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A review of definitions of fatigue – And a step towards a whole definition

Ross O. Phillips *

Institute of Transport Economics (TØI), Gaustadalléen 21, NO-0349 Oslo, Norway

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ABSTRACT

Despite its importance to health and safety, there is a long history of disagreement about how to operationalize fatigue when studying exertion in human transport operators. The current article reviews existing definitions, and consequently proposes a new definition as a step forward. A consideration of everyday use of the term finds that people often seem to use fatigue to describe a sensation related to exertion. Formal definitions of fatigue can be divided into a few broad definitions, capturing experiential, physiological and performance aspects of the construct, and many narrow definitions, focusing only on one or two of these aspects. Most existing definitions do not account explicitly for the role of sleep drives and sleepiness. They also fail to account for a wide range of factors associated with transport operator exertion, such as motivation and individual, organizational and environmental factors. Each of these points is assimilated in the derivation of a new "whole definition" of fatigue, in which the experience of human operator fatigue is a central aspect of the fatigue process. Although multidimensional and diffuse, the evolved definition does not detract from the measurement and study of limited aspects of fatigue. Rather, by describing the dynamic complexity of fatigue, it may help make explicit what different studies do or do not measure or account for in terms of the different aspects of fatigue. It is claimed that the proposed definition could be used to help harmonise attempts to study and tackle fatigue in transport health and safety contexts.

1. Introduction

The need for transport managers to understand and tackle fatigue for the purposes of safety is greater than ever as more demands are placed on operators in a 24-h society increasing in complexity and efficiency (Dinges, 2011; Ho et al., 2013; Lützhöft, Thorslund, Kircher, & Gillberg, 2007; Ricci, Chee, Lorandeau, & Berger, 2007; Strober & Deluca, 2013; Åkersted, 2000). Progress is hindered, however, by a long-term, unresolved lack of consensus about what fatigue is or how it should be measured (Bartley & Chute, 1947). Divergent attempts to operationalize safety-relevant fatigue mean that it is often difficult to generalize about its prevalence and risks for different types of operator. Failure by many applied transport studies to address how fatigue has been thought about and measured in relation to other studies does not help the situation. While some researchers create custom definitions for specific studies, others employ one of many validated measures originally developed for use with either clinical samples, the general population, or occupational or transport operator samples (Smith, Allen, & Wadsworth, 2006; Åhsberg, 2000; Matthews, Desmond, Neubauer, & Hancock, 2012). Other researchers

* Tel.: +47 47 68 33 81.
E-mail address: rph@toi.no

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let operators define fatigue for themselves (Hanowski, Hickman, Blanco, & Fitch, 2011; Williamson & Friswell, 2013), even though people seem to have trouble distinguishing fatigue from other subjective concepts with which it co-occurs, such as stress (Tepas & Price, 2000), anxiety (Lal & Craig, 2001), burnout (Huibers et al., 2003) or boredom (Scerbo, 2000).

Greater explicitness and convergence on operationalization of fatigue would lead to greater consistency of measurement, improve our ability to compare different findings, and help increase the priority of fatigue as a causal factor in relation to those causes that are more easily measured (Brown, 1995). It would also lead to more effective attempts at fatigue management, and consolidate the concept as one that is meaningful and useful (Phillips & Sagberg, 2010; Åhsberg, 1998; Stokes & Kite, 2000). The current article argues that the numerous attempts at definition in the relevant literature each have something to contribute to fatigue as an overarching, diffuse and multidimensional concept. However, due to the particular interests of researchers and the need to operationalize fatigue for specific types of study, most definitions to date may have been narrow, each effectively defining and measuring a different part of the same fatigue "elephant" (Hancock, Desmond, & Matthews, 2012). The article goes on to claim that by delimiting the origins, state and consequences of fatigue, a "whole" definition would help make explicit for different transport researchers, aspects of fatigue that different studies *do not* measure, as well as those that they do measure. As a starting point for debate, the article then goes on to propose such a definition.

2. Definitions of fatigue

2.1. Fatigue in everyday use

When researchers survey or talk to people about a concept in order to measure it, they often aim to optimise the face validity of their research by using an operational definition that reflects everyday usage (Gravetter & Forzano, 2012). According to English dictionaries, fatigue in humans is "extreme tiredness arising from mental or physical effort" (Oxford Dictionaries, 2013). A comparison with definitions for tiredness ("a need for sleep or rest") and sleepiness ("the state of being sleepy") shows that fatigue is unique in the way it is ascribed a cause, namely exertion (Oxford Dictionaries, 2013). Furthermore, while sleep is presumably the main way to recover from sleepiness (temporary circadian effects notwithstanding), it is not clear from the dictionary definition whether sleep or rest is required to recover from fatigue. We might also add that according to dictionary definitions, sleepiness may or may not occur in association with fatigue (Apostolopoulos, Sõnmez, Shattell, & Belzer, 2010).

It is important to question the assumption that dictionary definitions actually reflect everyday usage, which often sees unclear use of terms like sleepiness, tiredness and fatigue. However, popular use of the word in everyday language in phrases like "metal fatigue", "adrenal fatigue" or "battle fatigue" do seem to reflect dictionary definitions in that someone or something is "tired" to the extreme specifically because of some overuse, overexposure or exertion. Capturing this would thus seem to be important for the face validity of a whole definition of fatigue.

2.2. Fatigue as an experience

Several definitions in the research literature are closely related to dictionary definitions in that fatigue is described as a subjective feeling, experience, sense or awareness that is akin to tiredness (Table 1).

