving		12	28	**40**
Manufacturing / automation[1]		2	2	**4**
Medical		3	5	**8**
Process control		2	2	**4**
Rail		2	10	**12**
Teaching and learning		1	1	**2**
Agriculture			1	**1**
Military			4	**4**
Usability			1	**1**
Other transport[2]	1		1	**2**
Total	**15**	**54**	**87**	**156**

Table 2: Number of papers resulting from a decade-by-decade title search of 'mental workload' on the Ergo-Abs database, categorised into broad application areas.

Table notes: [1] Includes supervisory control

[2] Includes blind travellers' pedestrian wayfinding, and road traffic control