A conceptual framework and taxonomy for understanding and categorizing driver inattention

ITS COOPERATION

Johan Engström (AB Volvo), Christopher A. Monk (NHTSA)
Chairs, US-EU Driver Distraction and HMI Working Group

Contributors (in alphabetical order): Richard J. Hanowski (Virginia Tech), William J. Horrey (Liberty Mutual), John D. Lee (University of Wisconsin), Daniel V. McGehee (University of Iowa), Michael Regan (University of New South Wales, Australia), Alan Stevens (TRL), Eric Traube (NHTSA), Marko Tuukkanen (Nokia), Trent Victor (AB Volvo), C. Y. David Yang (FHWA)

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Summary

This documents reports on the results of the Inattention Taxonomy project, which was carried out by the Driver Distraction & Human Machine Interaction (DD & HMI) Working Group, under the framework of the United States and European Union Bilateral Intelligent Transportation Systems Technical Task Force (US-EU Bilateral ITS TF), with the main objective being to define a conceptual framework and taxonomy of driver inattention. While driver inattention is known as one of the main factors contributing to road crashes, commonly agreed definitions of key concepts are still lacking. This makes it difficult to estimate the true magnitude of road-safety problems associated with driver inattention and makes comparison of results across studies problematic. Thus a common taxonomy of inattention-related concepts such as driver distraction is strongly needed, both from scientific and applied standpoints.

The taxonomy developed in the project is mainly intended to be applied in the context of driver behaviour and incident/accident analysis, the design and interpretation of experimental studies and in the design and evaluation of vehicle systems. The term *taxonomy* here refers to the definition of key theoretical concepts and their mutual relationships. This should be distinguished from a *coding scheme*, which refers to detailed operational definitions of phenomena observable in the available data.

A key starting point for the project was that, in order to create a taxonomy of driver inattention, one first needs to be clear about what is meant by driver *attention*. To this end, a conceptual framework for driver attention was formulated in terms of a set of key principles. This framework proposes an action-oriented view of attention, where driver attention is generally defined as the allocation of resources to a set of (driving- or non-driving related) activities. The distribution of resources to activities depends on two main aspects. The first relates to *activation* (*how much* of one or more resource is allocated) while the second relates to *selectivity* (how resources are distributed between activities).

Driver *inattention* was then conceptualised in terms of *mismatches* between the driver's current resource allocation and that demanded by *activities critical for safe driving*, rather than in terms of attentional failures of the driver. This systemic perspective helps to circumvent conceptual problems associated with the notion of driver error related to hindsight bias and the attribution of blame.

Based on this conceptual framework, a general taxonomy of driver inattention was developed. Driver inattention was broadly divided into two general categories: (1) insufficient attention and (2) misdirected attention, relating to the activation and selective aspects of attention respectively. For each of these categories, a set of sub-processes giving rising to them was defined. The report ends with a discussion of some key implications of the proposed conceptual framework and inattention taxonomy, and how the taxonomy can be used for its intended applications.

Contents

1 Introduction

The United States and European Union Bilateral Intelligent Transportation Systems Technical Task Force (US-EU Bilateral ITS TF) was established in 2009 with the goal to promote enhanced collaboration between the US and the EU in research and deployment of Intelligent Transportation Systems. The Task Force (TF) has identified six primary topic areas: Safety Applications, Sustainability Applications, Assessment Tools, Standardisation, Glossary and Driver Distraction & Human Machine Interaction (DD & HMI). For each of these areas, Working Groups (WGs) have been formed with representatives from the US and EU[1].

One of the key issues identified initially by the DD & HMI WG was that, while driver inattention, especially driver distraction, is high on the political and scientific agenda, commonly agreed definitions of key terms are still lacking. This makes it difficult to estimate the true magnitude of road-safety problems associated with driver inattention and makes comparison of results across studies problematic.

As a first step towards a harmonised conceptualization of key terms relating to driver inattention, a Focus Group on driver distraction was organised in Berlin, Germany, on April 28, 2010. The Focus Group was convened by the WG chairs and involved six invited experts on driver distraction and inattention, three from the EU and three from the US. The Focus Group had two main goals: (1) to agree on a common general definition of driver distraction and (2) to identify the ten most important research questions in the area. The results from the Focus Group are documented in Binder et al. (2011).

The Focus Group discussions converged on the following general definition of driver distraction, which is similar to that proposed by Lee, Young and Regan (2009):

"Driver distraction is the diversion of attention from activities critical for safe driving to a competing activity."

However, a number of key issues for further consideration were also identified by the Focus Group, including how to precisely define "activities critical for safe driving" and "competing activity." Moreover, it was emphasised that driver distraction only represents one of several types of phenomena related to driver inattention. Thus, it was agreed that, in addition to a definition of driver distraction, there is a strong need for a more general *taxonomy* of safety-related driver inattention. Such a taxonomy is needed to establish common definitions and categories of driver inattention that can be used in crash and near-crash analysis (including on-site investigation as well as naturalistic driving studies), the design and interpretation of experimental studies and the design and evaluation of vehicle systems.

In order to address this need, the DD & HMI WG decided to launch a project with the objective to define a common general taxonomy of driver inattention. This taxonomy should help to reconcile divergent empirical findings and support more effective cooperation and understanding between researchers, industry and authorities. It was also agreed that a taxonomy of driver inattention needs to be grounded in a common conceptual framework of driver *attention* and, thus, the development of such a framework was defined as a key sub-goal of the project. The project group consisted of the DD & HMI WG plus the six US and EU experts that participated in the Driver Distraction Focus Group.

[1] See http://ec.europa.eu/information_society/activities/esafety/intlcoop/eu_us/index_en.htm and http://www.comesafety.org/index.php?id=161

The contributing project members were:

US: Chris Monk (NHTSA; co-chair of the DD & HMI WG), Eric Traube (NHTSA), David Yang (FHWA), Dan McGehee (University of Iowa), John Lee (University of Wisconsin), Rich Hanowski (Virginia Tech), Bill Horrey (Liberty Mutual)

EU: Johan Engström (Volvo; co-chair of the DD & HMI WG), Alan Stevens (TRL), Mike Regan (then at INRETS, now at University of New South Wales, Australia), Trent Victor (Volvo), Marko Tuukkanen (Nokia).

In addition, a Scandinavian mirror group linked to the SAFER competence centre in Gothenburg, Sweden, contributed to the project. The members of this group were Katja Kircher and Christer Ahlström (VTI), Fridulv Sagberg (TÖI) and Jonas Bärgman (Chalmers University of Technology).

This document reports the main results from the project. The report is organised as follows. Section 2 discusses the general concept of taxonomy and its relation to similar terms such as coding scheme, classification and ontology. Section 3 then provides a review of existing definitions and taxonomies of driver inattention. Section 4 introduces a general conceptual framework for understanding attention in the context of driving, intended to serve as the theoretical basis for the inattention taxonomy presented in Section 5. Finally, Section 6 summarises the proposed ideas, discusses some outstanding issues, relates the proposed taxonomy to existing taxonomies and discusses how the taxonomy can be applied for its intended purposes.

2 What is meant by "taxonomy"?

Before attempting to develop a taxonomy of driver inattention, it has to be clear what the term "taxonomy" itself refers to. In the following section, a general distinction between a taxonomy and a coding scheme is proposed. Section 2.2 then discusses how taxonomies relate to similar concepts such as classifications and ontologies.

2.1 Taxonomy vs. coding scheme

In the initial discussions about the objectives of the present project, it became clear that there was a need to distinguish between the more generic conceptualization and categorization of factors relating to inattention and the specific application of such a scheme, for example, to the development of coding schemes for on-site crash analysis or video-based analysis of naturalistic driving data. The development of a coding scheme for analysis of driver inattention depends strongly on the nature of the available data (in particular the information available on inattention-related factors) and the purpose of the analysis. For example, while naturalistic video provides detailed information on the nature and timing of observable behaviour (e.g., off road glances) just prior to the crash, post-crash interviews may provide information on drivers' intentions and/or mental state not directly observable from video. Moreover, data obtained from controlled laboratory experiments (e.g., driving simulator studies) may offer detailed information on the driver's physiological state, including brain imaging data not (yet) available in naturalistic driving data. Thus, coding schemes developed to analyse these different types of data need to be quite different. However, it is still desirable that they are based on the same general conceptualization of driver attention and inattention.

Thus, it was agreed to make a general distinction between (1) a general *taxonomy* and (2) more specific *coding schemes*. The former should define key theoretical concepts (e.g., "attention" and "distraction") and their mutual relationships. This generic taxonomy should also be grounded in a general conceptual framework for understanding attention in driving. By contrast, coding schemes should provide concrete operational definitions of phenomena observable in the available data (e.g., “phone use”, “dialling”, “conversation”), which, however, should be possible to relate back to the more general categories in the taxonomy. In other words, a coding scheme could be viewed as a particular instantiation of the general taxonomy, developed for a specific purpose and tailored to the available data. This distinction is further illustrated in Figure 1.

The present document focuses on the development of a taxonomy rather than a coding scheme. However, taxonomies and coding schemes are expected to evolve in an iterative fashion. Thus, when applying a coding scheme derived from a general taxonomy to the analysis of a specific dataset, issues may arise that makes it necessary to revise the coding scheme as well as the general taxonomy.

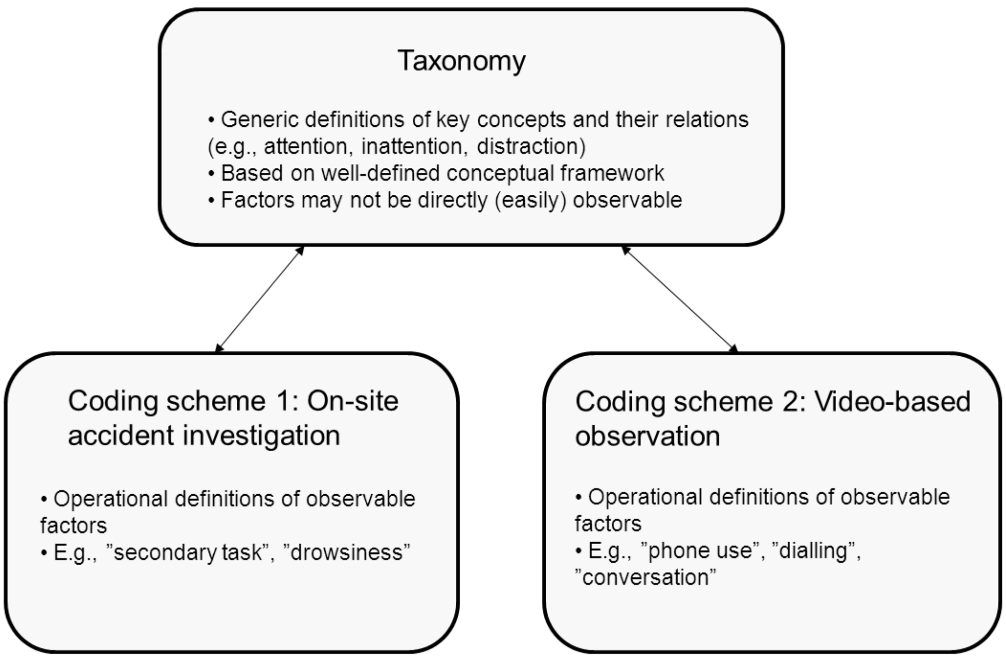


Figure 1 Illustration of the proposed distinction between taxonomy and coding schemes

2.2 Taxonomy vs. classification and ontology

Taxonomies can be distinguished from the related concepts of classifications and ontologies. *Classifications* often use arbitrary, surface features as a basis for defining class membership, placing elements into boxes with labels, while *taxonomies* define class membership according to features that reflect the essence of the element being classified. These relationships are often of the form of hierarchical category memberships (e.g., whole-part, means-ends, or is-a-member). An *ontology* underlies a taxonomy by defining the categories of the taxonomy and the relationships between them. Thus, a classification places elements into boxes while a taxonomy endeavours to classify elements according to their essential nature, and an ontology defines the concepts and relationships that implicitly or explicitly underlie the essential nature of the elements being classified.

An important property of a taxonomy is whether its categories are mutually exclusive or whether multiple categories are allowed to characterize the phenomenon of interest. For example, should "driver distraction" be categorized into a single category (e.g., visual distraction) given a set of alternatives (e.g., "visual" and "cognitive" distraction) or can a distracted driver be characterized by multiple categories (e.g., be both "visually" and "cognitively" distracted)? Of course, a taxonomy may include mutually exclusive categories for some aspects (e.g., vehicle type) while allowing for multiple categories for others (e.g., vehicle colour). The distinction between categories that are mutually exclusive and those that are not corresponds to the distinctions of *monothetic* and *polythetic* categories, which imply different coding schemes, statistical procedures, and theoretical interpretations (Bailey, 1994).

