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Review Article

Vigilance: discussion of related concepts and proposal for a definition

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ABSTRACT

We reviewed current definitions of vigilance to propose a definition, applicable in sleep medicine. As previous definitions contained terms such as attention, alertness, and arousal, we addressed these concepts too. We defined alertness as a quantitative measure of the mind state governing sensitivity to stimuli. Arousal comprises a stimulus-induced upward change in alertness, irrespective of the subsequent duration of the increased level of alertness. Vigilance is defined as the capability to be sensitive to potential changes in one's environment, ie the capability to reach a level of alertness above a threshold for a certain period of time rather than the state of alertness itself. It has quantitative and temporal dimensions. Attention adds direction towards a stimulus to alertness, requiring cognitive control: it involves being prepared to process stimuli coming from an expected direction. Sustained attention corresponds to a state in which some level of attention is purposefully maintained, adding a time factor to the definition of attention. Vigilance differs from sustained attention in that the latter in addition implies a direction to which attention is cognitively directed as well as a specification of duration. Attempts to measure vigilance, however, are often in fact measurements of sustained attention.

1. Introduction

A slip of the mind can result in an innocuous failure to perform some daily activity. Examples include putting a cup with a tea bag under the coffee tap of a coffee machine instead of under the hot water spout, or putting pea pods in a pan to cook and throwing the green peas in the waste bin. The behavior resulting from such slips is often referred to as automatic behavior [1]. The reason for such slips is that not enough attention was paid to these simple and ordinary tasks; the cause of this deficit in attention is a lack of vigilance. Not all such slips are innocuous: vigilance problems can have life-threatening consequences, eg when train drivers ignore a red signal. An excellent model of severely disturbed vigilance is the primary sleep disorder narcolepsy [2,3]. Patients with narcolepsy suffer considerably in daily life from impaired vigilance. Narcolepsy patients have for instance difficulty in recalling the content of a conversation, finishing reading a book, or keeping focused on a study or work.

In view of its importance for care and research vigilance impairment needs to be quantified, which in turn requires an accurate definition. Without it, different concepts may cause confusion, and impairments may be attributed to incorrect mechanisms or causes. Unfortunately, the definition of vigilance in the scientific literature is far from unambiguous. We reviewed part of the literature and attempted to reach a definition of vigilance that might be useful in the specific context of sleep medicine.

2. Vigilance in the literature

The Merriam-Webster dictionary defines vigilance as 'the quality or state of being vigilant' [4]. In turn, 'vigilant', derived from the Latin word vigilare (to keep watch, to stay awake) is then explained as 'alertly watchful, especially to avoid danger'. This primary definition thus relates vigilant to alert, which is described as 'watchful and prompt to meet danger or emergency' and 'quick to perceive and act'.

Abbreviations: ADHD, attention deficit hyperactivity disorder.

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Scientists often refer to Mackworth's publications about vigilance decrement for a first description of vigilance [5,6]. He defined vigilance *decrement* as a decline in attention-requiring performance developing and worsening after a prolonged period of time spent on the respective performance. This definition evolved simultaneously with the related 'signal detection theory' [7], which concerned the ability to distinguish relevant from irrelevant (background) stimuli based on certain determinants of how stimuli are detected. Some authors built upon Mackworth's decline in function as the foremost criterion to define vigilance. For instance, Sanders stated that vigilance is defined through the result of a cognitively simple task that is performed less well over time [8]. Although Mackworth's work is dominated by descriptions of decrement of vigilance, he did not use this decrease in performance as the defining feature of vigilance itself. Instead, he defined vigilance as a state of readiness to detect and respond to small changes in the environment, occurring at irregular times [9]. He had adapted this definition from Head, who described vigilance as a high state of physiological efficiency [10]. Head's description is now regarded the first definition of vigilance in the scientific literature.

At present the term vigilance is widely applied in the psychological field. Examples of definitions include short descriptions as 'the capacity to attend to external stimuli' [11]; other formulations include a time aspect, such as 'the ability to attend over long and generally continuous periods of time for the purpose of detecting and responding to relevant stimuli' [12].