However, there are limitations to definitions of fatigue that are exclusively experiential. Firstly, they may fail to capture important fatigue effects, since feeling tired may be a late stage in a process in which unwanted effects have already invaded performance (Hockey, 2013, p. 13). A second problem is that they do not meet Soames-Job and Dalziel (2000)'s criteria for a robust definition of fatigue i.e. one that describes the origins, state and consequences of fatigue. People experiencing fatigue are adept at compensating in order to conserve performance if they are motivated to do so, even though this may come at a cost to themselves in terms of increased effort and exhaustion (Hockey, 2010). If we measure the subjective experience of fatigue, we may find that motivated people experience more fatigue than non-motivated people do, but we will not fully understand why unless we also measure their respective performance. This implies that it is necessary to expand the concept of fatigue beyond mere experience in order to understand the dynamic role of *exertion* in fatigue. A third limitation with existing experiential definitions, arising from our discussion of face validity, is that they often do not actually relate human fatigue directly to exertion, but rather to perceived or actual resource deficiency (e.g. Brown's and Shen et al.'s definitions).

A further point about experiential definitions is that they are associated with attempts to reserve the term "fatigue" for extreme tiredness caused by mental activity, and "impairment" for that caused by physical activity (Brown, 2000). One may question the usefulness of this distinction given that (i) many jobs in the transport sector and elsewhere include a mixture of physical and mental tasks that together result in a merged, general feeling of fatigue, and (ii) mental tiredness often has a somatic basis (Domasio, 1994). In addition, authors have recently pointed to the possibility of a common physiological basis for mental and physical fatigue: "as the muscle is the organ of physical action, so the brain is the organ of cognitive action and each [depends on limited energy stores and] similar response strategies" (Hancock et al., 2012).

It was pointed out long ago that the experience of fatigue is central to everyone's understanding of the concept (Bartley & Chute, 1947), and while the links to performance are far from straightforward, few would argue that the experience of fatigue is a useful indicator of health and safety performance in the short or long term. On the other hand there is no clear

Table 1
Different definitions of fatigue grouped according to type.

Category	Example	Source
Dictionary	"...extreme tiredness resulting from mental or physical exertion or illness."	Oxford Dictionaries (2013)
Subjective	"feeling tired, sleepy or exhausted."	NASA (1996), cited in Soames-Job and Dalziel (2000)
	"subjectively experienced disinclination to continue performing the task because of perceived reductions in efficiency."	Brown (1995)
	"an overwhelming sense of tiredness, lack of energy and a feeling of exhaustion, associated with impaired physical and/or cognitive functioning"	Shen et al. (2006)
	"awareness of a decreased capacity for physical and/or mental activity due to inbalance in the availability, use and/or restoration of resources needed to perform an activity."	Aaronson et al. (1999), cited in Strober and Deluca (2013)
Physiological	"the state of an organism's muscles, viscera, or CNS, in which prior physical activity and/or mental processing, in the absence of sufficient rest, results in insufficient cellular capacity or system-wide energy to maintain the original level of activity and/or processing by using normal resources.	Soames-Job and Dalziel (2000)
	"weakness... from repeated exertion or a decreased response of cells, tissues, or organs after excessive stimulation, stress or activity."	Hirshkowitz (2013)
	...a change in psychophysiological state due to sustained performance [of one or more tasks at work]	van der Linden, Frese, and Meijman (2003)
Physiological/ performance	"reduced force production, loss of exercise capacity, increased sense of effort or perception of force"	Davis and Walsh (2010) in Strober and Deluca (2013)
	"...is the inability to function at the desired level due to incomplete recovery from demands of prior work and other waking activities. Acute fatigue can occur when there is inadequate time to rest and recover from a work period. Cumulative or chronic fatigue occurs when there is insufficient recovery from acute fatigue over time."	Gander et al. (2011)
Performance	"measurable decrements in performance of an activity caused by extended time performing it"	Bartlett (1953)
	"a diminished capacity for work and possibly decrements in attention, perception, decision making and skill performance"	Cercarelli and Ryan (1996)
	"decrements in performance on tasks requiring alertness and the manipulation and retrieval of information stored in the memory"	Gawron et al. (2000)
Multiple	"There are three aspects to fatigue: physiological, objective (work decrement), and subjective fatigue."	Bills (1934)
	"an individual's multi-dimensional physiological-cognitive state associated with stimulus repetition which results in a prolonged residence beyond a zone of performance comfort."	Hancock and Verwey (1997)
	A psychophysiological state that occurs when a person is driving and feeling tired or drowsy, to the extent that they have reduced capacity to function, resulting in performance decrements and negative emotions and boredom as they attempt to stay awake during the task	Craig et al. (2011)

argument for why a definition of fatigue should be *exclusively* subjective, especially when "[physiological and performance] measures can provide useful information on the nature, validity and reliability of fatigue as experienced by the individual" (Brown, 2000). Neither does it seem helpful to reserve the term fatigue for tiredness due to sustained mental activity, as the authors of several experiential definitions have attempted to do. Rather, placing the experience of fatigue at the core of the concept and linking it directly to all forms of exertion would seem to be important for face validity.

2.3. Fatigue as a physiological condition

The difficulties of operationalizing fatigue as an experience has made several authors turn away from everyday usage of the phrase, towards definitions of fatigue as a physiological state of weakness or depletion resulting from exertion (Table 1). One advantage of this approach is that as researchers start to elucidate the neurophysiological mechanisms of fatigue, framework physiological definitions may be "fleshed out" (Soames-Job & Dalziel, 2000). Thus, while the essence of the definitions would remain unchanged, they would become more detailed and accurate as our knowledge increased, and the "state" referred to in Soames-Job and Dalziel (2000)'s physiological definition (see Table 1) would be more accurately described in future definitions.

A further advantage of defining fatigue as a physiological state is that it allows for robust objective measurement of different dimensions of the operator's fatigue state by methods such as electroencephalography (EEG), electrocardiography (ECG), electrooculography (EOG), eye-blink rates, percentage eye closure or pupil dilation (Craig, Tran, & Wijesuriya, 2011; Lal & Craig, 2001; Hanowski et al., 2011). EEG for instance measures overall inhibitory and excitatory postsynaptic potentials of nerve cells at different frequencies, including delta waves associated with sleepiness, and theta waves, associated with low alertness and decreased processing activity (Lal & Craig, 2001).