Taxonomies organize information by classifying elements into categories that reflect meaningful similarities. Creating a taxonomy that can fulfil this seemingly simple role can be surprisingly difficult. One reason why useful taxonomies can be so challenging to create is that a taxonomy represents a model of what is being classified and also reflects the purpose of classification. Thus, to be a useful tool for communication and application to diverse issues, a taxonomy should make explicit the purpose and model behind it. In the context of inattention and driving safety, different taxonomies might emerge for different purposes, such as supporting design, guiding development of traffic law, coding crashes to attribute blame, etc. Likewise, implicit models of driver behaviour, such as the information processing model, might lend themselves to taxonomies that differ from those based on models with greater emphasis on contextual or societal influences on driver behaviour. Ultimately, taxonomies reflect, enable, as well as limit, abstraction from data. As such, a taxonomy of inattention represents a model or hypothesis of inattention and the associated consequences for driving safety. To ensure a taxonomy of driver inattention is useful, it is critical to convey the underlying conceptual framework.

In the case of driver inattention, technology is rapidly changing the nature of driving and the range of potential inattention sources. On the one hand, a taxonomy of inattention and its underlying conceptual framework should be generic enough to remain relatively stable in the face of technological advancements. However, at the same time, it must be open to future revision. Just as biologists must contend with species evolving over time, a taxonomy of inattention must contend with the changing nature of driving and array of potential inattention sources, as well as the need to support an evolving understanding of driver behaviour. The ultimate utility of a taxonomy of driver inattention rests on whether it can make coherent discriminations that designers, drivers, and regulators can act upon to enhance driving safety. A basic requirement is that the taxonomy must support the development of coding schemes that can be applied in a consistent manner.

Thus, to summarize, a taxonomy is an attempt to create a meaningful categorization, based on an underlying model of what is being categorized. The nature of the taxonomy depends critically on this underlying model, as well as the general purpose of the taxonomy. Moreover, while a taxonomy of driver inattention should be relatively stable over time, it should be flexible enough to be able to evolve with advancements in vehicle and road technology, measurement technology and the scientific understanding of driver behaviour and attention.

3 Existing definitions and taxonomies of driver inattention

This Section, which is largely based on Regan, Hallet and Gordon (2011), briefly reviews existing definitions and taxonomies of driver inattention. As pointed out by Regan et al. (2011), driver inattention, like driver distraction, is generally inconsistently defined in the literature. Some general definitions of attention and inattention can be found in English dictionaries, for example:

- *Attention*: "concentration of the mind upon an object; maximal integration of the higher mental processes" (Macquarie Dictionary, 1988, p. 147).
- *Inattention*: "failure to pay attention or take notice" (Shorter Oxford English Dictionary on Historical Principles, 2002, p. 1340).

The first definition (of *attention*) implies that people have control over their attention and that attention is associated with concentration and higher mental processes. The second definition (of *inattention*) implies that, to be inattentive, is to be somehow negligent or knowingly inadequate to the task (Regan et al., 2011).

Some of the relatively few attempts to define *driver* inattention in the literature include:

- "diminished attention to activities critical for safe driving in the absence of a competing activity" (Lee, Young & Regan, 2008, p. 32).
- "improper selection of information, either a lack of selection or the selection of irrelevant information" (Victor, Engström and Harbluk, 2008, p.137).
- "whenever a driver is delayed in the recognition of information needed to safely accomplish the driving task, because of having chosen to direct his attention elsewhere for some non-compelling reason" (Treat, 1980, p. 21).
- "any point in time that a driver engages in a secondary task, exhibits symptoms of moderate to severe drowsiness, or looks away from the forward roadway" (Klauer, et al., 2006, p. 21)
- "when the driver's mind has wandered from the driving task for some non-compelling reason such as when the driver is focusing on internal thoughts (i.e., daydreaming, problem solving, worrying about family problems, etc.) and not focusing attention on the driving task" (Craft & Preslopsky, 2009, p. 3).
- "low vigilance due to loss of focus" (Talbot and Fagerlind, 2009, p. 4).

Most existing *taxonomies* related to driver inattention derive from in-depth crash studies, where researchers have attempted to differentiate taxonomically between different "failures" or "perturbations" of attention which have been identified as factors contributing to crashes. Here, inattention is often viewed as one of several attentional "failures" attributed to the driver. For example, Treat (1980) proposed the following categories:

1) *Inattention:* "whenever a driver is delayed in the recognition of information needed to safely accomplish the driving task, because of having chosen to direct his attention elsewhere for some non-compelling reason" (p. 21).
2) *Internal distraction:* "Whenever a driver is delayed in the recognition of information needed to safely accomplish the driving task, because some event, activity, object, or person within his vehicle, compelled or tended to induce the driver's shifting of attention away from the driving task" (p. 21).
3) *External distraction:* "Whenever a driver is delayed in his recognition of information needed to safely accomplish the driving task, because some event, activity, object or person outside his vehicle compelled, or tended to induce, the driver's shifting of attention away from the driving task" (p. 22).
4) *Inadequate or improper lookout*: "Whenever a driver is delayed in his recognition of information needed to safely accomplish the driving task, because he encountered a situation requiring a distinct visual surveillance activity (for safe completion of the driving task), but either did not look or did look, but did so inadequately" (p. 22).

More recently, Hoel, Jaffard and van Elslande (2010) proposed the following three general categories of attentional failures:

- *Inattention:* Interference between a driving activity and "personal concerns" (i.e., internalised thoughts).
- *Attentional competition:* Interference between tasks that are relevant for driving, such as controlling the vehicle and navigating.
- *Distraction:* Interference between a driving activity and a non-driving-related activity.

Yet another taxonomy was suggested by Wallén Warner et al. (2008) as part of the revision of the Driver Reliability and Error Analysis Method (DREAM), developed for crash causation analysis based on on-site in-depth investigation (in particular interviews with victims and witnesses). They defined driver inattention as "any condition, state or event that causes the driver to pay less attention than required for the driving task" (Wallén Warner, et al., 2008, p.12). According to these authors, driver inattention can be brought about by any of several "specific genotypes", defined mainly in terms of the location of distractors and their relation to driving:

- "driving-related distractors inside vehicle";
- "driving-related distractors outside vehicle";
- "non-driving-related distractors inside vehicle";
- "non-driving-related distractors outside vehicle"; and
- "thoughts/daydreaming".

Pettit, Burnett and Stevens (2005), in their discussion on definitions of driver distraction, suggest that "…the result of distraction is inattentive driving. However inattention is not always caused by distraction" (p. 4). This implies that distraction can be viewed as one of several factors, or processes, that give rise to inattention. Based on this general view, Regan et al. (2011) defined inattention as "*insufficient, or no attention, to activities critical for safe driving*" and suggested the following general sub-categories representing processes, or mechanisms, that give rise to inattention.

1) *Driver Restricted Attention (DRA)*: "Insufficient or no attention to activities critical for safe driving brought about by something that physically prevents (due to biological factors) the driver from detecting (and hence from attending to) information critical for safe driving." (p. 1775)
2) *Driver Misprioritised Attention (DMPA)*: "Insufficient or no attention to activities critical for safe driving brought about by the driver focusing attention on one aspect of driving to the exclusion of another, which is more critical for safe driving." (p. 1775)
3) *Driver Neglected Attention (DNA)*: "Insufficient or no attention to activities critical for safe driving brought about by the driver neglecting to attend to activities critical for safe driving" (p. 1775).
4) *Driver Cursory Attention (DCA)*: "Insufficient or no attention to activities critical for safe driving brought about by the driver giving cursory or hurried attention to activities critical for safe driving" (p. 1776).
5) *Driver Diverted Attention (DDA)*: "The diversion of attention away from activities critical for safe driving toward a competing activity, which may result in insufficient or no attention to activities critical for safe driving". (p. 1776). The authors view DDA as equivalent to driver distraction.

As is clear from this brief review, there is little consensus in the literature on the definition of factors related to driver inattention and how to sub-divide the phenomenon into more specific categories. The term "inattention" itself variably refers to low vigilance, internalized thoughts, the diversion of attention for a non-compelling reason, or, alternatively, is used as a general umbrella term that subsumes more specific categories such as distraction, misprioritised attention, daydreaming, etc. Thus, inattention is sometimes viewed as a specific phenomenon that exists taxonomically at the same level as other attention "failures" (e.g., Treat, 1980; Hoel et al., 2010) and sometimes as a more general category that exists at a taxonomically higher level (e.g., Petitt et al., 2005; Wallén Warner et al., 2008; Regan et al., 2011). A more specific variant of the latter view is the idea of Petitt et al. (2005), also adopted by Regan et al. (2011), to view inattention as the general result of more specific processes giving rise to it.

Moreover, some definitions and taxonomies of inattention are concerned with the selection of *information* (Treat, 1980; Wallén Warner et al., 2008; Victor et al., 2008) while others view inattention more broadly in terms of the (inappropriate) selection of *activities* (Hoel et al., 2010; Regan et al., 2011). Aspects related to fatigue and/or drowsiness are generally not considered in the context of attention failures or inattention, but are rather treated as a separate category. Exceptions include Klauer et al., (2006) and Regan et al. (2011).

Most of the taxonomies reviewed above make a distinction between, on the one hand, driver distraction and, on the other, cases where attention is allocated to other driving and/or safety-related information/activities. Hoel et al. (2010) distinguish between "Distraction" and "Attentional Competition", where the former refers to interference between driving and a non-driving activity and the latter refers to interference between driving related tasks. Regan et al. (2011) make a similar distinction between Driver Diverted Attention (Driver Distraction) and Driver Misprioritised Attention[2]. A somewhat different approach is used by Wallén Warner et al. (2008) who distinguish between "driving- and non-driving-related distractors". Finally, Treat et al. (1980) distinguish between "distraction" (internal or external) and "inadequate or improper lookout". The common idea behind these distinctions is that the term "driver distraction" should be reserved for cases where attention is diverted away from driving/safety-related information/activities, while another category is needed for cases where attention is diverted away from certain driving/safety-related information/activities towards other driving/safety-related information/activities. However, none of the existing taxonomies offer a clear definition of driving/safety-related information/activities.

Existing definitions and taxonomies of driver inattention have generally been developed without reference to a clear definition or conceptualization of driver *attention*. Indeed, most of the taxonomies above seem to be derived from the "bottom-up", "common sense", interpretation of crash data at hand, rather than from a scientifically-based conceptual framework of driver attention. Thus, existing taxonomies of inattention exhibit a strong influence from the available data and, at least some of them (such as Treat, 1980, and Wallén Warner et al., 2008) may, according to the distinctions proposed in Section 2, be viewed as more akin to classifications than taxonomies. The lack of a common underlying conceptual framework for understanding driver attention is likely contributing to the current diversity in definitions and taxonomies of driver inattention.

Another general issue with existing taxonomies of inattention, also raised in the Distraction Focus Group and discussed in Binder et al. (2011), is that the common notion of "failure", or human error in general, relies on *hindsight bias* (Rasmussen, 1990). Often, it can only be determined after the fact whether a crash or near-crash may be attributed to driver error. This is particularly the case when several safety-critical activities demand the drivers' attention. In such cases, it may be difficult to objectively determine if, using Treat's (1980) terminology as an example, the driver's' "lookout" was "inappropriate". Thus, the attribution of attentional failures to the driver always involves an element of normative judgement.

To summarize, existing definitions and taxonomies of driver inattention are diverse and differ in several key aspects, such as the taxonomic level of inattention, whether inattention concerns problems in the selection of information or the selection of activities and whether fatigue-related factors are considered as

[2] An important difference between Hoel et al. (2010) and Regan et al., 2011) is Hoel et al. define inattention in terms of interference while Regan et al. does not require interference as a necessary condition for inattention.

forms of inattention. Most taxonomies attempt to distinguish driver distraction from other forms of attentional diversion but the terminology used to denote these other forms of inattention differs. None of the existing taxonomies offers a clear definition or conceptualization of driver attention and, finally, issues related to hindsight bias are generally left unaddressed.

4 A general conceptual framework for understanding driver attention

As discussed in Section 2, a taxonomy always represents an underlying model of what is being classified. However, as reviewed in the previous Section, existing taxonomies of inattention have generally not made explicit their underlying models. In particular, a clear conceptualization of driver *attention* is generally lacking. Thus, it was agreed that a critical first step towards the presently envisioned inattention taxonomy should be a clear, commonly understood, conceptualization of driver attention. As outlined in Section 2, such a conceptual framework can also be viewed as the basic *ontology* underlying the taxonomy. The present Section summarises a set of key ideas that were converged upon within the present project. This is not based on any specific existing theory of driving or attention but rather seeks to incorporate ideas from several theories into a generic conceptual framework that might be accepted by different theoretical camps.