3. Vigilance in relation to attention, arousal, and alertness

Attempts to define vigilance often contain the terms alertness, attention, sustained attention, or arousal. The use of any of these three words illustrates differences in interpretation and quantification of vigilance between fields of science. Oken and colleagues [13], who stated that a first concept of vigilance is used by animal behavior scientists and psychiatrists, interpreting vigilance as being alert for threats or dangers. Psychologists and cognitive neuroscientists define vigilance in a second manner, ie as the ability to sustain attention to a task for a period of time. Finally, clinical neurophysiologists and sleep scientists tend to restrict vigilance to the arousal level on the sleep-wake spectrum. These different interpretations of vigilance suggest that reflection on what attention, alertness, and arousal are, is essential before a common definition of vigilance can be attempted.

3.1. Alertness

Posner described 'alerting' as achieving and maintaining a state of high sensitivity to incoming stimuli [14]. A recent paper defined alertness not so much as a state, but as the capacity of the mind at a particular moment to respond appropriately to external and internal stimuli [15]. We will return to this difference later.

Alertness is sometimes subdivided in tonic and phasic alertness. Schmidt et al. [12] described tonic alertness as a slow, diurnal fluctuation in wakefulness and performance, and phasic alertness as a sudden increase in attentiveness, which immediately follows a stimulus requiring a rapid response. Such a stimulus can originate from surrounding factors (external, eg a fast approaching car) or from within the body itself (internal, eg pain, a sudden thought about unfinished business, etc). The term 'tonic alertness', sometimes called intrinsic alertness, has been proposed as a synonym for sustained attention or vigilance by Oken et al. [13] Some researchers intertwine the terms alertness and attention even further: in a paper about intrinsic and phasic alertness, Sturm and Willmes mentioned that intensity aspects of attention include both alertness, both intrinsic and phasic, and sustained attention. According to these authors, these intensity aspects form the basis that underlies selective aspects of attention, ie orienting and executive attention [16].

We extract the following concept of alertness from the literature above: alertness is defined as a quantitative description of the state of the mind, characterized by being *sensitive* to incoming stimuli. These can be either external or internal stimuli. Following this definition, any method to assess whether incoming stimuli are processed, can be used to quantify alertness. Examples include basic neurophysiological measures such as event-related potentials, but also attention tasks, as alertness is expressed through, and a requisite for attention. Alertness is broken down in two parts: one concerns an intrinsic aspect that slowly fluctuates over time ('tonic alertness'), and the other a stimulus-modulated aspect that may change more quickly ('phasic alertness') (Fig. 1A).

3.2. Attention and sustained attention

Posner and Petersen [17] proposed a model of attention consisting of three major functions: firstly, orienting to sensory events and directing attention spatially to important stimuli; secondly, detecting signals that need to be thoroughly and consciously processed; and thirdly, the ability to prepare and sustain alertness to process high-priority signals. The latter function, also referred to as sustained attention, is used interchangeably with vigilance by some [18]. Stuss et al. [19] defined sustained attention as a form of executive control that involves monitoring the activation of task-relevant brain areas, re-energizing activated areas when they are low, and inhibiting irrelevant brain areas if they become inappropriately selected. Robertson and Garavan summarized this as the ability to maintain a goal-directed focus in a context of a repetitive, nonarousing nature that provides little external stimulation [20]. In a paper, Robertson and colleagues referred to this capability as endogenous modulation of alertness (self-sustained attention), which they distinguished from exogenously controlled alertness, ie alertness driven by factors such as novelty, salience and stimulus change [21]. This distinction is also referred to as top-down (endogenous) versus bottom-up (exogenous) attentional control [22]. Though distinctive aspects, exogenous attentional control can influence endogenous attentional control, and the direction of this influence is depending of stimulus predictability [23].

