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State of science: mental workload in ergonomics

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Mental workload (MWL) is one of the most widely used concepts in ergonomics and human factors 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 MWL 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 neuroergonomics 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? How many people are needed to successfully carry out the task? Answers to these questions can be provided given that the MWL 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.

MWL has thus become a topic of increasing importance as modern technology imposes ever greater cognitive demands. The study of MWL 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). This increase no doubt partly reflects the growing coverage of the database in more recent years, as evidenced by equivalent searches for 'physical workload' and 'workload'. Nevertheless, the relative decade-on-decade increase in hits for MWL in the 2000s suggests a more recent prominence over the comparator terms – 36% for 'mental workload' against 17% for 'physical workload' and 'workload'.

A cursory review of these search results indicates that the focus in the 1980s was much more on the measurement of MWL, while the 1990s saw a shift towards theoretical developments and 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 twenty-first century has seen more examples of MWL applications coming to the fore. Thus, the general evolution of research in MWL has progressed from trying to measure it, through trying to define it, to the real-world applications of it today.

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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).

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

Our paper seeks to present the contemporary state of the art in MWL 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 MWL. As well as distilling contemporary knowledge in each of these areas, we also discuss the challenges facing MWL research now and in the future.

2. Concepts and definitions

MWL 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). Although the stress/strain comparison has been criticised for being too simplistic (e.g. Bainbridge 1974), even the international standard on MWL (ISO 10075, 2000) is heavily dependent on the analogy for its terminology. Demands (stress) can have multiple facets, such as time pressure and 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 and subjective metrics which we describe later (see, e.g., Bevan and Macleod 1994).

Therefore, when we consider that stress comprises multiple demand factors, and that strain itself shows multiple expressions depending on the resources available, explaining MWL in terms of demand/resource balance offers an attractive and parsimonious approach to this otherwise multidimensional construct (see Hancock and Warm 1989). Resources, in this arena of discussion, often refer to attentional resources (e.g. Wickens 1980, 2002); thus, MWL 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. Fixed resource models of workload are not without their drawbacks, though. For instance, absolute capacity demands are illusive; they do not directly consider nonattentional factors, such as experience, or more slowly changing variation in attentional resources due to learning or the reduction of capacity with age, or even the willingness to invest effort.

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, MWL 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 MWL.

Thus, MWL 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 MWL, Young and Stanton (2005, chap. 39-1) have suggested that MWL 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’. The terms in this definition have largely been drawn out in the preceding discussion, with a couple of exceptions. Performance criteria can be imposed by external authorities or may represent the internal goals of the individual (Hancock and Caird 1993). Meanwhile, external support may be in the form of peer assistance or technological aids.

One of the reasons to study MWL is to establish a relationship with operator performance. There is an element of cause and effect in the relationship: while performance can be an indicator of MWL, performance failure can also increase perceptions of workload (Hancock 1989). Nevertheless, the applied objective is to identify 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 while maintaining their own standards of performance. Excessive load can affect selective attention, leading to narrowed or inefficient sampling (Easterbrook 1959). Conversely, too little stimulation can lead to underload, as resources are either allocated elsewhere or otherwise shrink through underuse (cf. Young and Stanton 2002).

Underload itself, while an intuitive concept, is in many ways a more nebulous term than MWL, as different researchers take it to mean different things. It is easier to state what underload is not: it is not vigilance (since the consensus has been for some time that vigilant monitoring is actually a highly demanding task; Warm, Dember, and Hancock 1996) nor is it boredom (usually it is about doing very little rather than doing nothing at all). In the present authors' view, there has to be some engagement in the task, but such engagement is exceptionally low. Nevertheless, it is probably fair to say that the jury is out as to whether underload is distinct from other influences on performance such as automation-related complacency and supervisory control. Indeed, as with MWL more generally, the underload effect is typically observed indirectly through its effects on performance (and we return to this thorny issue later in the paper).

That said, there is a strong consensus that mental underload can be just as detrimental to performance as mental overload, with both leading to performance degradation, attentional lapses and errors (Wilson and Rajan 1995). Indeed, the current opinion is that there is an optimum range of MWL which is associated with best performance (Hancock and Warm 1989; see also Figure 1). This 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). Therefore, there is no direct guarantee that simply reducing MWL improves performance, and in fact the opposite may be true.