In the following section, a set of key principles of driver attention is outlined. Based on these principles, summarised in Section 4.2, Section 4.3 discusses how different types of *problems* in drivers' attention deployment and selection may be conceptualised based on these principles. Section 5 then outlines a concrete proposal for how these problems may be categorized in terms of a general taxonomy of driver inattention.

4.1 Key principles

The main ideas underlying the proposed conceptual framework of driver attention can be summarised in terms of a set of key principles. These principles represent the key assumptions, or tenets, on the nature of driver attention, on which the taxonomy outlined in Section 5 is based. Each principle is derived from existing scientific models and/or empirical results referred to in the text.

1. Attention as adaptive behaviour
Drivers generally regulate their behaviour in order to strike a balance between, on the one hand, the accomplishment of driving goals and other motives, and, on the other, the subjective experience of risk (Näätänen and Summala, 1976), or more generally, feelings of discomfort (Summala, 2007). These motivational factors that drive adaptive behaviour may also be conceptualised as *needs* (Boer and Hoedemaeker, 1998) which, on the one hand, include *benefits* that the driver wants to achieve and, on the other, *costs* that constrain goal achievement.

Drivers normally act as satisficers rather than optimizers. This means that they chose actions that are *good enough* in the sense that benefits outweighs costs (Boer and Hoedemaeker, 1998) while this may not yield optimal performance. A useful way to conceptualise satisficing in driving is the *comfort zone* (Summala, 2007; Ljung Aust and Engström, 2012). The comfort zone can be viewed as a range of states that a particular driver views as satisfactory, and is subjectively experienced in terms of feelings. Factors determining the driver's experience of being, or not-being, within the comfort zone include the sense of driving progress, compliance to social and legal norms and the *safety margins* to other road users and infrastructure elements (Summala, 2007).

Probably the first conceptualization of safety margins in driving was offered by Gibson and Crooks (1938) who proposed that drivers aim to control their vehicle within a *field of safe travel*, which “consists, at any given moment, of the field of possible paths which the car may take unimpeded” (p. 454). Thus the field of safe travel specifies an objectively defined *safety zone*, the boundary of which defines when a crash becomes unavoidable. However, since the driving task is only predictable within limits, the driver needs to adopt an additional margin to remain within his/her comfort zone. The *safety margin* adopted by the driver can be defined as the spatio-temporal distance to the safety zone boundary. The *minimum safety margin* accepted by the driver is thus a key factor determining the comfort zone boundary. The safety margin actually adopted by the driver in a particular situation is thus determined by the driver’s subjective perception of what is safe and comfortable and may thus not reflect the actual (objectively defined) safety zone.

The control of safety margins may be described at different levels of the driving task (e.g., Michon, 1985; Lee, Regan and Young, 2009). The lowest, *operational*, level involves activities related to the momentary vehicle control, in particular maintaining safe margins to the road edges and other road users. The middle, *tactical*, level involves the scheduling and target-setting of operational control activities, such as adopting a minimum desired headway and lateral time/distance margins, adjusting speed to conditions, deciding whether to yield at an intersection, controlling the time sharing between driving and a secondary task etc. The highest, *strategic*, level deals with the setting of driving goals and priorities, for example decisions on whether to engage in a secondary task in a demanding situation or whether to stop and take a coffee break when feeling drowsy.

The adaptive regulation of safety margins may thus involve reducing speed and increasing headway when driving demand and/or uncertainty increases. However, attention allocation can also be viewed as an integral part of this continuous adaptation process. For example, at the tactical level, the attentional effort devoted to driving may be increased in anticipation of demanding or uncertain situations, for example when entering into a complex intersection. In such situations, attention and gaze will also normally be biased towards the locations and objects judged as most relevant for maintaining acceptable safety margins. If the driver is under time pressure, increased attentional effort may be deployed to compensate for intentionally reduced safety margins (e.g., higher speed and shorter headways; van der Hulst, Rothengatter and Meijman, 1998). Another example of attention-related compensatory behaviour is when a bored and/or sleepy driver intentionally engages in non-driving activities in order to maintain arousal at an acceptable level (Oron-Gilad, Ronen and Shinar, 2008; Toole et al., 2013).

Thus, it is useful to view attention allocation in natural driving situations as an integral part of adaptive driver behaviour (Engström, Markkula and Victor, 2012). Attention deployment and selection (e.g., concentrating on detecting vehicles potentially appearing behind a blind corner) and the adaptation of physical safety margins (e.g., slowing down to increase available time in case a vehicle appears) can be viewed as two sides of the same coin: the adaptive regulation of behaviour to strike a satisfactory balance between benefits and costs.

2. Driver attention as the allocation of resources to activities

While attention is often traditionally conceived of in terms of the selection of perceptual *information*, in natural tasks such as driving it may be useful to view driver attention more broadly in terms of the *allocation of resources to a set of activities*.

Resources are traditionally associated with limited capacity and mental effort (e.g., Kahneman, 1973). However, the resource concept is here used in a broader sense to denote any sensory, actuator, perceptual, motor or cognitive mechanism that is utilised in performing activities. Hence, by contrast to the traditional meaning, resources may also include mechanisms underlying automatized performance of routine activities (see Principle 8). Figure 2 provides an illustration of the resource concept as conceived here, based on a generic resource model that distinguishes between sensory, actuator, perceptual, motor and cognitive resources[3]. Sensory resources include sense organs such as the eyes or the ears while actuator resources refer to actuators such as the hands or the feet. Perceptual resources refer to neural mechanisms underlying detection and interpretation of information and motor resources to neural mechanisms that control overt action. Finally, cognitive resources refer to neural mechanisms underlying cognitive control, which relates to working memory and the effortful deployment of resources to deal with non-routine tasks (the concept of cognitive control further explained in Principle 8).

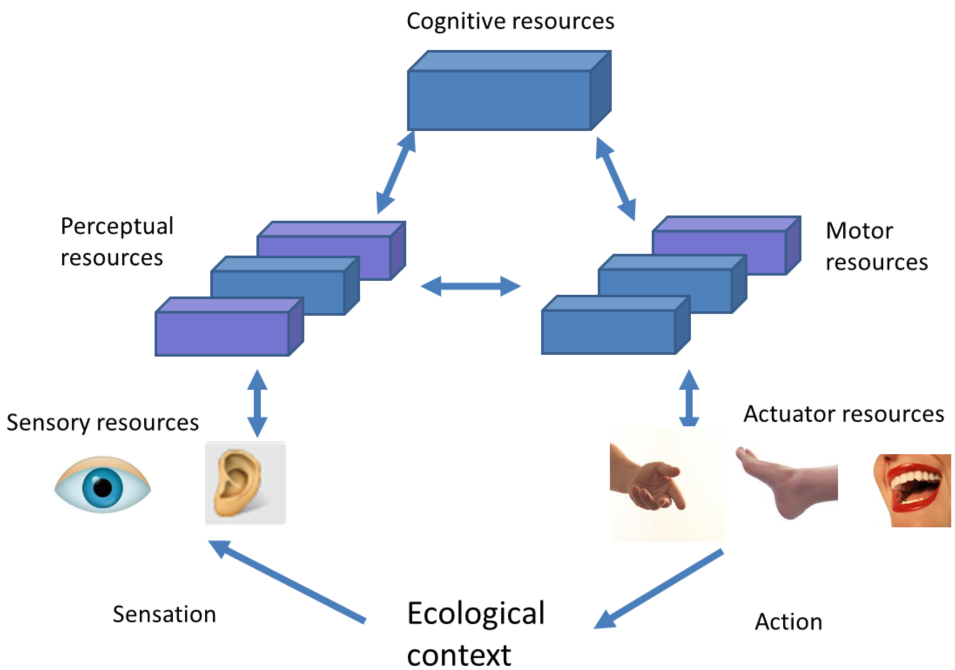


Figure 2 Illustration of the present conceptualization of resources

Attending to an activity thus means allocating a selected set of resources to that activity. Activities may involve the selection of information as well as the preparation and execution of actions in a dynamic perception-action cycle (see further Principle 4). *Overt* activities extend into the environment, for example in terms of manipulation of objects and/or active perception, for example by eye-, head-, or whole-body movements. However, activities may also be *covert*, in the case of purely mental processes without any overt motor components (e.g., internalised thoughts and mind wandering).

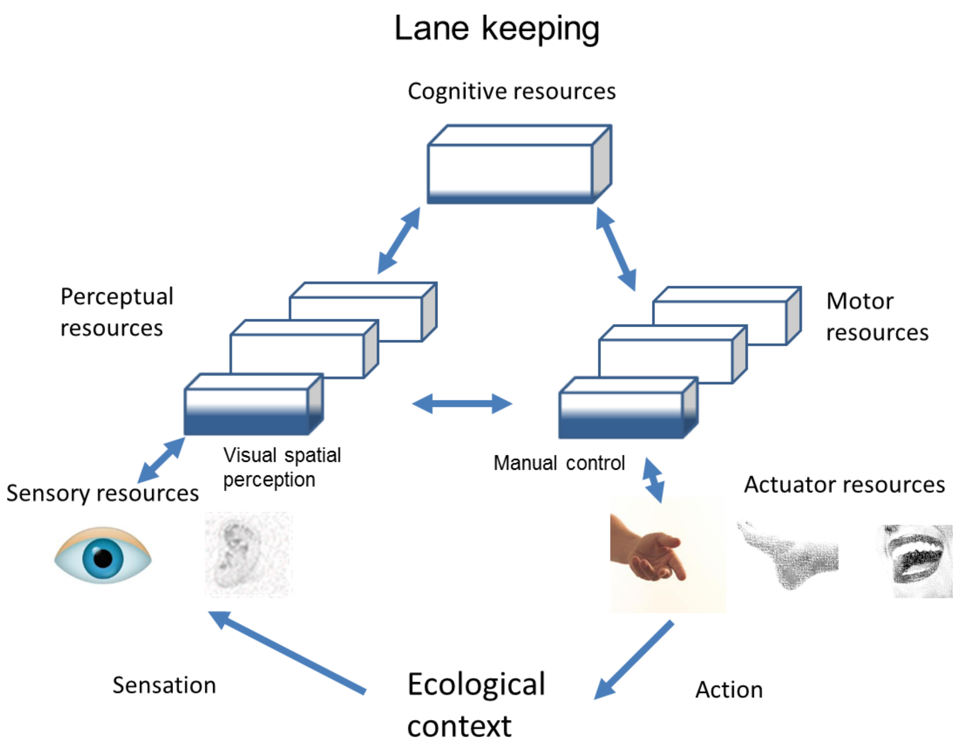
Goal-directed activities (such as, for example, making a phone call or turning right at an intersection) may be viewed as *tasks*, which may be hierarchically sub-divided into *sub-tasks*. Thus, for example, making a phone call may subsume a number of sub-tasks such as dialling, conversation and hanging up. The analysis of tasks in terms of their component sub-tasks is commonly known as *hierarchical task analysis*

[3] The general conceptualisation of attention proposed here does, however, not depend on the exact resource model used.

(see, e.g., Stanton, 2006). To the extent that a covert activity is goal-directed, it could also be regarded as a task or sub-task (for example, mentally rehearsing a phone number before entering it on the keypad), even if it does not involve any motor activity. Mind wandering and daydreaming are examples of non-goal-directed covert activities (which should thus not be characterised as tasks).

Tasks and sub-tasks may be generally characterised according to (1) their *goals*, (2) the *operations* involved and (3) the *demands* they impose on the driver. A *goal* refers to the intended result of an activity. *Operations* refer to the physical or mental actions needed to accomplish the goal. A particular goal is often possible to attain by different sets of operations. For example, dialling a phone number may often be accomplished by manual entry on a keypad as well as by means of voice control. Finally, *demands* refer to the resources required to perform the operations and may, based on the resource model above, be broadly divided into sensory, actuator, perceptual, motor and cognitive demands.