The term 'alertness' was mentioned in descriptions of attentional processes in the literature cited above, indicating that attention and alertness are closely related. They are distinguished by the direction towards a specific stimulus that characterizes attention but not alertness (Fig. 1B). Hence, attention requires some executive control: being prepared to process incoming stimuli there, where stimuli can be expected (eg a task, or any internal cognitive activity such as reviewing an experienced event). In other words, alertness corresponds to an implicit sensitivity to unpredictable incoming stimuli, while attention refers to an explicit focus on a certain stimulus.

We conclude that sustained attention corresponds to a state in which a certain level of attention is purposefully maintained (Fig. 1F), adding a time factor to the definition of attention. This implies that attention can also drop below this particular level. This decrease can be prevented by a stimulating environment, reflected by the arrows in Fig. 1F, as well as by endogenous modulation of attention.

3.3. Arousal

Arousal is probably defined as poorly as vigilance itself, although it is less frequently mixed with definitions of alertness or attention. Arousal is often described as the neurobiological mechanism

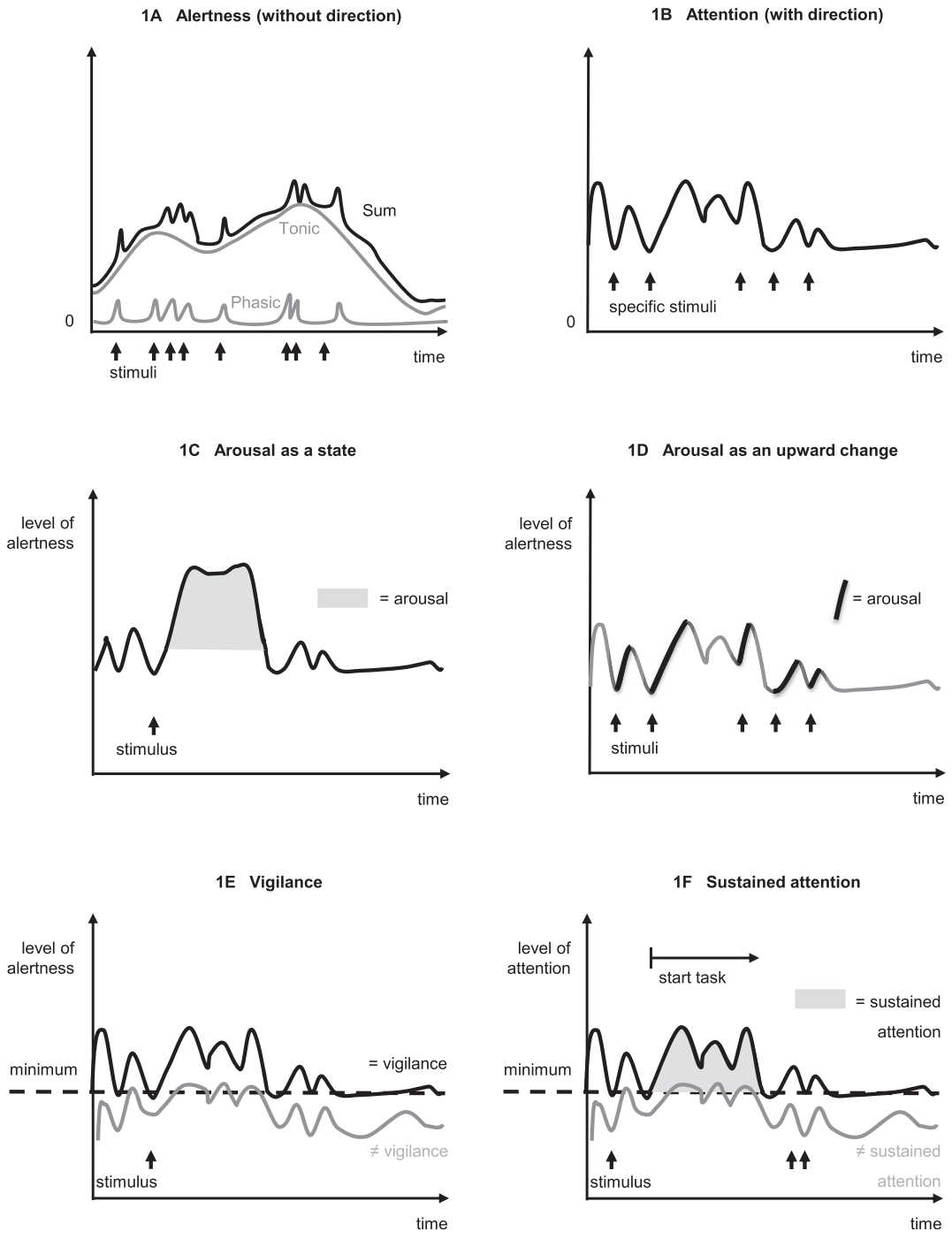

Fig. 1. Illustration of intensity and time aspects of the reviewed terms. A. Alertness: The grey lines represent the tonic and phasic components, ie the slowly fluctuating level and stimulus-provoked, temporary increase. The black line combines these aspects; it illustrates the quantitative dimension the state of sensitivity of the mind to incoming stimuli. **B.** Attention: this figure resembles the figure of alertness, as attention also comprises a quantitative dimension, fluctuating over time. Attention differs from alertness in that it has a direction (not drawn): there, where stimuli can be expected. **C**. Arousal as a state is represented by the shaded part of the figure; it corresponds to the mechanism underlying a prolonged period with a higher level of alertness compared to an implicit baseline. **D.** Arousal as an upward change is represented by the blackened part of the line; it corresponds to the mechanism underlying an upward change in the level of alertness. **E.** Vigilance: the black line corresponds to someone with the capability to maintain a certain level of alertness over a period of time, ie someone with a normal vigilance. In contrast, the grey line corresponds to someone without such capability, ie someone with a disturbed vigilance. **F.