Performance decrements due to overload or underload can be compensated for to some extent by the investment of additional resources, which is a voluntary, strategic and effortful process (Hancock and Warm 1989; Hockey 1997; Matthews and Davies 2001). Thus, performance can be maintained at the cost of individual strain or vice versa. Consequently, if effort is invested, then MWL will be increased (cf. Shaw et al. 2013) – which may be a positive adaptation in circumstances of underload, but could be further detrimental when faced with overload. As an alternative to exerting effort, then, the operator might decide to change the (sub)goals of the task (e.g. Sperandio 1978; see also Brookhuis and de Waard 2000).

In the complex, safety-critical systems where MWL research is usually most pertinent and/or most pursued (such as transport, as we shall see later), both underload and overload are very real concerns. But while both low and high MWL are undoubtedly basic precursors to errors, an exact relationship between MWL 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. Basic criteria for when impairment is below a certain acceptability threshold (i.e. leading to accidents) have been established (see Brookhuis, de Waard, and Fairclough 2003), but the coupling to accident causation is not a direct one. The relationship between accidents and MWL (high or low) is thus dependent upon accurate measurement of MWL if we are to quantitatively specify those threshold criteria.

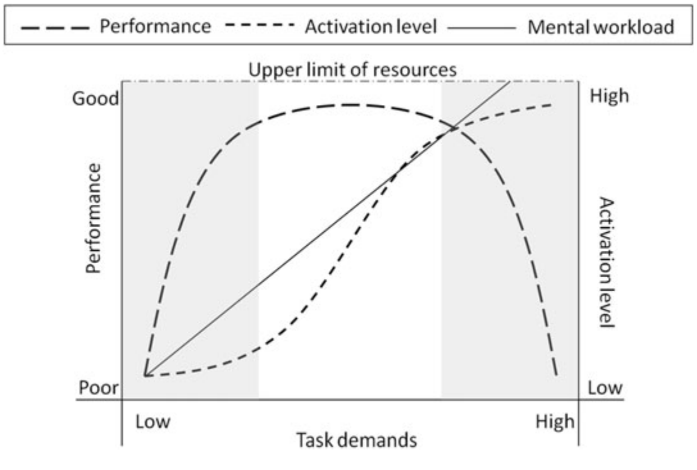

Figure 1. The relationship between activation level, workload (task demands) and performance (adapted from de Waard 1996).

3. Measurement

As we have noted, the multidimensional nature of MWL is reflected in the variety of workload metrics available (see also, e.g. Gawron 2008). In most areas of applied research into MWL, 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 Brookhuis and de Waard 2000; Eggemeier and Wilson 1991). 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 where one task takes priority over the other, performance on the secondary task (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). Visual perception is crucial for drivers while concurrent execution of another in-vehicle visual task (for instance, looking at a cell phone) competes for visual attention with the primary driving task. Thus, a secondary task that is designed to occupy the same resources as the primary task can be used as a metric of MWL. But care must be taken to ensure that the secondary task does not intrude upon or increase MWL on the primary task.

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 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).

MWL 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), among others. 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. Nevertheless, there remain some methodological issues with subjective measures of workload, such as trading off the intrusiveness of online or live ratings against the retrospective bias of post-task ratings.

Physiological measures are a natural type of workload index since work demands physiological activity by definition. Suboptimal workload may also emerge from disruptions in the operator's physiology, for instance when under stress (Hancock and Warm 1989), although other non-workload stressors (such as from the environment or sleep loss) can influence these indices. While 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).

MWL 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 (Brookhuis and de Waard 1993; de Waard and Brookhuis 1991) and of certain facial muscles, such as the corrugator supercilii (Hoogendoorn et al. 2010; Jessurun, Steyvers, and Brookhuis 1993). 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 (e.g. Makeig et al. 2002), while more integrated approaches such as neuroergonomics, suggested by Parasuraman (2011), open new windows to the study of MWL.

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. Ayaz et al. 2012; Huppert et al. 2006) have demonstrated the feasibility of NIRS, and extensions in brain activity measurements may become increasingly accessible, affordable and portable in the immediate future (see, e.g., Mehta and Parasuraman 2013). Operator conditions in fixed positions such as operating motor vehicles, trains and airplanes are suitable for this next generation of MWL field studies. Recently, Posner (2012) illustrated that new methods to study human operators at work are gaining momentum, advancing our understanding of brain plasticity.