Despite the advantages, there are drawbacks to an exclusively physiological definition. Firstly there is the need include the experience of fatigue as central for the purposes of face validity. Secondly, most operators never reach their physiological limitations, even under demanding work conditions, i.e. we need to include the experience of operators as a way of

accounting for the important role of psychology in fatigue (Hockey, 2013). Thirdly, while there is no doubt that physiology plays a fundamental role in fatigue, and while we are finding out more and more about the neurological processes underpinning human fatigue, we are still a long way off understanding the whole array of physiological mechanisms responsible for fatigue. Indeed we may never understand the physiology of abstract concepts such as consciousness, attention, and competing goal-based activity that are involved in exertion. Moreover some authors conceive of fatigue not only as exertion but as the summative result of different biochemical and psychophysiological mechanisms, including in addition to exertion, glucose depletion, sleep cycle drives, psychosocial factors and diet (Grandjean, 1979; Hancock et al., 2012). It would thus appear that fatigue has inordinately complex and intractable psychological and physiological aspects, i.e. it is a psychophysiological concept. As such both psychological and physiological components need to be defined and measured in order to best understand it.

2.4. Fatigue as performance decrement

Definitions have also been put forward which conceptualise fatigue solely in terms of its effects on performance output (Table 1). The effects of tiredness on metabolic activity within the prefrontal parietal cortices have consequences for a wide range of cognitive functions, mainly via effects on the prefrontal cortex (Kilgore, 2012). The implications of this for operator performance are wide and varied, and many relevant measures are available for assessing cognitive and related psychomotor performance decrements in transport operators (Curcio, Casagrande, & Bertini, 2001). Thus defining fatigue in terms of performance makes possible robust objective measurement of fatigue in terms of safety-relevant behaviour, something which may appeal especially to transport safety managers and authorities.

However, no matter how interested we may be in performance, to ignore how people experience fatigue leads not only to problems of face validity, but to an incomplete understanding of the concept and its consequences. When expressing fatigue solely in terms of performance, the covert costs of fatigue to the operator are not considered. These costs may themselves cause fatigue and be detrimental to safety performance and operator health in the longer term (Brown, 1995; Fairclough, 2000; Hockey, 1997). The problem of ignoring experiential aspects is also well illustrated by the work on wake state instability, which describes that the net effect of attentional lapses on cognition in non-rested individuals is instability of performance due an ongoing "tug-of-war" between the drive for sleep and motivation to remain awake (Kilgore, 2012; Doran, van Dongen, & Dinges, 2001). The result is that severe and unpredictable decrements punctuate otherwise safe performance by the operator. Thus it is important to account for operator *exertion* in addition to performance, if we are to understand how it develops and what its consequences can be.

Another problem with performance definitions is that performance effects of fatigue are often task-specific, i.e. related to *how* the operator exerts his or her self (Bruce, Bruce, & Arnett, 2010; May, 2011; Saxby, Matthews, Warm, Hitchcock, & Neubauer, 2013). For instance, despite increased reports of fatigue in prolonged driving tasks, the effects on safety performance are surprisingly weak even after 11 h of driving[1] (Hamelin, 1987; Strober & Deluca, 2013), and yet other cognitive tasks show performance decrements after only 5 min (Dinges & Kribbs, 1991). The clear implication is that fatigue is inadequately defined in terms of performance alone, and that any definition of fatigue should make explicit the role of the nature and context of exertion, as well as the value of performing to the operator.

2.5. Fatigue as a dynamic multidimensional concept

The problems of definitions based exclusively on selected dimensions of fatigue are highlighted not least by studies showing dissociation between experiential, physiological and performance indicators of fatigue. Studies showing dissociation between experiential and physiological measures include that of Verwey and Zaidel (2000), who find that during sustained vigilance tasks individuals report increased mental effort even though heart rate variability measurements indicate decreased mental effort. Craig, Tran, Wijesuriya, and Boord (2006) also show dissociation between experiential (self-reports on fatigue before and after driver simulation event) and physiological measures (video analysis of blink rate, yawns). We have already described studies showing dissociation between experiential and performance measures of fatigue, and one would also expect dissociation between physiological and performance measures as a result of increased exertion on striving to maintain performance (Hockey, 2013).

It can be seen then that researchers who have attempted to define fatigue by emphasizing one particular aspect (experience, physiology or performance) have described only a limited part of a larger, multifaceted concept of fatigue. These attempts have inevitably led to definitions that have been viewed as unsatisfactory or incomplete by researchers interested in other or multiple aspects of fatigue. Indeed, a triad of experiential, physiological and performance aspects for fatigue is increasingly accepted, not least by those wishing to understand and tackle fatigue in order to improve occupational safety in the transport sector (Matthews et al., 2012; Åhsberg, 1998). Calls for a multidimensional definition have also been echoed by clinicians (Shen, Barbera, & Shapiro, 2006), and several multidimensional definitions of fatigue are now available (e.g. Table 1). These do have certain limitations, however, as a "whole" definitions. Of those in Table 1, (Bills, 1934)'s definition does not describe the origins and consequences of fatigue. Hancock and Verwey's (1997) is too narrow in that it accounts

[1] NB the state instability hypothesis is based on observations that are apparent after 16–18 h of driving.

only for stimulus repetition as a cause, i.e. it fails to account for fatigue-inducing activities that are less task-specific, like decision-making or having to repeat a certain behaviour. Craig et al.'s (2011) definition does not describe the origins of fatigue – it simply "occurs" – and is restricted to driving. Before we propose a way to address these limitations, we first need to address some further requirements of a whole definition, by discussing fatigue in relation to exertion and sleepiness.