** Sustained attention: this figure closely resembles the figure of vigilance: the black line corresponds to someone with the capability to maintain a certain level of attention over a period of time for the purpose of successfully completing a task, represented by the shaded part of the figure. The grey line represents someone without such capability. Vigilance differs from sustained attention in the concepts underlying the y-axis, ie the quantitative aspect, which in turn reflects the absence of a direction (alertness) or the presence (attention).

behind vigilance [24], with low levels corresponding to sleep, high levels to a vigilant state, and too high levels to a 'hyperaroused' state as proposed in models for insomnia [25]. Probably the most common definition of arousal, used by neurophysiologists, is a sudden activation occurring during sleep [26]. Although both definitions link arousal to sleep, there is an essential difference

between the two: the first definition describes arousal as a concept with a certain level, ranging from low to high and relative to an implicit baseline depending on the circumstances (Fig. 1C), whereas the second definition is limited to an upward change of state, ie from any sleep stage to a lighter sleep stage or to the waking state.

In contrast to authors who link arousal to sleep, Moller et al. took a different view: they advocated that a low level of alertness should not be regarded as equalling sleepiness. They regard arousal as a mechanism underlying an upward switch between levels of alertness (Fig. 1D) rather than between states of consciousness such as sleep or wake [15]. As such, there is a direct causal relation between arousal and alertness. This relation ties in with the use of the term arousal in descriptions of the neurohormonal response in situations of acute stress: here too the stimulus results in an increased sensitivity to stimuli and increased preparedness to respond, ie an increased alertness [25]. Schmidt et al. even decided to unite the terms alertness and arousal [12].

An unambiguous definition of arousal cannot be distilled from these descriptions. Compared to the scientific literature, the linguistic definition is clearer. The Merriam-Webster dictionary refers to the verb 'to arouse', which is described as 'to awaken from sleep' or 'to rouse to action' [3]. The Shorter Oxford English Dictionary [27] describes arousal as 'the action of arousing or being aroused', and 'to arouse' in turn as 'to raise or stir up from sleep or inactivity', 'to stir into activity', or 'to wake up'. Linguistically, arousal thus refers to an upward change in either the sleep/wake state or the activity spectrum, ie an awakening or a change towards action.