As further elaborated in Principle 5, resources can be allocated to activities in different amounts. The momentary attentional state can be conceptualized as the current distribution of resources. This is further illustrated Figure 3. The top part of the Figure illustrates a hypothetical resource allocation for keeping the vehicle in the lane in normal (non-demanding) conditions, which is here assumed to demand the eyes, the hands, visual spatial perception and manual control, but little cognitive resources. By contrast, hands-free phone conversation requires the ear(s), the speech system, auditory perception and speech control, and a relatively large amount of cognitive resources due to demands on working memory. Different activities may thus demand different resources, and resources may be allocated to different degrees (except for the sensory and actuator resources which can be thought of as allocated in a more all-or-none fashion – e.g., either the hand is used or not). The resource demands associated with two tasks largely determine the degree of interference between them when performed concurrently. Task interference is further addressed in Principle 10 and in section 4.3.5.



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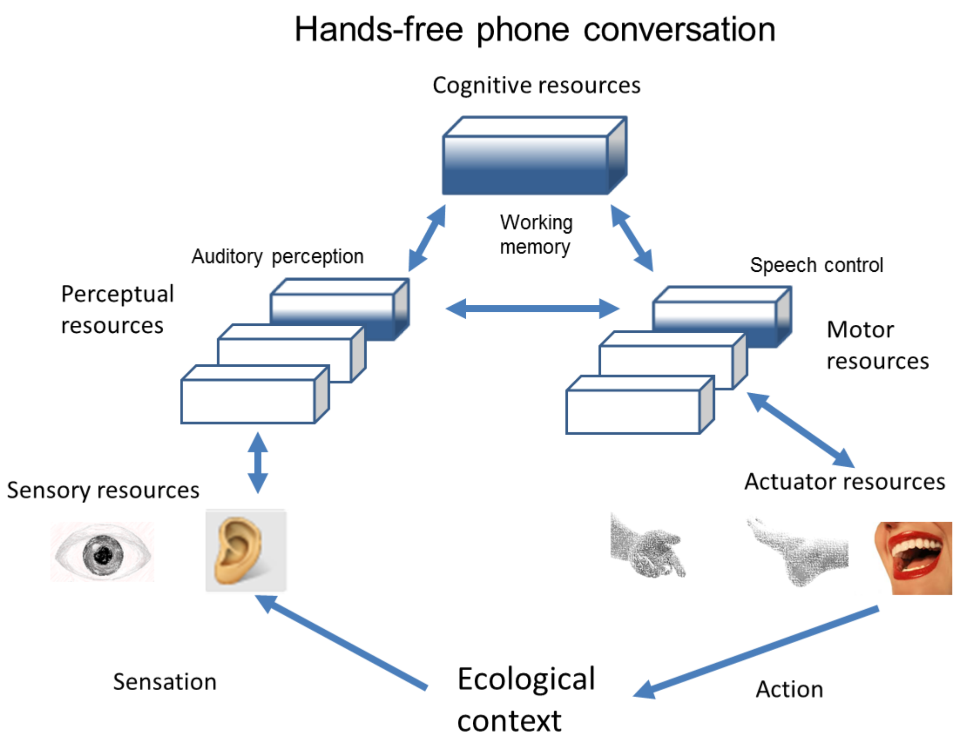

b

Figure 3 Illustration of resource allocation to two different activities. a: Lane keeping in normal conditions (e.g., daylight, dry road surface, sparse traffic, wide lane). b: hands-free phone conversation

3. Activities as more or less relevant to driving and more or less critical for safe driving

While it is very difficult to draw a distinct line between activities that relate to driving and those that do not, it may be useful to think about activities along a continuum from driving-related to entirely non-driving related activities. At the driving-related end of the scale, one would thus find activities like keeping the vehicle in the lane, deciding when to initiate overtaking and navigating to the intended destination while entirely non-driving activities at the other extreme would include texting or reading roadside commercial signs. Activities in the "middle" of the scale would include adjusting the climate controls and obtaining directions via the phone. At the driving-related end of the scale, one may distinguish *activities critical for safe driving* from other driving-related activities that are not critical for safe driving. For present purposes we define activities critical for safe driving as *those activities required for the control of safety margins*.

This definition of activities critical for safe driving thus includes activities at all levels that are required to maintain acceptable safety margins, such as maintaining headway, keeping in the lane, visually scanning an intersection for oncoming vehicles, deciding whether to yield and interpreting safety-related traffic signs, but excludes those driving-related activities that are not directly related to safety margin control, such as navigation, route finding and eco-driving.

4. Driver attention as situated in an ecological context

As stated in Principle 2, driver attention is here conceptualised as the allocation of resources to a set of activities. The allocation process can be described in terms of an evolving perception-action cycle where engagement in one activity leads to action outcomes that change the driver/vehicle's relation to the environment and produces updated sensory input as well as an updated attentional state (i.e., resource distribution; cf., Neisser, 1976; Brouwer, 2002; Hollnagel and Woods, 2005). Thus, the driver's attentional state evolves dynamically with the current situation driven both exogenously (bottom up, by updated sensory input from the environment) and endogenously (top-down, by goals and expectations). A key aspect determining the allocation process is the predictability of the situation and the driver's subjectively experienced degree of certainty on how the situation will develop. If the situation is predictable and the driver is relatively certain on how it will play out, attention may be focused entirely on the limited set of aspects expected to be relevant in that situation. However, if the situation is unpredictable, and the driver feels uncertain on how it will develop, attention needs to be more distributed to account for a wider range of possibilities.

A key implication of this *systemic* view is that driver attention (i.e., resource allocation) is determined as much by the environment as by the driver. This point is illustrated by Herbert Simon's classical example of an ant walking on the beach, where the ant's path is determined endogenously by the ant's internal state as well as exogenously by the layout of the beach (Simon, 1969). Thus, in understanding driver attention, it is of key importance to account not only for the driver, but also the ecological context in which the driver operates (or functions). Some examples of key environmental factors that determine the evolution of the driver's attentional state in a given situation are road surface conditions, road infrastructure layout, visibility and the behaviour of other road users.

An important implication of this perspective, further elaborated in Section 4.3, is that *inattention* can be understood in terms of a *mismatch* between the current allocation of resources and that demanded by activities critical for safe driving. This implies a view of inattention as a breakdown of the system as a whole (the driver situated in the ecological context) rather than a failure attributed to the driver. This helps in working around problems associated with hindsight bias discussed in the previous Section. This idea, which was originally formulated by Lee, Young and Regan (2009), is further elaborated in Section 4.3.1.

5. Activation and selectivity as the key dimensions of attention
Attention, when viewed as the allocation of resources to activities (Principle 2), can be characterised along the two dimensions of *activation* and *selectivity*.

Activation refers to the degree to which resources are allocated to activities (i.e., the degree to which the boxes are filled in Figure 3). This is partly determined by the demands of the activities. For example, lane keeping in adverse visibility conditions requires stronger activation of perceptual/motor resources than lane keeping in normal conditions. However, activation may also be increased to optimise performance (e.g., in racing) or to compensate for intentionally reduced safety margins (e.g., when in a hurry; see van der Hulst et al., 1998). Moreover, in uncertain situations, the overall activation level may be increased to enhance the ability to react fast to unexpected events. In order to raise the attentional activation level over the normal (baseline) level, *mental effort* is generally needed. However, since this is energetically costly, the mobilisation of mental effort is generally traded against performance accuracy so that no more effort is spent than is needed to obtain satisfactory performance (i.e., satisficing as discussed under Principle 1). This issue is further addressed in Principle 6 below.

Selectivity refers to how resources are distributed between activities. If there are multiple activities with competing resource demands, the driver has to prioritise certain activities above other activities. *Selecting* an activity at a particular moment in time can thus be understood as allocating resources to that activity.

Thus, the driver may select to perform an activity (e.g., lane keeping), but allocate insufficient resources to it (e.g., when bored or drowsy). This thus represents a problem of attentional activation. Alternatively, the driver may allocate sufficient attention to an activity (e.g. texting), but that activity may recruit resources (e.g., the eyes and visual perception) currently also demanded by activities critical for safe driving (e.g, responding to a slowing lead vehicle). This represents a problem in attentional selectivity. Factors that drive activation and selectivity are addressed in Principle 6 and 7 respectively.

6. Factors that drive activation
The degree to which resources are allocated to one or more tasks is partly determined by the endogenous regulation of brain and body activation and partly by exogenous factors such as the nature of the task and the time spent on the task. A term commonly used to refer to this general level of activation is *arousal*; which, however, like attention, lacks a clear-cut definition in the literature. *Fatigue* generally refers to the overall negative *effect* of endogenous (brain regulating) and exogenous (task-related) factors on arousal, performance and safety although, again, a commonly agreed definition is lacking, Williamson et al. (2009) proposed to define fatigue as “a biological drive for recuperative rest” (p. 499).

The endogenous regulation of arousal is governed by multiple neurobiological processes which are only partly scientifically understood. However, for present purposes, a general distinction could be made between processes related to (1) the regulation of *alertness* and (2) to the regulation of *attentional effort*.

The term *alertness* is here used to refer specifically to the regulation of sleep (e.g., Gunzelmann et al., 2009; although a consistent terminology is lacking here as well). Contemporary models of sleep regulation suggest that alertness is governed by two main processes: (1) the circadian cycle and (2) sleep homeostasis (Borbely and Achermann, 1999). The former oscillates in an approximately 24h cycle producing variations of alertness within a single day, while the sleep homeostasis system produces reduced alertness with increased awake time, which recovers with sleep. Based on this model, the endogenously controlled level of alertness depends mainly on the time of day and recent sleep history. Alertness can also be directly or indirectly affected by various drugs, for example alcohol.

The second general endogenous factor that drives activation is the regulation of *attentional effort*. Attentional effort has traditionally been of central importance in models of attention, in particular the classical single resource model by Kahneman (1973). Attentional effort is also closely related to the concept of mental workload. In natural driving, drivers self-regulate the degree of resources invested in order to strike a balance between, on the one hand, the motivation to accomplish the task and, on the other, the energetic costs associated with attentional effort (see Hockey, 1997, for a general model and van der Hulst et al., 1998, for empirical results demonstrating self-regulation of attention in the driving domain). The deployment of attentional effort is thus intimately linked to motivation and the brain's value system. At the same time, it is at the heart of the distinction between automatic and controlled performance, and the notion of cognitive control, further discussed under Principle 8. Furthermore, it has been suggested that a key effect of fatigue is that it affects the ability to regulate attentional effort due to a depletion of cognitive resources in the fatigued state (Hockey et al., 1998). The physiological correlates of attentional effort can be measured with relatively high accuracy in terms of, for example, pupil dilation, heart rate and skin conductance (Kahneman, 1973; Mehler et al., 2009).

Exogenous factors influencing the activation level include the nature of the task performed (e.g., its degree of monotony or complexity) and the time-on-task (Williamson et al., 2009). Numerous studies have demonstrated that the ability to sustain attention (i.e., maintain vigilance) degrades with increased time on task (e.g., Warm, 1984). In practice, these endogenous and exogenous factors interact in non-trivial ways, and it is difficult to isolate the effect of a single factor experimentally, especially in real-world driving settings (Williamson et al., 2009).

According to the classical Yerkes-Dodson law (Yerkes and Dodson, 1908), performance is optimal at medium levels of general arousal. At low arousal levels, the overall level of cognitive functioning is insufficient, leading to performance decrements on most tasks. However, as suggested by, for example, Easterbrook (1959) and Kahneman (1973), high levels of arousal generally lead to increased selectivity, a phenomenon sometimes referred to as attentional narrowing (e.g., Dirkin and Hancock, 1985). While this increased selectivity may enhance performance on simpler tasks, performance on complex tasks, requiring a broader selection of information and actions, may thus become impaired when arousal is too high. Thus, according to this model, a highly aroused driver entering into a complex intersection may fail to pick up a sufficiently broad range of information to successfully manage the intersection, hence the optimum performance at medium arousal levels. However, to the knowledge of the present authors, attentional narrowing due to high arousal has not been demonstrated experimentally in the driving domain (but see Hockey, 1970, for a laboratory demonstration of the phenomenon). This interpretation of the Yerkes-Dodson law implies a non-trivial dependency between the activation and selectivity aspects of attention.

7. Factors that drive selection

Like activation level (Principle 6), the *selection* of activities is also driven exogenously and endogenously (Posner, 1980). Exogenous selection is partly determined by basic physical stimulus properties such as intensity, size and background contrast (Hills, 1980), as well as stimulus novelty (Yantis, 1993). The *orienting reaction* (e.g., Lynn 1966), represents a biologically hardwired mechanism that orients attention to unexpected, but potentially behaviourally relevant, stimuli. In particular, visual transients, such as abrupt onsets, translational movement and looming (the optical expansion of closing objects) are efficient in capturing attention exogenously (Franconeri and Simons 2003). If such visual transients are masked (e.g., during a blink), or occur outside the field of view (e.g., during an off-road glance), they are prone to pass unnoticed, as demonstrated by recent studies on *change blindness* (e.g., O'Regan et al., 2000).