3. Fatigue, exertion and sleepiness

3.1. Fatigue and exertion

Exertion has been an important part of our discussion so far, both in terms of face validity and as an intractable aspect of the concept of fatigue. Though Table 1 includes no formal definitions that define fatigue as exertion, some influential treatments of fatigue do consider it in terms of the form of exertion from which it results. A prime example is (Desmond & Hancock, 2001)'s conceptualisation of different forms of task-related fatigue as "active fatigue" and "passive fatigue". Active fatigue describes fatigue that occurs due to exertion from overload in high-demand driving conditions, where there may be dense traffic, time pressure, and other tasks besides the main driving task. Passive fatigue is due to exertion from having to perform in conditions of underload, i.e. low-demand conditions in which the driver acts as a passive monitor, such as on long open roads with little traffic, using cruise control, and where driving the only task to be performed. Active and passive fatigue are also described as fatigued *states* with different dimensional profiles, and with differing implications for fatigue management (May & Baldwin, 2009). Thus the form and context of exertion (the origin of fatigue) has important implications for the degree, dimensional state and consequences of fatigue.

Despite the importance of this account for transport operator fatigue, we also need to consider that forms of exertion other than those described by active and passive fatigue can lead to safety-relevant fatigue states in transport operators. On a related note, a whole definition of fatigue needs to account for exertion beyond that occurring due to just "absence of sufficient rest" (see Soames-Job & Dalziel, 2000 in Table 1). An array of studies show how health status, health habits and food intake influence subjective fatigue and performance (Tanaka, Mizuno, Fukuda, Shigihara, & Watanabe, 2008; Taylor & Dorn, 2005), and how individual differences, the external environment, conflicting intrinsic goals and psychosocial influences also affect the level of fatigue present in the workplace (Waterhouse, 2012; Bakker, Demerouti, & Euwema, 2005; Hockey, 2010). These findings suggest that the exertion required to achieve the same level of performance using the same strategy is greater when one is hungry or thirsty, out of condition, in poor health, or experiencing extreme ambient conditions, conflicting intrinsic goals or unfavorable psychosocial conditions and so on. As such each of these factors may contribute to the level of fatigue in transport operators. While the actual *exertion* causes fatigue, surrounding conditions contribute to increase fatigue for a given level of performance, by increasing the level of exertion required.

3.2. Fatigue and sleepiness

According to the two-process model of sleep, sleepiness is driven by the combined effect of sleep homeostasis factors, which increases linearly throughout the day after waking, and circadian factors, which are especially responsible for increasing sleepiness in the early hours of the morning (Borbély, 1982). Forced desynchronization experiments show that each process influences both subjective sleepiness and mental performance (Waterhouse, 2012). Many studies have also been done on the effects of sleep loss on mental performance, with complex, continuous and vigilance-requiring tasks being most affected (Dinges, 1995; Gawron, French, & Funke, 2000). Studies also show that sleepiness is detrimental to driving performance (Connor, 2011).

Acceptance of the two-process model of sleepiness, a large degree of overlap between the two concepts, and a failure to achieve consensus on how we should operationalize fatigue, have led some authors to treat fatigue and sleepiness synonymously (Johns, 1998). In the transport domain, some researchers have called for a focus on sleepiness, with sleep drives being seen as all-important for safety (Dawson & McCulloch, 2005). However, there remain good reasons to distinguish fatigue from sleepiness so that it can be studied in its own right. Firstly, there is evidence that when assisted by robustly operationalized measures, not only can people clearly distinguish between fatigue and sleepiness, but fatigue may be more prevalent (Dement, Hall, & Walsh, 2003). Secondly, several studies suggest that sleepiness alone fails to explain all of the important performance effects related to tiredness. For example, laboratory or simulator studies show rapid task-related reductions in vigilance performance, the safety-related task for most transport operators (Smit, Eling, & Coenen, 2004). The length of time certain tasks are performed has also been shown to have main effects on sustained mental performance that are independent of sleep drives (van Dongen, Belenky, & Krueger, 2010). Moreover, reviews of time-on-task studies conclude that monotony associated with driving long distances may promote the onset of sleepiness (Connor, 2011). This last idea is reflected in May and Baldwin's (2009) account of fatigue, in which active and passive fatigue can reduce driving performance either directly, through task effects, or indirectly, by worsening "sleep-related fatigue" (May & Baldwin, 2009). A further reason to consider fatigue in accounting for transport operator safety relates to peak risks for traffic accidents occurring earlier than would be expected solely from variations in circadian rhythm i.e. at midnight rather than the early hours between 0300 h and 0600 h. This difference in timing could be associated with the homeostatic component of sleep-wake cycle. For instance, after 17–18 h of wakefulness (around midnight for the average sleeper), neurobehavioural performance

begins to degrade to levels similar to those for blood alcohol levels of .05 (Williamson & Feyer, 2000; Dawson & Reid, 1997). However, the way in which sleep drives affect performance may also be influenced by prior exertion. This is implied by Williamson et al. (2011), who state that "the most obvious reason for [crash rate peaks around midnight] would appear to be that the trends in risk are confounded by differences in other factors that contribute to overall fatigue". Finally, studying fatigue also offers the potential to capture the longer-term effects on operator health and performance of sustained exertion, which can result in exhausted but non-sleepy states associated with stress and burnout (Maslach, 2000).

Thus we conclude that a failure to clearly delimit the concepts of fatigue and sleepiness and a focus on the latter may lead to insufficient consideration of how the job and life of a transport operator leads to tiredness-related performance decrements. To be able to consider the whole impact of tiredness on performance in future, transport researchers need clarity about the role of sleepiness in relation to any concept of fatigue. Transport managers and authorities also need clarity, such that those countermeasures most appropriate for sleepiness- and task-related fatigue can be selected, and their effects predicted, according to particular transport operator contexts (May & Baldwin, 2009).