If the linguistic lead is followed, ie arousal signifies an upward change only, then it would be useful to have a word for a downward change. In literature on animal research, this is sometimes called a dearousal [28]. According to the Merriam-Webster dictionary, the antonym of 'to arouse' is 'to lull' [4]. This is defined as 'to cause (someone) to fall asleep, to become sleepy, or to rest', and, interestingly, 'to cause (someone) to feel safe and relaxed instead of careful and alert' or 'to cause to relax vigilance'. As the antonym of 'to arouse' refers to the cause of a drop of alertness or vigilance, the term 'arousal' and its opposite linguistically purely reflect a change of states, rather than a state itself.

One possible solution to deal with the multiple definitions of arousal would simply be to accept that the term is ambiguous and has multiple meanings. Arousal could then both refer to an upward change between states of wakefulness or alertness, or to such a state itself. This will cause confusion, though.

An alternative approach is to reappraise the definition of arousal in the context of alertness, now that we deduced a definition of alertness from the literature. It is likely that the different definitions of arousal have evolved from its linguistic definition as a result of imprecise definitions of vigilance and alertness. Defined as above, alertness is determined by an intrinsic and extrinsic, stimulus-provoked aspect. As such, arousal as a sudden upward change refers to the mechanism behind a stimulus-caused change in alertness, irrespective of the subsequent duration of the increased level of alertness. In other words, whether the increased alertness lasts for half a second or a half a day does not matter: an upward change is called an arousal. A prolonged period with a high level of alertness as a consequence of an arousal could be referred to as 'an aroused state'. If such an aroused state exceeds the level appropriate to the circumstances, this may be called a hyperaroused state.

We here advocate that arousal be defined as an upward change for three reasons: 1) it is biophysically represented by electroencephalographic changes, 2) it follows the linguistic definition most closely, and 3) it adds to the definition of alertness, explaining the mechanism behind a stimulus-caused change in alertness.

3.4. Vigilance, alertness and arousal

There is a striking resemblance between the descriptions of vigilance and alertness. Consider the following examples: 'watchful and prompt to meet danger' (used to explain the meaning of both terms), 'quick to perceive and act' (alertness), 'readiness to detect and respond to changes in the environment' (vigilance), 'a state of high sensitivity to incoming stimuli' (alertness), and 'the capacity of the mind at that moment to respond appropriately to external and internal stimuli' (both terms).

Is alertness a synonym of vigilance? Firstly, some authors indeed seem to regard it as such, based on definitions such as 'maintaining a vigilant or alert state' [17]. Others assume a slightly different definition. Secondly, those who differentiate between tonic and phasic alertness, equate vigilance to the 'tonic', intrinsic fluctuation of alertness [13]. This interpretation of vigilance is narrow and not generally accepted; it excludes phasic, stimulus-provoked alertness. Then again, this stimulus-provoked change in the level of alertness can be referred to by the term arousal. Thus, if vigilance were restricted to the intrinsic fluctuation of alertness, arousal and vigilance would be complementary terms in the description of the spectrum of alertness. Thirdly, some do not equate vigilance to either alertness or tonic alertness. Instead, they consider alertness to be a quantitative measure, whereas vigilance refers to the capacity to maintain a sufficiently high level of alertness, ie to maintain a level of alertness above a threshold required to detect unpredictable changes in the environment [23]. The definition of vigilance proposed below corresponds to this last view.

4. What is vigilance?

The following three aspects of vigilance can be derived from the literature cited above and should be included in a comprehensive definition. Firstly, being vigilant refers to a quality or state of mind, described by keywords such as 'alertly watchful, especially to avoid danger', 'a readiness to detect and respond to changes in the environment', and 'being alert for threats or danger'. Secondly, vigilance is the extent to which someone is vigilant, so it must contain a quantitative aspect. Thirdly, this level is known to decrease over time in a non-stimulating environment, thus including a temporal dimension. The core elements of the term vigilance as defined above, as well as the position of this term in relation to the terms alertness, sustained attention, and arousal, resulted in the following proposal, also summarized in Fig. 1E.