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, higher task demand leading to increased MWL does not have to affect performance, and not all measures have to be strongly correlated. Figure 1 shows a theoretical 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 (right) and the resultant task performance (left). 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 mobilised to meet the increasing demand. In the central region, workload gradually increases while performance is at its best, remaining relatively constant. As a limited capacity or limited resource system, when demand exceeds supply, no further resources can be supplied (i.e. a ceiling effect). So, in the region on the right, increases in workload result in degradation of performance.

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 MWL has been very much driven by the applied concerns of the modern workplace. A review of trends in applied MWL 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.

The result of this search shows that the first decade of the twenty-first century saw a total of 87 publications concerning specific applications of MWL. When taken in conjunction with the pattern of results observed in Table 1, this represents some 46% of the total publications in the field for that decade. Compared to the 1990s (39%) and the 1980s (26%), this would seem to suggest a relative increase in focus on applications from the earlier publications on MWL to the present.

In terms of thematic trends within the MWL 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

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.

	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[a]		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[b]	1		1	2
Total	15	54	87	156

[a] Includes supervisory control.
[b] Includes road traffic control and blind travellers' pedestrian wayfinding.

area especially in the last decade, although we should also note the rapid growth of MWL 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 MWL scene has evolved over time.

4.1 1980s

Studies of MWL 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, among other CAD tasks. Also, Hayashi (1988; Hayashi and Kosugo 1987) examined the MWL 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 MWL and provide appropriate assistance, with implications for MWL assessment techniques. Similarly, Nowakowski (1987) was also concerned with online MWL 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 MWL, 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 MWL.

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 MWL with a view to understanding the different determinants of workload – such as road type, weather and traffic conditions. Other research into driving MWL 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. Lenior and Gobel (1997) and MacDonald (1999) looked at train controllers' (i.e. signallers') workload in relation to their area of coverage, and 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 MWL 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 MWL 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 (e.g. Ward et al. 2006) and 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 MWL (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, MWL 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). Diverted attention is a major cause of collisions in motorised traffic (see also Regan, Lee, and Victor 2013). Performance may well deteriorate seriously when the operator is distracted; dividing attention in itself leads to increases in workload as well. Here, then, MWL 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 redline', or where and what exactly this redline is (see Brookhuis, de Waard, and Fairclough 2003). MWL 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 et al. 2005a, 2005b; Wilson et al. 2005). As with previous research, the focus is very much on signaller MWL 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 et al. (2005, 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 among MWL 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, and 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 MWL 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, Wickens, and Sarter 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 and 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 MWL, 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 developed 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 redline of workload, and so at issue is how the person handles these two tasks, now above the redline.

5. Current/future issues and challenges

We conclude our assessment of the state of understanding on the issue of MWL assessment first by setting this concern within the larger social framework. In the modern workplace, individuals and organisations alike are increasingly concerned with monitoring performance and efficiency. The accurate and absolute measurement of workload will assume increasing importance within such organisational and cultural contexts, particularly as culture can have such an influence on subjective and physiological measures of MWL (e.g. Widyanti et al. 2013).

While these may feel like modern concerns born from the rise of technology, times have not changed so much when we consider 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. While 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 no less difficult, science.

Indeed, the contribution of physical demands to MWL is often neglected in applied research, despite the oft-quoted analogy between mental and physical load, as well as numerous other implicit and explicit acknowledgements of its influence. More formally, ISO 10075 is not alone in considering physical load itself to be a component of MWL – seminal metrics for quantifying MWL (e.g. the NASA-TLX; Hart and Staveland 1988) include physical workload in their dimensions. Both physical workload and MWL are well known to have a clear impact on heart rate, heart rate variability and respiration (Mulder 1992), and delineating the effects of one over the other can prove troublesome in applied research. In fact, recent research has explored the interaction between physical and MWL 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). All of this chimes with recent suggestions that mind and body cannot be separated in ergonomics research (cf. Marras and Hancock 2014). Developments in neuroergonomics are lately embracing such duality in evaluating physical and cognitive work (Mehta and Parasuraman 2013).