4. A new "whole definition" of fatigue

From our discussion we can identify several requirements of a whole definition of fatigue for use in transport research. A whole definition would do well to maintain face validity by describing how fatigue is experienced as a result of exertion. It should describe the state of fatigue as a psychophysiological condition, i.e. one with intractable psychological and physiological aspects. It should account for the role of exertion in the development of fatigue in terms of the dynamic interaction between subjective experience and performance aspects, and allow for all the different ways in which transport operators might exert themselves. It must account for the fact that many researchers regard sleep and wake factors as having the greatest effect on sustained transport operations, and while this does not mean we should confine fatigue to an account of these factors, the definition should make clear the importance of sleep and how it should be thought about in relation to fatigue. Finally, we can add that a whole definition would provide conceptual clarity by implying how to harmonise use of the term fatigue.

On the basis of these requirements, and influenced by the definitions in Table 1, the following definition is proposed:

> *Fatigue is a suboptimal psychophysiological condition caused by exertion. The degree and dimensional character of the condition depends on the form, dynamics and context of exertion. The context of exertion is described by the value and meaning of performance to the individual; rest and sleep history; circadian effects; psychosocial factors spanning work and home life; individual traits; diet; health, fitness and other individual states; and environmental conditions. The fatigue condition results in changes in strategies or resource use such that original levels of mental processing or physical activity are maintained or reduced.*

According to this whole definition the origins of fatigue are "exertion", while the term "fatigue" describes the suboptimal psychophysiological state or condition. The consequences of fatigue are described both in terms of changes in strategies or resources associated with performance, in line with (Hockey, 1997), and actual performance. In the sense that these consequences themselves overlap with ensuing exertion and its role in developing fatigue, fatigue as defined here is a dynamic and evolving process.

The definition implies that we should measure two aspects of the psychophysiological condition of fatigue. Firstly, its degree relative to an optimal subjective or objective state, where an optimal state is one found in a fully recovered, rested and healthy individual, or the average for a group of fully recovered, rested and healthy individuals. Secondly, its dimensional character in terms of psychological and physiological dimensions and their respective subdimensions. Examples of psychological subdimensions are cognitive, conative, affective, self-regulatory experiences, and sleepiness. Examples of physiological subdimensions are biochemical indicators, outwardly observable effects of fatigue such as facial tone, and various changes in electropotentials. The definition also implies that fatigue is a condition best understood by considering in addition to the fatigue condition measures of exertion, strategic changes and performance outcomes.

Exertion leading to fatigue can be defined as "mental processing or physical performance requiring directed effort". The definition states that the form and dynamics of exertion determines the dimensional character of fatigue. By "form of exertion" we mean the sort of mental processing or physical performance involved, in terms of a single cognitive function or psychomotor task, a characteristic task set (e.g. passive versus active driving task), a whole job, or even a total consideration of life and work exertion. The form of exertion will depend on the characteristics of the task(s) performed, and will be influenced by contextual factors (including motivation). The dynamics of exertion describes the history of exertion, and whether effort is expended for a long or short time, continuously or continually.

Contextual factors together describe exertion in terms of the various factors that effort is being directed against. Exertion may be caused by having already exerted and having to continue performing in the face of a wide range of factors, including not only circadian lows or lack of sleep or rest, but extreme temperatures, poor lighting, time pressure, worries about the family, hassle from passengers, heavy traffic and so on. Understanding which of these are most influential for the development of fatigue is important in improving transport operator fatigue.

The value and importance of maintaining performance to the operator will to a large degree determine the extent of sustained effort. On first becoming fatigued, the operator may be motivated to maintain performance (Hockey, 2013). This can

be done by increasing exertion and increasing fatigue. Alternatively, exertion may be conserved or reduced by making strategic adjustments. One example of this is a bus driver choosing to down-prioritise effort expended on passengers and punctuality in order to focus on driving safely. Strategic adjustments may also be made at the cognitive or psychomotor level. Note that an operator may be motivated to maintain performance because he or she wants to, needs to or has to (Hockey, 2013). While one may still become fatigued if one wants to perform (this depends on other contextual factors), having or needing to perform in the face of conflicting intrinsic goals or values may be more fatiguing. On the other hand the operator may not be motivated to perform, in which case he or she may reduce exertion and accept poorer performance, or simply withdraw from the task or job.

Our conceptualisation assimilates sleepiness into the concept of fatigue in two main ways. Firstly, the psychophysiological state of sleepiness overlaps partially with the psychophysiological state of fatigue. Perceptions of the sleepiness state (the felt need for sleep) are included as a subdimension of the experiential dimension of the fatigue condition. Cognitive, conative, affective and self-regulatory dimensions of fatigue will also have sleepiness-related subdimensions.

Secondly, sleep drives described by Borbély (1982)'s two-process model (homeostatic and circadian factors) are included as particularly important contextual influences on exertion that leads to operator fatigue. Sleep and wake factors are important contextual factors for transport operators, in the sense that fatigue may be caused by effort to stay awake. If an operator has been awake a long time and performance is important to the operator, the operator will strive to stay awake, and the tiredness that results will be due both to the effort of staying awake (exertion) and sleep drives (increasing homeostatic pressure), in addition to any other forms of exertion. In this way exertion can increase the extent to which sleep cycle factors result in tiredness in the transport operator (May & Baldwin, 2009). Importantly, fatigue will vary according to building exertion ("time-on-task"), but also according to "time-of-day" where there is exertion to stay awake. Thus our idea of fatigue is more than just a restitution theory (Tepas & Price, 2000). If on the other hand an operator has been awake a long time but there is and has been no wish or perceived need to exert oneself to stay awake, tiredness will be due to homeostatic and circadian sleep drives alone. According to the proposed definition, this is not fatigue, because exertion is necessary for fatigue to occur.