4.1. Definition

Vigilance is here proposed to be the capability to be aware of relevant, unpredictable changes in one's environment, irrespective of whether or not such changes occur. This capability has two dimensions. The first is quantitative and refers to the level of alertness that is required for being vigilant. The second dimension follows from the fact that vigilance can change over time: it has a temporal dimension.

5. Implications & consequences for measurements of vigilance

Vigilance is a prerequisite for being able to pay attention. The ability to maintain a high level of attention over a length of time is summarized by the term sustained attention. Sustained attention differs from vigilance: it is directed towards something, whereas vigilance implies alertness to any possible, relevant new happening, ie it does not require a specific focus. The ability to

restrict attention to such a task, rather than dividing it, is an aspect of attention itself, not of vigilance. The disorders attention deficit hyperactivity disorder (ADHD) and narcolepsy illustrate this difference. ADHD comprises increased distractibility by lack of continued focus to a task, ie lack of sustained attention, whereas narcolepsy comprises a disorder in which vigilance is impaired irrespective of a directional aspect. Though outside the scope of this review, this distinction is reflected by anatomical and biochemical differences between these diseases. The attentional disorder is predominantly a dysfunction of the prefrontal cortex, caudate nucleus and cerebellum, and is mainly dependent on dopaminergic and noradrenergic neurotransmitter systems. In contrast, the vigilance disorder narcolepsy is caused by hypothalamic hypocretin cell loss with broader impact on the monoaminergic systems.

Nevertheless, as vigilance is expressed through attention, measurements of vigilance and attention partially overlap: in fact, measuring sustained attention can be regarded as a method to obtain a quantitative assessment of the underlying construct vigilance, at least in one way. The capability to sustain attention presumes the capability to sustained alertness. The opposite is not necessarily true: the inability to sustain attention can also result from the inability to direct attention or to ignore distracting stimuli. In that case, alertness and vigilance are unaffected.

To illustrate this, note that sustained attention is mainly measured by response tasks in which subjects are asked to appropriately detect changes in the environment by means of appearing or changing stimuli. The performance on such tasks is scored using measurements of accuracy, speed or both. This corresponds to the first part of the definition of vigilance provided above, ie it refers to the quantitative dimension of vigilance. Finally, tests of sustained attention mostly account for the temporal dimension by extending the measurements over a certain period of time, so that fluctuations in the level of intrinsic alertness affecting attention can become manifest. This corresponds to the view of Oken et al. [13].

The definition of vigilance proposed in this paper does not include the ability to respond to the stimuli or the nature of such responses. This is in accordance with the literature, where vigilance has been defined as the readiness to respond without including the response itself, suggesting that the ability to respond is not part of vigilance. However, vigilance can hardly be assessed without evaluating responses, and the ability to respond may with reason be regarded as the very reason to be vigilant. Such considerations suggest that responsiveness might be included in the definition of vigilance, which would turn vigilance into a much broader concept. The consequence of doing so would be that a failure to respond might be interpreted as impaired vigilance, without any indication whether the failure was due to an impairment of vigilance in the restricted sense as defined above or of responding to a stimulus. As this may once again increase confusion, we prefer to exclude responsiveness from the definition of vigilance. Measuring vigilance through sustained attention nevertheless requires responding. One should therefore realize that tests of sustained attention will never be specific for impairments in vigilance or attention, and that the results of such tests should always be interpreted in a broader context, evaluating interference of response characteristics.

6. Implications for sleep medicine

Two sleep disorders have been shortly mentioned above: narcolepsy as a model of a vigilance disorder and insomnia as a model of a 'hyperaroused state', ie a period with a level of alertness that exceeds the level appropriate to the circumstances. In other words, different aspects are expressed in different sleep disorders. Box 1 comprises some additional examples.

Our attempt to reach a definition of vigilance resulted from the necessity to quantify this concept, in view of its growing importance for patient care and research in sleep medicine. Having reached a definition of vigilance, we therefore subsequently addressed the implications of this definition for its measurement. Sleep medicine does not only concern objective measurements; there is also the patient's perceptions. Patients may well report symptoms related to these concepts that are not supported by deficits in objective measurements [29,30]. The apparent paradox is increasingly acknowledged in the scientific literature and deserves more attention, but this topic is outside the scope of this review.