By contrast, endogenous selection is driven by goals and expectations (e.g., Desimone and Duncan, 1995; Trick et al., 2004). Thus, in driving, activities are selected and resources allocated based on what the driver wants to accomplish and his/her expectations on how the current driving situation is going to develop in the near future. Thus, when entering into a driving situation, drivers select the locations/objects/features expected to be most relevant in that situation (Wickens and Horrey, 2006; Summala and Räsänen, 2000; Trick et al., 2004; Engström et al., 2012) and adjust safety margins to remain in their comfort zones. In terms of the present framework, expectancy can thus be generally understood in terms of the endogenous (or *proactive*) allocation of resources. This endogenous allocation is also determined by the *certainty* of the expectation. For example, if the driver feels very certain that a lead vehicle will not brake (e.g., when driving on a sparsely trafficked highway), he may be more prone to take the eyes off the road than in a situation where he feels more uncertain about how the lead vehicle will behave (e.g., when driving in a dense traffic queue). As further outlined in Principles 8 and 9, proactive attention allocation can be viewed as an increasingly automatized skill established through repeated exposure to statistical regularities in the driving environment. Thus, expectations may be invoked by both controlled and automatic processes (Principle 8) and it follows that expectations do not necessarily have to involve substantial attentional effort or be accessible to consciousness.

Moreover, both endogenous and exogenous selection are influenced by various other factors. For example, the emotional value of an activity (e.g., the social value of sending a text message) strongly affects its chance of being selected (e.g., Vuilleumier, 2005) but, as noted under Principle 6, emotional value may also influence the general activation level (e.g., by inducing increased attentional effort and arousal). Moreover, the intake of drugs may affect attention selection. For example, alcohol intoxication has been demonstrated to affect visual search (e.g., Maylor et al., 1987) as well as other psychomotor and cognitive abilities (Moskovitz and Fiorentino, 2000).

As stated in Principle 4, during the performance of real-world naturalistic tasks such as driving, attention allocation generally occurs through a dynamic interaction between exogenous and endogenous factors in an evolving perception-action cycle. Although they subscribe to different terminologies, exogenous and endogenous control of attention are hallmarks of a variety of attention and performance models (e.g., Senders, 1964; Carbonell et al., 1968; Norman and Shallice, 1986; Wickens, et al., 2003; Engström et al., 2012).

8. Automatic versus controlled performance

A classical distinction in psychology is that between controlled and automatic performance. Automatic performance is effortless, not available to consciousness and established through repeated exposure to (i.e., learning of) consistent mappings between stimuli and responses (Schneider and Shiffrin, 1977; see Principle 9). By contrast, controlled performance, relying on executive cognitive functions such as working memory, requires attentional effort and is needed to deal with novel, non-routine or inherently difficult tasks (Schneider and Shiffrin, 1977). This effortful, conscious, focusing of attention, resulting in controlled performance, has been referred to as *cognitive control* (e.g., Miller and Cohen, 2001), *supervisory control* (Norman and Shallice, 1986) or *executive attention* (Posner and Fan, 2008). Here we adopt the former term but view it as essentially equivalent to the two latter terms. As suggested by Cohen, Dunbar & McClelland (1990), automaticity is best viewed in terms of a continuum rather than an all-or-none phenomenon.

Terms like “attention” and “resources” are often traditionally associated with controlled performance (e.g., Posner and Petersen, 1990; see also the dictionary definition of attention in Section 3), while automatic tasks are considered to not require attention and/or mental resources. However, in driving, many, if not most, activities may be considered more or less automatized, at least for experienced drivers in routine situations. Furthermore, endogenous selection is traditionally considered as controlled while exogenous selection is viewed as automatic. However, as pointed out by Trick et al. (2004), this view is problematic in the context of driving. In particular, endogenous selection in routine driving situations is often automatized. For example, when entering into an intersection (in right-hand traffic), attention and gaze are normally proactively allocated to the left to check for oncoming traffic (Summala and Räsänen, 2000). While such proactive attention selection is clearly goal-driven, thus endogenous, it is still largely automatized for experienced drivers.[4] Trick et al. (2004) also suggest that exogenous selection may sometimes be considered controlled, e.g., in active visual scanning of the road environment not guided by a particular goal. Hence, the exogenous-endogenous and controlled-automatic dichotomies are best viewed as independent, orthogonal, dimensions (Trick et al., 2004).

9. Attention as an acquired skill

As noted under Principle 8, attention allocation in routine driving situations is to a large extent automatized for experienced drivers. By contrast, novice drivers generally have to deploy conscious effort (cognitive control) to determine what aspects of the situation to focus on. Thus, attention allocation can be viewed as a skill acquired through repeated practice, or more specifically, the exposure to consistent regularities (i.e., consistent mappings) in the driving environment. With increasing experience, the attention allocation process becomes increasingly automatized and less dependent on the deployment of cognitive control. However, even for experienced drivers, cognitive control is needed when encountering novel or inherently difficult situations. As suggested by Fuller (1984), this gradual learning process can be understood in terms of the conditioning of actions on environmental cues that reliably predict the value (positive or negative) of action outcomes.[5]

10. Interference between activities

Based on the classical dual task paradigm, interference between two concurrent activities occurs when they impose overlapping resource demands on the operator (see e.g., Wickens, 1984; see Principle 2). Below, five general types of task interference are proposed, based on the resource model outlined in Principle 2:

a. Sensory interference refers to the case when two or more activities demand the same sense organ, for example when the eyes are needed both for lane keeping and to write a text message.

b. Actuator interference refers to the case when two or more activities demand the same actuator, for example when the hands are needed to perform a rapid steering avoidance manoeuvre while being occupied by peeling a banana. Sensory and actuator interference are both fundamental in the sense that they are not reduced with practice (however, the ability to *deal with* sensory and actuator interference by scheduling, or time-sharing, attention between two tasks, e.g. by shifting gaze, is a skill developed with practice).

c. Perceptual interference relates to the concurrent demands for perceptual systems in the brain. Perceptual interference has been demonstrated in laboratory studies where the ability of irrelevant peripheral visual stimuli to capture attention exogenously during performance of a primary task is reduced as the visual perceptual load of the primary task increases (Lavie 2005; Lavie and de Fockert 2006).

d. Motor interference relates to concurrent demands for motor systems in the brain. A prototypical example is the difficulty to tap different rhythms with the left and right hands. It may be generally suggested that activities requiring similar perceptual/motor resources (e.g., use similar perceptual modalities or response codes) interfere more than tasks that use different resources (Wickens, 1984). By

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[4] However, it would not be automatized for a UK driver driving in right-hand traffic for the first time; in this case cognitive control is needed to override the automatized tendency to look right (Miller and Cohen, 2000).

[5] This general idea is strongly related to Damasio's somatic marker hypothesis (Damasio, 1994), which has recently been applied in the driving domain by Vaa (2007) and Fuller (2007). It is also supported by recent computational models relating reinforcement learning algorithms to the brain's dopamine system (see e.g., Schultz, Dayan and Montague 1997; Hayhoe and Ballard, 2005).

contrast to sensory and actuator interference, perceptual and motor interference is generally reduced with practice (i.e., as tasks become increasingly automatized; see Principle 8).

e. Cognitive interference relates to concurrent demands for cognitive resources, or more specifically, cognitive control. As noted under Principle 8, cognitive control refers to effortful, conscious, resource allocation, needed to deal with non-routine and inherently difficult tasks, resulting in controlled performance, (e.g., Miller and Cohen, 2001). Based on this, the *cognitive load* of a task or activity may be defined as the degree of cognitive control that is demanded by the task from the driver. Thus driving will generally be experienced as more cognitively loading by a novice driver compared to an experienced driver since the latter has developed more or less automatized routines to deal with common driving situations. Cognitive interference thus, by definition, occurs between two non-automatized tasks (i.e., tasks requiring cognitive control), regardless of any sensory, actuator, perceptual or motor interference (akin to Wickens', 2002, notion of a general cost of concurrence). Hence, by contrast to the other interference types, cognitive interference is amodal (i.e., not specific to any sensory/actuator or perceptual/motor modality). Cognitive interference is *by definition* reduced with practice and increased automaticity. A typical example of cognitive interference in driving is the commonly observed interference between mobile phone conversation and certain (typically cognitively demanding) aspects of driving (Horrey and Wickens, 2006).

In addition to these general task interference types, more fine-grained categories are possible. For example, for perceptual and motor interference, further distinctions could be made based on perceptual modalities and response codes (e.g., Wickens, 1984). Regardless of the granularity of the resource categories, there are computational algorithms that can model the anticipated degree of interference between two tasks, based on the demands of each task and a model of the assumed interference when the tasks are performed concurrently (e.g., Horrey and Wickens, 2003).

It should be noted that the actual degree of interference between two (driving or non-driving-related) tasks in naturalistic driving conditions depends strongly on adaptive driver behaviour, in particular the willingness to engage in secondary tasks (Lee, Regan and Young, 2009). As stated under Principle 1, drivers generally regulate their behaviour based on expectations in order to accomplish driving goals while avoiding feelings of risk/discomfort. Thus, when drivers are free to regulate their behaviour, they are less willing to engage in interfering secondary tasks when the driving task is demanding or uncertain (although this regulation may still break down due to, for example, erroneous expectations, overestimation of own capabilities and/or strong motivations to engage in secondary tasks; see Sections 4.3.3 and 4.3.4). This contrasts with many experimental studies based on the dual task paradigm where subjects are instructed to engage in secondary tasks under conditions where they may not normally have chosen to engage.

11. Functional limitations

The ability to dynamically allocate resources to match driving demands is constrained by more permanent limitations of the driver. This includes *diminished sense organ capabilities* such as impaired visual acuity (not corrected for) and impaired hearing. *Biomechanical impairments* refer to biomechanical restrictions in head, limb and/or whole body movements that constrain active attention allocation while driving. Finally, *cognitive impairments* refer to more or less permanent neurological impairments such as dementia, Parkinson's disease, epilepsy etc. Brouwer (2002) offers a review of different cognitive impairments in the context of driving. At least the first two types of limitations are typically compensated for by increased safety margins (e.g., lower speed) and a general avoidance of complex driving situations, which may explain why older drivers are not more overrepresented in crash statistics than might be expected given their higher susceptibility to functional impairments (Evans, 1991).

12. Stimulus quality

The ability to allocate resources to match driving demands is fundamentally limited by the quality of information reaching the sense organs. This may be related to visual occlusions where the perception of safety-critical information, for example a vehicle on collision course, is prevented by an occluding object. Here a general distinction could be made between endogenous and exogenous sources of occlusion. The former refers to occlusions generated by the driver, for example when rubbing the eyes or when blinking. By contrast exogenous occlusions refer to occlusions by objects external to the driver such as such as other vehicles, infrastructure elements, the a-pillar or a passenger. Other factors that may limit the visibility of safety-critical information include darkness, glare (e.g., from sunshine or headlights), visual clutter (e.g., from multiple light sources at night), fog and heavy precipitation. While such constraints on stimulus quality are not related to attention allocation *per se*, they may contribute to attentional mismatches in real-world situations.

4.2 Summary

The proposed general framework of driver attention, based on the principles outlined above, is summarised in Figure 4. Driver attention, which is viewed as an integral part of adaptive driver behaviour (Principle 1), can be generally understood as the allocation of resources to activities (Principle 2). Activities are more or less related to driving and driving-related activities are more or less safety critical (Principle 3). The driver's allocation of resources evolves dynamically with the ecological context in which it is situated (Principle 4).

Attention can be characterised in terms of (1) activation and (2) selectivity (Principle 5). Activation refers to how much resources are allocated while selectivity refers to the distribution of resources between activities. The current resource allocation can be viewed as the momentary attentional state of the driver, which may be more or less matched to driving demands. Thus, resources may be allocated at different amounts and potentially also shared between activities, but some activities may also be selected at the expense of others. Both activation and selection are driven by a range of exogenous and endogenous factors (Principles 6-7). The performance of activities, as well as attention allocation, can be characterised on a continuum from automatized to controlled performance (Principle 8) and attention allocation is a skill gradually learned, and increasingly automatized, through repeated exposure to statistical environmental regularities in everyday driving (Principle 9). The simultaneous performance of multiple activities may lead to interference if these activities place concurrent demands on the same resources (Principle 10). Attention is constrained by functional limitations of the driver (Principle 11) as well as by the quality of information reaching the sensory organs (Principle 12).