5. Discussion

This article has outlined the need to consider the everyday use of fatigue in addition to its experiential, physiological and performance aspects, in order to define fatigue validly and usefully for the study of human transport operators. Definitions to date have tended to consider individual aspects or dimensions of fatigue in isolation, and by doing so have failed to capture the wholeness of the concept of fatigue. There is a need capture this wholeness in a definition of fatigue that could form the basis for consensus operationalization. Researchers and practitioners in the transport sector with differing interests (e.g. company health care services, occupational psychologists) continuing to use the same word for their subject of study (i.e. fatigue), would learn from each other optimally by agreeing on a broad consensus definition. Establishing that fatigue is a state or condition resulting from exertion, and talking about fatigue in the context of particular form(s) of exertion, may help harmonise progress by avoiding confusion as to the cause and state of fatigue. Accepting this, the cause of fatigue should be expressed as an exertion e.g. sleep-related exertion, active task-related exertion, passive task-related exertion, while the state of fatigue can then be described in terms of its dimensions and subdimensions e.g. sleepiness, emotional fatigue, cognitive fatigue. Performance can then be referred to in terms of the performance of interest e.g. cognitive performance, speeding behaviour or punctuality. Thus, for example, stating that active task exertion can lead to cognitive fatigue and a reduction in cognitive task performance is more helpful than using the term "active fatigue" for cause, state and effect.

The broad operational definition provided makes explicit the challenge of measuring fatigue. A cross-sectional study using self-reports to measure various subdimensions of the experience of fatigue will lead to a partial *characterisation* of the fatigue state, because there will be no assessment of subconscious psychological fatigue or physiological aspects. While this nevertheless may be informative for the purposes of comparison, there will be a lack of *understanding* of the origins, consequences and dynamics of the developing fatigue state, and thus a lack of understanding of how to improve health and safety. This shows how it is important to understand what individual studies do not measure, in order to be able to fully understand the data obtained from what is measured. Consensus about the process of fatigue is important in this regard.

The whole definition presented here also makes explicit difficulties in comparing prevalence rates for different populations. What is measured in some cases is the *experience* of fatigue, i.e. the subjective tiredness, while in other cases operators can be asked to report on *behavioural* symptoms of fatigue in terms of safety behaviour. To capture all risks related to tiredness, a broader concept of fatigue is more helpful than sleepiness, not least because it accounts for the fact that vigilance tasks typical of those performed by many transport operators are especially susceptible to time-on-task performance decrements that go beyond the effects of sleepiness (van Dongen et al., 2010; Connor, 2011). Fatigue also captures longer-term effects on operator health and performance of sustained exertion, which can result in exhausted but non-sleepy states associated with stress and burnout (Maslach, 2000). With this in mind it is worth noting that the definition accommodates several dualistic accounts of fatigue, such as acute versus chronic fatigue and local versus general fatigue. For example, whether fatigue is acute or chronic will depend on the temporal dynamics of exertion, but both forms are described by the definition. Likewise, the form of exertion may be at the local, muscular level (local fatigue) or general psychomotor level (general fatigue). Finally, the definition can also account for various aspects of many operator jobs that may lead to fatigue, but which

have been somewhat overlooked, e.g. poor nutrition, organizational injustice, major life events, long-term health issues or too much overtime. In this sense, consensus on a broader concept of fatigue is very much needed.

Clearly, a broad consensus definition in and of itself cannot resolve all operationalization issues. Remaining issues include how to set an appropriate threshold for safety-relevant fatigue and how to converge on a standard way to measure it. What the definition does do, however, is offer the potential for explicit consensus about diffuse nature of fatigue, and thereby a common basis for agreement about important aspects that have not been sufficiently addressed. If other authors agree, then this would be a good place to start.