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, MWL assessment lies very much within both the cognitive revolution of psychology and is also encompassed by the more recent developments in neuroergonomics.

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), 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, and 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. Many of the measures are also differentially sensitive in the different regions.

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), in applying different remedies when this overload condition occurs and in establishing workload standards. When this performance decrement results because of multitasking overload, models such as the multiple resource model (Wickens 2002, 2005, 2008) or models of crosstalk interference (Wickens et al. 2013) 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, reassigning 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 multitask resource demand, and this reduction can be quantified by computational models (e.g. Horrey and Wickens 2003; Salvucci and Taatgen 2011; 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.

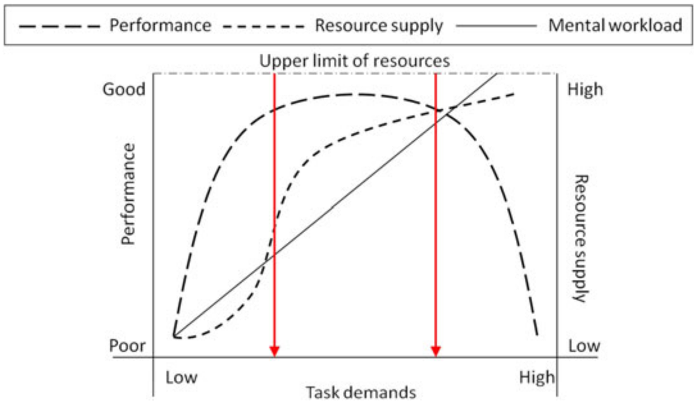

Figure 2. An interpretation of the supply–demand relationship associated with mental workload and performance, highlighting the redlines of overload and underload.

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, Wilson, and Philips 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, Wilson, and Philips 1998). For tracking bandwidth, it is roughly one cycle per second (Wickens and Hollands 2000).

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, and the complexity of the airspace, greatly affects 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 multitask circumstances, is time: simple timeline analysis computes the ratio of time required to time available, or TR/TA (Parks and Boucek 1989). More specifically, timeline 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% of a time interval, workload is 100% 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%, can be identified as potential bottlenecks.

Importantly, timeline 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). While 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 multitask demands in the overload region above the redline, simple measures of performance are adequate to measure 'workload', and models of multitask 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 multitask interference models cannot easily do so at the current stage of their maturity.

One of the most critical items on the research agenda remains how to predict the different strategies that people will adopt when the redline is crossed – and how this 'gear change' affects their workload and performance. Does this move them away from the redline back to the middle of the curve or just serve to keep them under the redline? If the latter, under what circumstances do they allow all tasks to degrade gracefully, rather than 'catastrophically' shedding certain tasks altogether (Wickens and McCarley 2008)? If task shedding takes place, what attributes determine what is shed, and what is continued (Gutzwiller, Wickens, and Clegg 2014)? If it does not, then what circumstances might enable the mobilisation of more effort – and thus mental resources – to cope with the increasing demands? Certainly this latter variance between people (Matthews and Davies 2001) adds to the fuzziness of the 'redline' specification, expanding it into a red zone.

While 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). As we have already seen earlier in this paper, effort is voluntary and is related to resource investment (cf. Shaw et al. 2013), 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 automation-related complacency. 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 underload 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. While 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; Shaw et al. 2013) 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 MWL and its historical development in the field of ergonomics and have 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 MWL, 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; MWL 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. Research in this field has so far failed to provide absolute limits on human performance due to the complex nature of the subject and of the processes involved. But there has been greater success in identifying relative differences in MWL across tasks, thanks to the wide array of tools and metrics that have been developed. Indeed, in measurement, new neuroergonomics techniques are emerging as strong contenders for finally ascertaining the physiological correlates of mental demand. These metrics suggest a resolution of the physical versus MWL 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 MWL scene in recent years. 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. In other domains, similar concerns can also be voiced regarding air traffic, along with health-care demands given the ageing population. Advances in mobile and wearable computing, augmented reality and similar technologies no doubt present great challenges for MWL research in the near future. These advances also reflect and further emphasise the role of mental work over physical work in the modern workplace. To quote Hancock (2009, 114), ‘within two generations, the currency of modern work has gone from joules to bytes and it promises no future return’.

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