As suggested under Principle 4, and further elaborated in the following section, *inattention* may be understood in terms of the degree to which the current attentional state (i.e. the resource distribution) *matches* the demands of activities critical for safe driving (Lee, Young and Regan, 2009). This is illustrated by the bi-directional arrow in the centre of Figure 4.

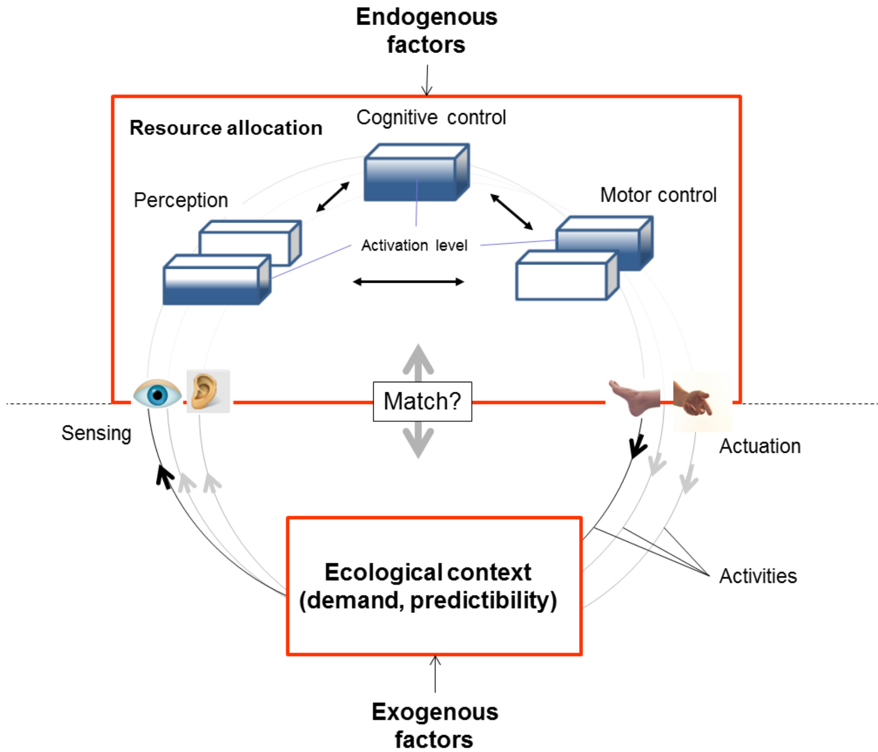


Figure 4 General illustration of the proposed conceptual framework for attention selection in driving (see the text for explanation)

4.3 Conceptualizing driver inattention

This Section discusses how driver inattention may be conceptualized based on the framework of driver attention outlined above and how various forms of driver inattention may arise.

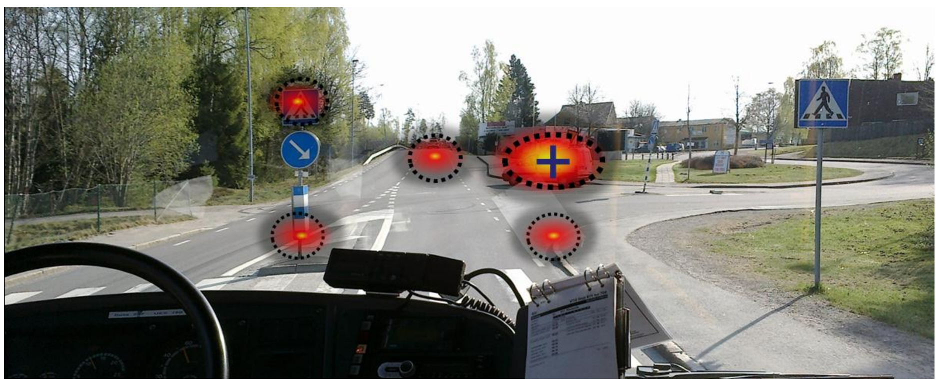
4.3.1 Inattention as a mismatch

In daily language, inattention implies a failure to attend to *something* that one "should have" attended to. In this sense, the concept of inattention is inherently normative and depends on subjective judgement of what is important to attend to in a particular situation. In the context of driving, it seems reasonable to say that the driver should attend to driving and, if he fails to do so, we can say that he is inattentive. However, from a scientific standpoint, such a definition is problematic for several reasons. First, driving consists of a variety of sub-tasks (Principle 2) and it may not be possible to attend to all at the same time. Determining which sub-task that is most important (and the driver thus should attend to) can often only be determined after the fact (i.e., after a crash or incident occurred) and, hence, this attribution of inattention is somewhat arbitrary (see Hancock, Mouloua and Senders, 2008). This is the issue of *hindsight bias*, which is a fundamental problem in all definitions involving human error (Rasmussen, 1990). Furthermore, defining inattention in terms of a failure of the driver implies the assignment of blame, which is often not relevant for the *scientific understanding* of crash causation. This may be contrasted with crash investigations conducted from a legal perspective, where the assignment of blame is naturally the main objective.

The present conceptual framework offers an alternative approach where inattention may be understood in terms of a *mismatch* between the current allocation of resources and those resources demanded by activities critical for safe driving, an idea originally proposed by Lee, Young and Regan (2009) in the more specific context of driver distraction. A key issue is then what constitutes safe driving. As suggested in Principle 3, activities critical for safe driving can be more precisely defined as those required for the control of safety margins. Thus, given this definition, *inattention occurs when the driver's allocation of resources to activities does not match the demands of activities required for the control of safety margins*. This represents a systemic perspective where inattention is defined in terms of failures (mismatches) in the entire driver-vehicle-environment system rather than as failures attributed to the driver[6]. This helps circumventing issues related to hindsight bias and the assignment of blame. The general idea is further illustrated in Figure 5. For the purpose of illustration, attention is here viewed specifically in terms of the allocation of visual sensory and perceptual resources. However, the same principles apply to any of the resource types described under Principle 2. Figure 5a shows spatial locations that need to be selected in order to ensure safe driving in this driving scenario. In Figure 5b, the driver's attention allocation matches that demanded for safe driving. In Figure 5c, the driver's attention allocation does not match that demanded for safe driving (a pedestrian in an unexpected location is not attended to). It should be noted that the notion of a mismatch does not imply anything regarding the normative question whether the driver "should have" attended differently. It plainly states that the resource allocation does not match that demanded by activities critical for safe driving at a particular moment in time.

[6] It should be emphasized that this systemic perspective does not in any way diminish the responsibility of the driver to allocate attention in a safe way. Rather, it represents an attempt to keep the purely scientific investigation of driver inattention separate from legal considerations of culpability.

a



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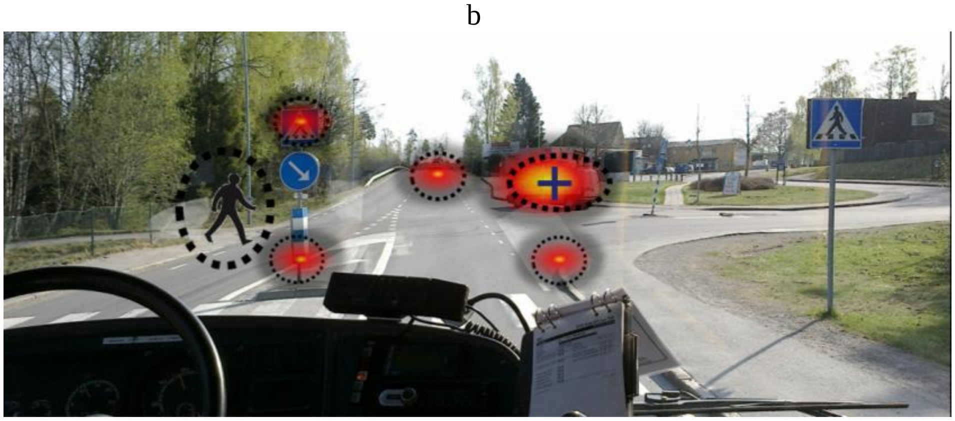


c

Figure 5 Conceptualization of inattention in terms of mismatches between the driver's actual resource allocation (heat maps) and that demanded by activities critical for safe driving (dashed rings). The attentional activation level is represented by the intensity of the heat map while the activation demanded is represented by the line width of the rings. The "+" represents the current gaze direction

In order to further understand how this way of conceptualizing inattention helps to alleviate the conceptual problems associated with hindsight bias, consider again Figure 5c. If the pedestrian encroaches into the driver's path and the driver is unable to bring the vehicle to a stop, it may be unclear whether to consider the resulting crash as due to an attentional failure of the driver. On the one hand, the sudden appearance of the pedestrian in this location was strongly unexpected and it was the pedestrian that violated traffic rules. One may thus say that the driver was “unlucky” and the victim of unfortunate circumstances. On the other hand, one could also argue that, with hindsight, the driver still could have done a better job at scanning the roadside for potentially hazardous events. Thus, how to classify the situation ultimately boils down to a normative judgement of what the driver “should have done” (and whether it is reasonable to blame the driver for not doing it). This issue is related to Moray’s (2003) discussion on “eutactic” behavior, where even “perfect” attention allocation in time and space (within limits of human abilities) will sometimes result in attention mismatches due to the sudden occurrence, or co-occurrence, of safety-critical events (see also Lee, Young and Regan, 2009). By instead viewing the situation as a mismatch between the actual resource allocation and that demanded by activities critical for safe driving, the reliance on hindsight is reduced and (the often implicit) considerations of where to put the blame are avoided. From this system-level perspective, we would say that inattention first occurred at the moment when keeping track of the pedestrian became an activity critical for safe driving. However, this does not necessarily mean that inattention contributed to the crash. If for example, the pedestrian was initially occluded by a tree and entered the road very late, the driver may not have been able to react in time even if he initially attended to the location where the pedestrian appeared.

One important implication of this is that inattention, conceptualized in terms of mismatches, does not necessarily have to lead to adverse consequences; even if the driver does not attend to the pedestrian, the situation will only lead to a crash or near crash if the pedestrian enters the road. Thus, inattention induces an increased *vulnerability* to sudden changes in the driving environmental not anticipated by the driver.

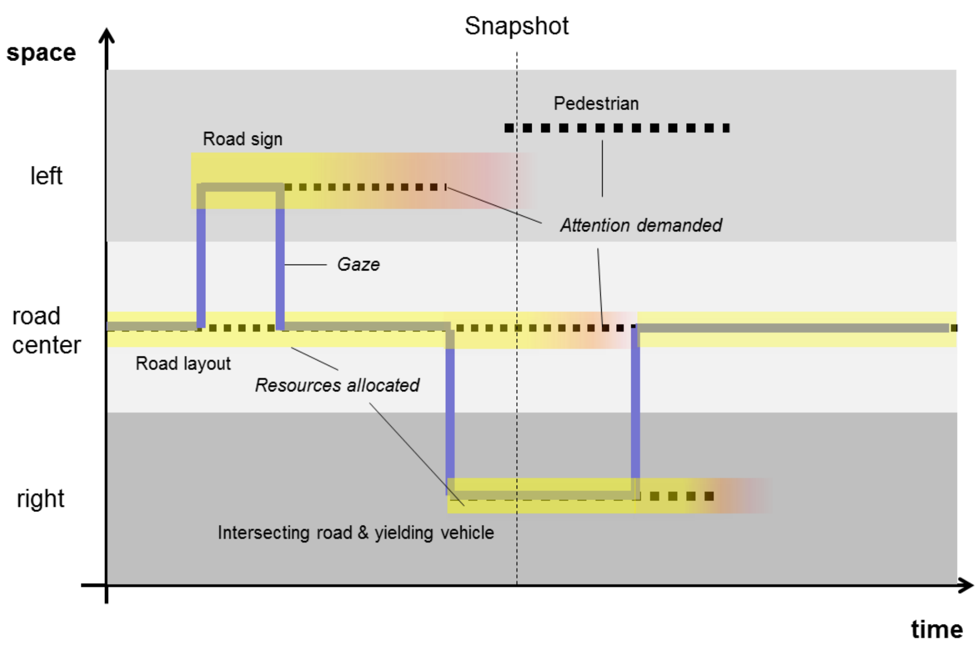


Figure 6 Illustration of the temporal aspect of attention allocation for the example scenario in Figure 5. The thick bars illustrate the actual allocation of visual perceptual resources (corresponding to the heat maps in Figure 5) while the dashed lines represent the resources demanded by activities critical for safe driving. Gaze is represented by the blue line. As shown, attention allocation is not solely determined by gaze direction. The vertical dashed line represents the moment of the snapshot in Figure 5. The mismatch occurs here due to the driver attending to the right intersecting road at the moment when the pedestrian appears to the left.