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References

Åhsberg, E. (1998). *Perceived fatigue related to work* (Vol. Report Number 19). Stockholm: University of Stockholm, National Institute for Working Life.
Åhsberg, E. (2000). Dimensions of fatigue in different working populations. *Scandinavian Journal of Psychology, 41*(3), 231–241.
Åkersted, T. (2000). Consensus statement. *Journal of Sleep Research*.
Apostolopoulos, Y., Sõnmez, S., Shattell, M., & Belzer, M. H. (2010). Worksite-induced morbidities of truck drivers in the United States. *AAOHN Journal, 58*(7), 285–296. <http://works.bepress.com/mona_shattell/9>.
Bakker, A. B., Demerouti, E., & Euwema, M. C. (2005). Job resources buffer the impact of job demands on burnout. *Journal of Occupational Health Psychology, 10*(2), 170–180.
Bartlett, F. C. (1953). Psychological criteria of fatigue. In W. F. Floyd & A. T. Welford (Eds.), *Symposium on fatigue* (pp. 1–5). London: Lewis.
Bartley, S. H., & Chute, E. (1947). *Fatigue and impairment in man*. McGraw-Hill.
Bills, A. (1934). *General experimental psychology*. New York: Longmans, Green & Co.
Borbély, A. A. (1982). A two-process model of sleep regulation. *Human Neurobiology, 1*, 195–204.
Brown, I. (1995). Methodological issues in driver fatigue research. In L. Hartley (Ed.), *Fatigue & driving*. London: Taylor & Francis.
Brown, I. (2000). Coping with driver fatigue: Is the long journey over? In P. A. Hancock & P. A. Desmond (Eds.), *Stress, workload and fatigue*. NY: Lawrence Elbaum.
Bruce, J. M., Bruce, A. S., & Arnett, P. A. (2010). Response variability is associated with self-reported cognitive fatigue in multiple sclerosis. *Neuropsychology Review, 24*(1), 77–83.
Cercarelli, R., & Ryan, G.A. (1996). Long distance driving behaviour of Western Australian drivers. *Paper presented at the proceedings of the ineternational conference on fatigue and transportation*.
Connor, J. (2011). The role of driver sleepiness in car crashes: A systematic review of epidemiological studies. In J. C. Verster & C. F. P. George (Eds.), *Sleep, sleepiness and traffic safety*. NY: Nova Science Publishers Inc.
Craig, A., Tran, Y., & Wijesuriya, N. (2011). Psychophysiological characteristics of driver fatigue. In J. C. Verster & C. F. P. George (Eds.), *Sleep, sleepiness and traffic safety*. NY: Nova Science Publishers Inc.
Craig, A., Tran, Y., Wijesuriya, N., & Boord, P. (2006). A controlled investigation into the psychological determinants of fatigue. *Biological Psychology, 72*(1), 78–87. http://dx.doi.org/10.1016/j.biopsycho.2005.07.005.
Curcio, G., Casagrande, M., & Bertini, M. (2001). Sleepiness: Evaluating and quantifying methods. *International Journal of Psychophysiology, 41*, 251–263.
Dawson, D., & McCulloch, K. (2005). Managing fatigue: It's about sleep. *Sleep Medicine Reviews* (5), 365–380. October.
Dawson, D., & Reid, K. (1997). Fatigue, alcohol and performance impairment. *Nature, 388*(6639), 235.
Dement, W. C., Hall, J., & Walsh, J. K. (2003). Tiredness versus sleepiness: Semantics or a target for public education? *Sleep, 26*(4), 485–486.
Desmond, P. A., & Hancock, P. A. (2001). Active and passive fatigue states. In P. A. Hancock & P. A. Desmond (Eds.), *Stress, workload and fatigue*. NY: CRC Press.
Dinges, D. F. (1995). An overview of sleepiness and accidents. *Journal of Sleep Research, 4*, 4–14.
Dinges, D. F. (2011). What do we know about recovery from schedules that involve sleep restriction? In *20th International symposium on shiftwork and working time, Stockholm, Sweden*, June 28–July 1, 2011.
Dinges, D. F., & Kribbs, N. B. (1991). Performing while sleepy: Effects of experimentally induced sleepiness. In T. H. Monk (Ed.), *Sleep, sleepiness and performance*. Chichester: John Wiley and Sons.
Domasio, A. R. (1994). *Descartes' error*. London: Vintage.
Doran, S. M., van Dongen, H. P. A., & Dinges, D. F. (2001). Sustained attention performance during sleep deprivation: Evidence of state instability. *Archives Italiennes de Biologie, 139*, 253–267.
Fairclough, S. (2000). Mental effort and the functional impairment of the driver. In P. A. Desmond & P. A. Hancock (Eds.), *Stress, workload and fatigue*. Mahwah, NJ, USA: Lawrence Erlbaum Associates Inc.
Gander, P., Hartley, L., Powell, D., Cabon, P., Hitchcock, E., & Mills, A. (2011). Fatigue risk management: Organizational factors at the regulatory and industry/company level. *Accident Analysis & Prevention, 43*, 573–590.
Gawron, V. J., French, J., & Funke, D. (2000). An overview of fatigue. In P. A. Hancock & P. A. Desmond (Eds.), *Stress, workload and fatigue*. NY: Lawrence Elbaum.
Grandjean, E. (1979). Fatigue in industry. *British Journal of Industrial Medicine, 36*, 175–186.
Gravetter, F. J., & Forzano, L. B. (2012). *Research methods for the behavioural sciences*. Belmont, CA: Wadsworth.
Hamelin, P. (1987). Lorry drivers' time habits in work and their involvement in traffic accidents. *Ergonomics, 30*(9), 1323.
Hancock, P. A., Desmond, P. A., & Matthews, G. (2012). Conceptualizing and defining fatigue. In G. Matthews, P. Desmond, C. Neubauer, & P. A. Hancock (Eds.), *The handbook of operator fatigue*. Farnham, Surrey, UK: Ashgate Publishing Ltd.
Hancock, P. A., & Verwey, W. B. (1997). Fatigue, workload and adaptive driver systems. *Accident Analysis & Prevention, 29*(4), 495–506.
Hanowski, R. J., Hickman, J. S., Blanco, M., & Fitch, G. M. (2011). Long-haul truck driving and traffic safety: Studying drowsiness and truck driver safety using a naturalistic driving method. In J. C. Verster & C. F. P. George (Eds.), *Sleep, sleepiness and traffic safety*. NY: Nova Science Publishers Inc.
Hirshkowitz, M. (2013). Fatigue, sleepiness and safety. Definitions, assessment, methodology. *Sleep Medicine Clinics, 8*, 183–189.
Ho, J.-C., Lee, M.-B., Chen, R.-Y., Chen, C.-J., Chang, W. P., Yeh, C.-Y., et al (2013). Work-related fatigue among medical personnel in Taiwan. *Journal of the Formosan Medical Association, 112*(10), 608–615. http://dx.doi.org/10.1016/j.jfma.2013.05.009.
Hockey, G. R. L. (1997). Compensatory control in the regulation of human performance under stress and high workload: A cognitive-energetical framework. *Biological Psychology, 45*, 73–93.
Hockey, R. (2013). *The psychology of fatigue: Work, effort and control*. Cambridge: Cambridge University Press.
Hockey, G. R. L. (2010). A motivational control theory of cognitive fatigue. In P. L. Ackerman (Ed.), *Cognitive fatigue: Multidisciplinary perspectives on current research and future applications*. Washington, DC: American Psychological Association.

Huibers, M. J. H., Beurskens, A. J. H. M., Prins, J. B., Kant, I., Bazelmans, E., van Schayck, C. P., et al (2003). Fatigue, burnout, and chronic fatigue syndrome among employees on sick leave: Do attributions make the difference? *Occupational and Environmental Medicine, 60*(Suppl. 1), i26–i31. http://dx.doi.org/10.1136/oem.60.suppl_1.i26.

Johns, M. W. (1998). Rethinking the assessment of sleepiness. *Sleep Medicine Reviews, 2*(1), 3–15.

Kilgore, W. D. S. (2012). Socio-emotional and neurocognitive effects of sleep loss. In G. Matthews, P. A. Desmon, C. Neubauer, & P. Hancock (Eds.), *The handbook of operator fatigue* (pp. 173–185). Furnham, Surrey, UK: Ashgate.