Though the concepts discussed above are important in sleep medicine, they are often not a patients' presenting symptom. Patients tend to present with the chief complaint of "tiredness". This is a highly heterogeneous complaint, which can refer to either sleepiness or fatigue, which two terms should be regarded as reflecting two distinct phenomena [31]. Attempts to disentangle the meanings of sleepiness and fatigue reflect a similar lack of consensus as we encountered with concepts such as vigilance or arousal. The definitions in use for fatigue and sleepiness are largely operational in nature. In the case of sleepiness, definitions vary from the tendency to fall asleep (as conceptualized by objective measurements such as the multiple sleep latency test [32] and maintenance of

Box 1
Examples of relevant concepts in several sleep disorders and in good sleepers

Narcolepsy: The main disturbance concerns vigilance, ie the capability to maintain a certain level of alertness over a period of time. Alertness itself can still vary throughout the day and even reach high levels. High levels of alertness occur, however, mainly phasic, stimulus-provoked, and quickly decrease again in the absence of further stimuli. As vigilance is a prerequisite for attention, attention and sustained attention are impaired by consequence.

Sleep deprivation: The same concepts are affected as in narcolepsy, though in severity dependent of the duration and amount of sleep deprivation, and reversible after recovery [39].

Sleep apnea syndrome: reviews of cognitive performance in this group indicate that both vigilance and attention are affected [40,41]. Some studies have demonstrated persistent impaired attentional functions despite of normalization of vigilance after continuous positive airway pressure treatment. Therefore, only part of the disturbances of attention and sustained attention is the consequence of the vigilance disturbance in this patient group. Attentional functions are also separately affected.

Insomnia: Alertness is affected in the opposite direction as above when trying to fall asleep or sustain sleep: the level of alertness exceeds the level appropriate to the circumstances; patients have difficulty to 'de-arouse'. Most studies of daytime functioning do not indicate deficits in vigilance, attention and sustained attention [29,42].

Good sleepers: These concepts should all be unaffected in otherwise also completely healthy individuals. Note that other factors than sleep can influence both alertness and attention, such as neurological/psychiatric morbidities (most prevalent ADD/ADHD) or physical/psychosocial stress factors.

wakefulness test [33]) to the subjective perception of the momentary state between sleep and wakefulness (conceptualized by visual-analog scales or validated sleep questionnaires, and sometimes referred to as the state on the arousal spectrum) [31,34–36]. In the case of fatigue, only subjective measurements are available; conceptualizations vary from dichotomous models (eg acute vs. chronic fatigue) to a more multidimensional approach including both internal sensations (eg feeling of exhaustion) and associated consequences (eg impaired cognitive functioning) [34]. The reader is referred to references nr. [31,34,35] and [37] for an extensive overview of the concepts fatigue and sleepiness in patients with sleep disorders. Though distinct entities, both subjective sleepiness and fatigue are sometimes intertwined with subjective alertness. Examples of this entanglement include the items of the Stanford Sleepiness Scale [38], and the multidimensional model of fatigue mentioned above [34]). Therefore, the discussion of concepts in this paper may not only be of use in future studies of vigilance, but might contribute to further understanding of subjective sleepiness and fatigue as well.

7. Conclusions

The definition of vigilance is linked to definitions of alertness, sustained attention and arousal. Before defining vigilance itself, alertness has to be defined.

- Alertness is the quantification of the state of mind sensitive to incoming stimuli.
- Vigilance is defined as the capability to be aware of potential relevant, unpredictable changes in one's environment, including a quantitative dimension, a sufficient level of alertness, and a temporal dimension.
- Attention adds a direction, requiring cognitive control, to this capability.
- Sustained attention adds the prolongation of this capability over time.
- Arousal is a qualitatively distinct concept, which describes a sudden, possibly long-standing, upward change in alertness.

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Conflict of interest

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