While Figure 5 emphasizes the spatial aspects of attention allocation, the *timing* of the allocation also has to match the demands of activities critical for safe driving (Victor and Dozza, 2011). This is further illustrated in Figure 6. One further point illustrated in Figures 5 and 6 is that the attentional state is not solely determined by the direction of gaze. Rather, perceptual and motor resources may be covertly allocated to an activity even after gaze has moved away from the location/object towards which the activity is directed, although the activation level may fade with time until the location/object is visually sampled again.

Furthermore, it should be noted that, even if the resource allocation is matched spatially and temporally to that demanded by activities critical for safe driving, a mismatch may still occur if the relevant *aspects* (e.g. a particular object or feature) of the scene are not selected. For example, Most and Astur (2007), in a driving simulator study, demonstrated that subjects searching for a coloured arrow giving turn instructions at an intersection crashed less frequently with a suddenly veering motorcycle if the motorcycle was of the same colour as the arrow compared to when the motorcycle had a different colour. Similarly, a driver negotiating an intersection may focus attention mainly on cars, but this attentional focus may lead to delayed detection (or non-detection) of other, less expected, objects such as motorcycles (Brown, 1990). Such effects can be understood in terms of a mismatch between endogenously driven attentional tuning to certain objects/features (attentional set; Most and Astur, 2007) and the actual situation.[7]

The following Sections discuss different forms of attentional mismatches and the potential mechanisms underlying them.

4.3.2 Mismatches due to insufficient activation

As noted under Principle 6, the general activation level of perceptual, motor and cognitive resources is influenced by a range of endogenous and exogenous factors including the circadian cycle, sleep homeostasis, time on task and the nature of the task. Fatigue may be understood as a biological drive for recuperative rest (Williamson et al., 2009) induced by such factors. Thus, for instance, a driver's lack of sleep during the previous night may induce a reduced general activation level as well as episodes of micro sleeps, most likely in certain phases of the circadian cycle, and exacerbated by long continuous driving hours in a non-stimulating environment.

States of sleep or severe drowsiness will in themselves induce attentional mismatches due to the inability of the drowsy or sleeping driver to respond to sudden increases in attentional demand by activities critical for safe driving (such as a lead vehicle slowing). This effect is exacerbated by eye closures which prevent salient visual stimuli from entering the retina and waking up the driver.

However, low activation levels may also induce more subtle forms of attentional mismatches. As suggested by Hockey et al. (1998), fatigue-inducing factors may affect the ability to regulate attentional effort. When the general activation level is low (e.g., due to sleep loss and/or long driving hours),

[7] This phenomenon is related to inattentional blindness (IB), where subjects focusing attention on a demanding task are unable to report salient objects even if they appear in the central visual field (e.g. Mack and Rock, 1998). However a key difference is that IB studies typically use verbal reports rather than overt performance to probe for IB. Thus, it is difficult to distinguish IB from "inattentional amnesia" (Wolfe, 2000), in which case the subject saw the salient object but forgot it before being able to report it, or "inattentional agnosia" (Simons, 2000) which refers to the possibility that the subject sees the object but does not encode it as an object and thus cannot report it. However, this is clearly not an issue for the attentional set mismatch phenomenon demonstrated by Most and Astur (2007), as it is directly probed in terms of overt performance.

resources needed for cognitive control are depleted and the ability to mobilise attentional effort is impaired. Thus, low activation levels may lead to a *loss of task-related effort*, in particular in monotonous, non-stimulating and non-motivating driving tasks (Williamson et al., 2009). In terms of the present framework, this represents a mismatch between the activation level of the resources deployed and the activation level demanded by activities critical for safe driving. As an example, consider a sleep-deprived driver who has been driving for long hours without rest on sparsely trafficked motorway. He then enters into an intersection in a built-up area. Due to the fatigued state, he fails to mobilise additional attentional resources and, thus, the general level of resource allocation is too low to detect and respond to a pedestrian that enters a crosswalk.

However, even a non-fatigued driver may fail to deploy a sufficient general level of attention to critical aspects of the driving task. Regan et al. (2010) proposed the term "driver cursory attention" to account for this type of phenomenon, which they define as: "Insufficient or no attention to activities critical for safe driving brought about by the driver giving cursory or hurried attention to activities critical for safe driving" (p. 1776). It could be further suggested that cursory attention can be understood in terms of a trade-off between energy, speed and accuracy. Since attentional effort is energetically costly (Hockey, 1997), and performance speed is sometimes highly valued, these factors are generally traded against performance accuracy. This is related to the fact that drivers normally act as satisficers rather than optimizers, that is, they do not invest more effort than needed to obtain what they perceive as satisfactory performance (Boer and Hoedemaeker, 1998; Principle 1). Thus, for example, an alert but hurried or "lazy" driver entering into an intersection in the example above may fail to allocate the perceptual resources needed to detect the pedestrian in time.

4.3.3 Expectation mismatches

As described under Principle 7, the endogenous allocation of resources is strongly based on drivers' expectations of how a situation will develop. When expectations do not match the way the situation actually develops, this may result in a failure to adapt properly to the evolving situation and, eventually, to a crash. In such situations, drivers may develop a *false certainty* that the situation will develop in a certain way; the stronger the certainty, the stronger the potential mismatch. Expectation mismatches may be induced by the local environmental context (e.g., the behaviour of other road users or the infrastructure layout) as well as by more general world knowledge and beliefs brought into the situation by the driver.

As an example, consider the following scenario studied by Summala and colleagues (see Summala and Räsänen, 2000). A Swedish driver enters an intersection where he intends to turn right. The intersection features a two-way bicycle lane, a recently introduced infrastructure element which our driver is not accustomed to. Thus, the driver does not expect bicyclists to appear from the right, and rather allocates attention and gaze towards the main expected hazards in this scenario, that is, cars approaching from the left. This increases the risk of missing bicyclists unexpectedly appearing from the right (who may not yield given that they have the right of way and thus expects our driver to stop). Summala and colleagues found that this type of expectancy problem, leading to mismatching attention allocation as well as a lack of speed adaptation, was the key factor behind car-bicycle collisions at intersections in Sweden and Finland. This also illustrates how failures in proactive attention selection and failures of safety margin adaptation (in this case, speed selection) could be viewed as two sides of the same coin (Principle 1)[8].

[8] The authors also suggested the high speed itself contributed to the erroneous visual search patterns. Hence, a lack of adaptation of safety margins may interact with proactive attention allocation, while both have their origin in erroneous expectations on how the situation will develop.

Somewhat surprisingly, there is relatively little empirical work on attention failures related to expectation mismatches in the driver behaviour literature. Some notable exceptions (in addition to Summala and Räsänen, 2000) include Alexander and Lunenfelt (1986), Theeuwes (1996), Shinoda, Hayhoe and Shrivastava (2001) and Martens (2007).

4.3.4 Mismatches induced by motivational factors

Mismatches in endogenous resource allocation may also be related to motivational factors. As noted in Principle 1, driver behaviour, including attention allocation, is ultimately driven by motivation. If the driver has a strong desire to accomplish a certain task, resources may be focused on this task which may result in insufficient resources being allocated to activities critical for safe driving.

For example, consider a driver engaged in a real-time texting conversation with a friend on a topic of strong emotional significance. The driver may thus feel an urge to reply quickly and may thus choose to engage in the texting task in a potentially risky driving situation where he would normally be reluctant take the eyes off the road. Thus, motivational and emotional factors may temporarily induce strong biases towards the performance of a certain task that shifts the balance between benefits (from accomplishing the task) and costs (discomfort associated with increased crash risk; see Principle 1).

4.3.5 Task interference

While, as noted above, expectation and proactive attention deployment/selection have attracted relatively little interest in the driver behaviour literature, there is a vast literature on the potential effects of task interference on driving performance and crash risk, in particular driven by the public mobile phone debate (see e.g., Horrey and Wickens, 2006). As noted under Principle 10, interference between two tasks may occur when overlapping concurrent demands are placed on common resources, which may degrade performance on one or both tasks (Wickens, 1984). Interference between driving/non-driving related activities and activities critical for safe driving can thus be considered a key mechanism by which inattention leads to crashes.

Under Principle 10, five general types of task interference were proposed: (a) *Sensory interference*, (b) *actuator interference*, (c) *perceptual interference*, (d) *motor interference* and (e) *cognitive interference*. How these general forms of task interference may be related to inattention could be exemplified by revisiting the intersection scenario introduced in the previous section (Summala and Räsänen, 2000). Recall that expectation mismatches induced a focus of attention and gaze towards cars expected from the left, which led to an increased risk of missing bicyclists unexpectedly appearing from the right. However, this analysis does so far not specify the precise reason why the bicyclist was eventually missed. One possibility (advocated by Summala and Räsänen, 2000) is that the bicyclist is typically missed simply because he appears outside the driver's field of view when gaze is directed to the left. This would then be an example of (visual) sensory interference. However, as pointed out by Theeuwes (2000), another possibility is that the bicyclist appears in an unexpected location *within* the visual field of view, and that the strong perceptual focus on cars coming from the left would supress the ability of the bicyclist to attract attention bottom-up. This phenomenon, which is akin to the effect of attentional set demonstrated by Most and Astur (2007) cited above, and the effects of perceptual load demonstrated by Lavie and colleagues (Lavie 2005; Lavie and De Fockert 2006), would be an example of visual perceptual interference.

Finally, assume that a driver who experienced a near crash with a bicyclist in our example scenario approaches a similar intersection a few weeks later. The previously experienced near-crash has taught the driver that he also needs to scan to the right for bicyclists. However, since this novel scanning behaviour is not yet automatized, cognitive control is needed to override the prevailing routine scanning pattern (just scanning for cars on the left). However, this time, the driver is heavily engaged in a phone conversation with high demands on working memory and, hence, cognitive control. Thus, in the absence of available cognitive control resources, the driver reverts to the old, automatized, scanning routine and, hence, still fails to check for bicyclists to the right. This would constitute an example of cognitive interference due to the cognitive load induced by the phone conversation.

4.3.6 Other factors contributing to attentional mismatches

As noted under Principles 11 and 12, drivers' attention selection is influenced by a number of factors not directly related to attention *per se*, in particular functional limitations of the driver and constraints on the information available to the driver.

With respect to functional impairments, a cognitively impaired older driver in our intersection example scenario may find it more difficult to override automatized attention selection patterns in order to proactively attend to potential bicyclists (in the same way as a cognitively loaded driver). Visual occlusion and/or limited visibility of critical objects may strongly contribute to the development of attentional mismatches. For example, if the approaching bicyclist in our example is initially occluded from the driver's view, or appears in the dark without reflexes or lights, this naturally reduces the chances that the bicyclist will capture the driver's attention in time.

Finally, the detection of impending hazards may be impaired due to the change blindness phenomenon (O'Regan et al, 2000; Principle 7). This may occur in situations where the hazard (e.g., a lead vehicle braking) is signalised by a discrete visual transient that is not registered at the retina due to masking (e.g., by an eye closure) or an off-road glance. For example, consider a driver that looks off road towards an in-vehicle display while a lead vehicle brakes far ahead, as signalised by the onset of brake lights. When the driver looks back to the road, the brake lights, which are now onset, are likely to pass unnoticed due to change blindness. If looming (optical expansion) cues are still weak (due to the large distance to the lead vehicle), the driver may fail to detect that he is closing in on the lead vehicle and eventually decide to look back towards the display.

5 A general taxonomy for classifying different forms of inattention in driving

This section outlines the proposed general taxonomy of inattention. As noted in Section 2, two issues are of critical importance in the development of a taxonomy: (1) to define its purpose and (2) to ground it in a clear conceptual framework. The overall purpose of the present taxonomy is to provide a common language for safety-related driver inattention that can be used in crash/near crash analysis (including onsite investigation and naturalistic driving studies), the design and interpretation of experimental studies and the design and evaluation of vehicle systems. A main objective is to define the general concepts relating to inattention and their mutual relations, based on the conceptual framework of driver attention outlined in the previous Section. The proposed taxonomy is thus defined at a relatively high-level, containing only the most general categories. However, we believe that this is an appropriate starting point given the limited current consensus on terminology even at this level. More fine-grained categories may be elaborated in future developments of the taxonomy.

A key starting point for the taxonomy is the view of driver attention as the allocation of resources to activities, as an alternative to the more traditional view of attention as the selection of information (Principle 2). *Driver inattention* is then conceived of in terms of *mismatches* between the current resource allocation and that demanded by *activities critical for safe driving* (Principle 4, Section 4.3.1), where "activities critical for safe driving" are defined as those activities required for the control of safety margins (Principle 3). Attentional mismatches may be due to insufficient resource allocation (the activation aspect of attention) or due to allocation of resources to the "wrong" activities (the selective aspect of attention). Furthermore, the presence of inattention is independent of the outcome of the event and, thus, inattention, as defined here, does not have to lead to adverse consequences; nor does it, necessarily, imply driver error.