Lal, S. K. L., & Craig, A. (2001). A critical review of the psychophysiology of driver fatigue. *Biological Psychology, 55*(3), 173–194.

Lützhöft, M., Thorslund, B., Kircher, A., & Gillberg, M. (2007). *Fatigue at sea – A field study in Swedish shipping VTI rapport*. Linköping: Swedish National Road and Transport Research Institute.

Maslach, C. (2000). A multidimensional theory of burnout. In C. L. Cooper (Ed.), *Theories of organizational stress*. Oxford: OUP.

Matthews, G., Desmond, P., Neubauer, C., & Hancock, P. A. (2012). An overview of operator fatigue. In G. Matthews, P. Desmond, C. Neubauer, & P. A. Hancock (Eds.), *The handbook of operator fatigue*. Farnham, Surrey, UK: Ashgate Publishing Ltd.

May, J. F., & Baldwin, C. L. (2009). Driver fatigue: The importance of identifying causal factors of fatigue when considering detection and countermeasure technologies. *Transportation Research Part F, 12*, 218–224.

May, J. F. (2011). Driver fatigue. In B. E. Porter (Ed.), *Traffic psychology* (1st ed. Amsterdam: Academic Press.

Oxford Dictionaries (2013). *Definition of fatigue in English*. Oxford Dictionaries Online. Retrieved 14.10.13.

Phillips, R. O. & Sagberg, F. (2010a). Fatigue management in occupational driving. An assessment by literature review. *TØI Report*. Oslo: Institute of Transport Economics.

Ricci, J. A., Chee, E., Lorandeau, A. L., & Berger, J. (2007). Fatigue in the US workforce: Prevalence and implications for lost productive work time. *Journal of Occupational and Environmental Medicine, 49*(1), 1–10.

Saxby, D. J., Matthews, G., Warm, J. S., Hitchcock, E., & Neubauer, C. (2013). Active and passive fatigue in simulated driving: Discriminating styles of workload regulation and their safety impacts. *Journal of Experimental Psychology: Applied*. http://dx.doi.org/10.1037/a0034386.

Scerbo, M. W. (2000). Stress, workload and boredom in vigilance: A problem and an answer. In P. Hancock (Ed.), *Stress workload, and fatigue*. NY: CRC Press.

Shen, J., Barbera, J., & Shapiro, C. M. (2006). Distinguishing sleepiness and fatigue: Focus on definition and measurement. *Sleep Medicine Reviews, 10*(1), 63–76. http://dx.doi.org/10.1016/j.smrv.2005.05.004.

Smit, A. S., Eling, P. A. T. M., & Coenen, A. M. L. (2004). Mental effort causes vigilance decrease due to resource depletion. *Acta Psychologica, 115*, 35–42.

Smith, A., Allen, P. H., & Wadsworth, E. J. K. (2006). *Seafarer fatigue: The Cardiff research programme*. Cardiff: Centre for Occupational and Health Psychology, Cardiff University.

Soames-Job, R. F., & Dalziel, J. (2000). Defining fatigue as a condition of the organism and distinguishing it from habituation, adaptation and boredom. In P. A. Hancock & P. A. Desmond (Eds.), *Stress, workload and fatigue*. NY: CRC Press.

Stokes, A. F., & Kite, K. (2000). On grasping a nettle and becoming emotional. In P. Hancock & P. Desmond (Eds.), *Stress, workload and fatigue*. NY: CRC Press.

Strober, L. B. & Deluca, I. (2013). Fatigue: Its influence on cognition and assessment. In P. Arnett (Ed.), *Secondary influences on neuropsychological test performance* (pp. 117).

Tanaka, M., Mizuno, K., Fukuda, S., Shigihara, Y., & Watanabe, Y. (2008). Relationships between dietary habits and the prevalence of fatigue in medical students. *Nutrition, 24*(10), 985–989.

Taylor, A. H., & Dorn, L. (2005). Stress, fatigue, health and risk of road traffic accidents among professional drivers: The contribution of physical inactivity. *Annual Review of Public Health, 27*(2).

Tepas, D. I., & Price, J. M. (2000). What is stress and what is fatigue? In P. A. Hancock & P. A. Desmond (Eds.), *Stress, workload and fatigue*. NY: Lawrence Elbaum.

van der Linden, D., Frese, M., & Meijman, T. F. (2003). Mental fatigue and the control of cognitive processes: effects on preservation and planning. *Acta Psychologica, 113*, 45–65.

van Dongen, H. P. A., Belenky, G., & Krueger, P. M. (2010). Investigating the temporal dynamics underlying mechanisms of cognitive fatigue. In P. L. Ackerman (Ed.), *Cognitive fatigue: Multidisciplinary perspectives on current research and future applications*. Washington, DC: American Psychological Association.

Verwey, W. B., & Zaidel, D. M. (2000). Predicting drowsiness accidents from personal attributes, eye blinks and ongoing driver behaviour. *Personality and Individual Differences, 28*, 123–142.

Waterhouse, J. (2012). Circadian rhythms and mental performance. In C. E. Matthews, P. A. Desmond, C. Neubauer, & P. Hancock (Eds.), *Operator fatigue*. Ashgate.

Williamson, A., & Feyer, A. M. (2000). Moderate sleep deprivation produces impairments in cognitive and motor performance equivalent to legally prescribed levels of alcohol intoxication. *Occupational and Environmental Medicine, 57*(10), 640–655.

Williamson, A., & Friswell, R. (2013). The effect of external non-driving factors, payment type and waiting and queuing on fatigue in long distance trucking. *Accident Analysis & Prevention, 58*, 26–34. http://dx.doi.org/10.1016/j.aap.2013.04.017.

Williamson, A., Lombardi, D. A., Folkard, S., Stutts, J., Courtney, T. K., & Connor, J. L. (2011). The link between fatigue and safety. *Accident Analysis & Prevention, 43*(2), 498–515.