Based on this, two general forms of inattention are proposed: *insufficient attention* and *misdirected attention*, relating to the activation and the selective aspects of attention selection, respectively (Principle 5). Following Pettit et al. (2005) and Regan et al. (2011), for each of these general types of inattention, a number of sub-categories, defined by mechanisms, or *processes*, giving rise to inattention are proposed. Since several such processes may simultaneously give rise to inattention, the taxonomy generally allows for the assignment of multiple categories (rather than being restricted to mutually exclusive categories). Hence, the taxonomy is mutually inclusive (polythetic) as explained in Section 2.2.

5.1 Insufficient attention

This category relates to the activation aspect of attention, that is, *how much* resources are allocated to activities (Principle 6). *Insufficient attention occurs when the degree to which resources are allocated fails to match that demanded by activities critical for safe driving.*

Two main sub-categories of insufficient attention are proposed: (1) sleep-related impairment and (2) insufficient attentional effort. Importantly, these processes may co-exist in producing insufficient attention and are thus not mutually exclusive.

5.1.1 Sleep-related impairment

This sub-category refers to cases where the *driver's allocation of resources to activities critical for safe driving does not match the demand of these activities due to factors related to sleep regulation*, in particular the circadian rhythm and sleep homeostasis. The sleep process may be further exacerbated by exogenous factors such as monotony and time-on task. The category may be sub-divided based on the stage of the sleep process:

a. Sleepy: This represents an inclination to sleep characterized by slow eye closures and occurs immediately before falling asleep.

b. Asleep: The process of sleeping with measurable differences, compared to the awake state, in brain wave activity, muscle tone and eye movement.

Example: A sleep-deprived truck driver is required to reach the terminal before 7 AM and thus continues to drive despite feeling sleepy. Eventually the driver falls asleep at the wheel and thus does not allocate any resources at all to activities critical for safe driving (see Figure 7).

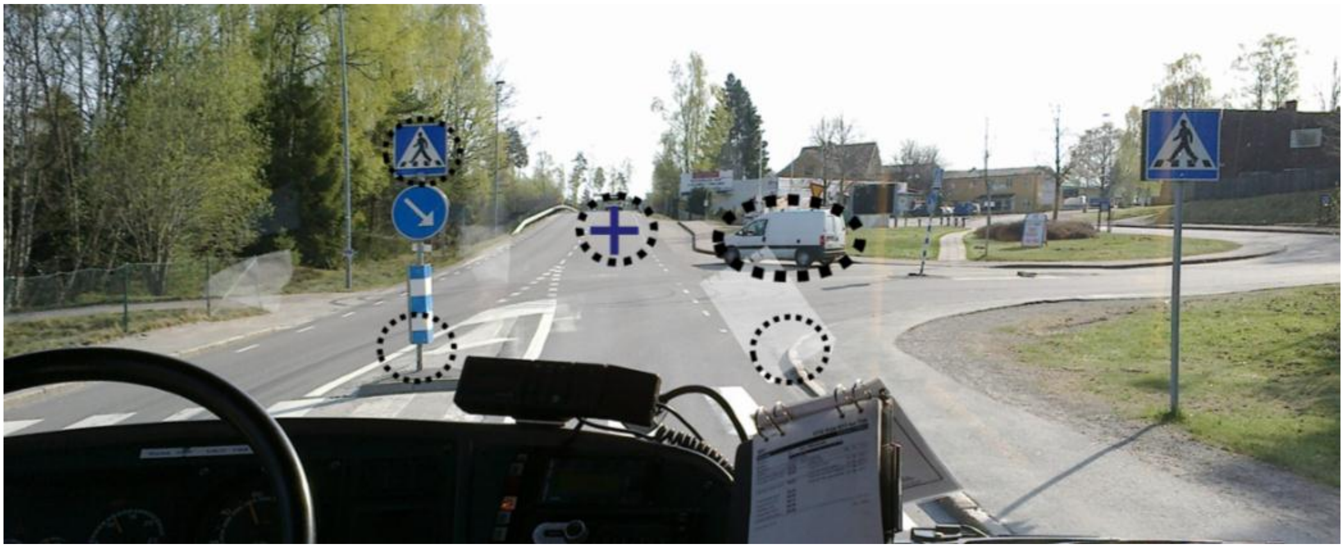


Figure 7 Example of attentional mismatch due to sleep-related impairment. The driver is asleep and thus does not allocate any resources at all to activities critical for safe driving.

5.1.2 Insufficient attentional effort

This sub-category refers to cases where *the driver's allocation of resources to activities critical for safe driving does not match the demand of these activities due to an inability of the driver to mobilise sufficient attentional effort.* This may be due to fatigue (Hockey et al., 2008; Williamson et al., 2009) but also due to a trade-off between performance effort and accuracy. The latter can thus be understood as a form of "attentional satisficing", where even a non-fatigued driver, due to energetic costs, does not invest as much attentional effort as is actually needed to allocate resources sufficient to match activities critical for safe driving. This illustrated in Figure 8.

Examples:

- A driver drives for five consecutive hours on an empty motorway. Due to fatigue induced by the monotonous task, he only allocates a minimum amount of resources to activities critical for safe driving. As he approaches a car stopped in his lane ahead the resources allocated to monitoring the forward roadway are insufficient to detect in time that the vehicle is stopped.
- A hurried driver enters into a complex intersection but does not invest any additional effort to look for potential hazards. The resources allocated are thus insufficient to detect and react to a pedestrian entering a crosswalk ahead.

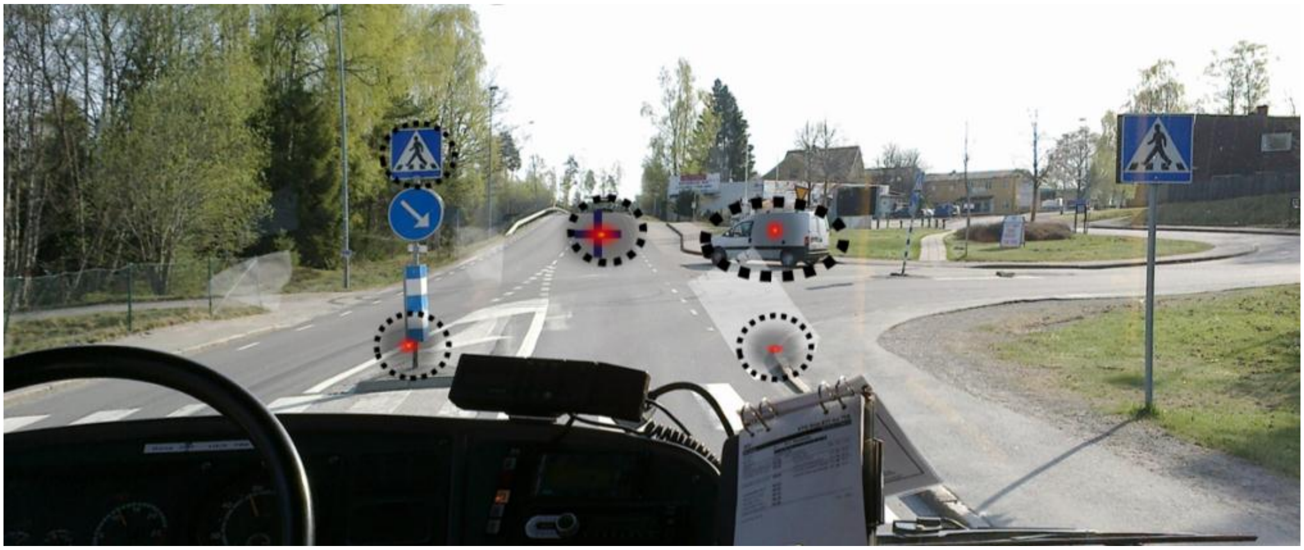


Figure 8 Example of an attentional mismatch due insufficient attention. The driver allocates some resources to activities critical for safe driving but the amount of resources allocated is insufficient to match the attentional demands of those activities.

5.2 Misdirected attention

This category relates to the selective aspect of attention (see Principle 5), that is, *how resources are distributed between activities*. Hence, *misdirected attention occurs when the demands of activities currently critical for safe driving are not matched due to the allocation of resources to other safety-critical or non-critical activities.*

It should be noted that a single driving scenario may involve a sequence of instances of misdirected attention that may be causally linked. For example, a phone conversation may initially impair the detection of a sign indicating that bicyclists may potentially appear from the right. This has the consequence that the driver only scans for cars to the left but not for bicyclists to the right. Misdirected attention may of course also co-occur with the different forms of insufficient attention outlined in Section 5.1. Two sub-categories of misdirected attention may be distinguished: (1) Incomplete selection of safety-critical activities and (2) driver distraction.

5.2.1 Incomplete selection of safety-critical activities

This category refers to situations where *the driver allocates sufficient resources to one or more activities critical for safe driving, or believed by the driver to be critical for safe driving, while the resources allocated to other activities critical for safe driving do not match the demands of these activities*. In other words, this category includes cases where the driver attends to some, but not all, activities critical for safe driving. This includes situations where multiple activities critical for safe driving have overlapping resource demands (e.g., checking both the rear mirror and the headway to the vehicle in front). However, it also includes cases where the driver misunderstands the situation and thus allocates resources away from a safety critical activity to another (possibly less) safety critical activity (which, however, is believed by the driver to be the most safety critical).

Examples:

- A driver is following another vehicle and decides to change lane. He checks the left mirror and thus momentarily fails to allocate sufficient visual resources to the task of maintaining a safe distance to the lead vehicle.
- A driver enters into a busy intersection and actively scans for oncoming vehicles. However, due to the focusing of resources on scanning for vehicles, there are insufficient resources left to detect a crossing pedestrian.
- A US tourist in the UK (used to right-hand traffic) is about to turn left at an intersection but fails to scan to the right for oncoming traffic
- A driver enters an intersection and allocates visual resources based on his expectation of where potential hazards normally appear. However, this results in a mismatch due to a pedestrian suddenly appearing at an unexpected location and encroaching into the driver's path (this corresponds to the example in Figure 9)

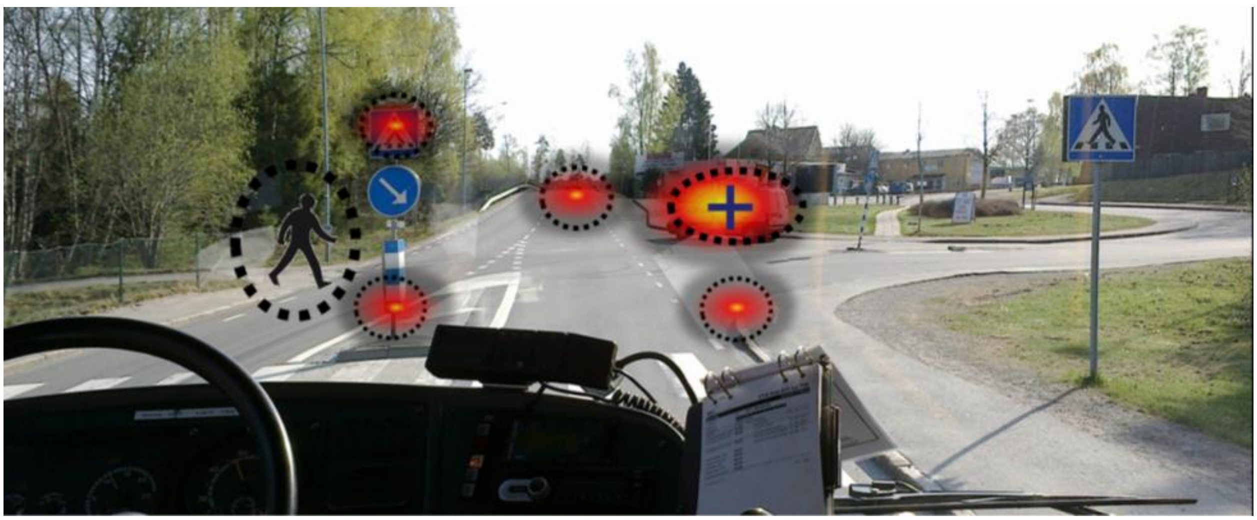


Figure 9 Example of mismatch due to incomplete selection of safety-critical activities (same as Figure 5). The driver generally allocates sufficient resources to locations expected to be relevant for safe driving but fails to account for the pedestrian appearing from the left.

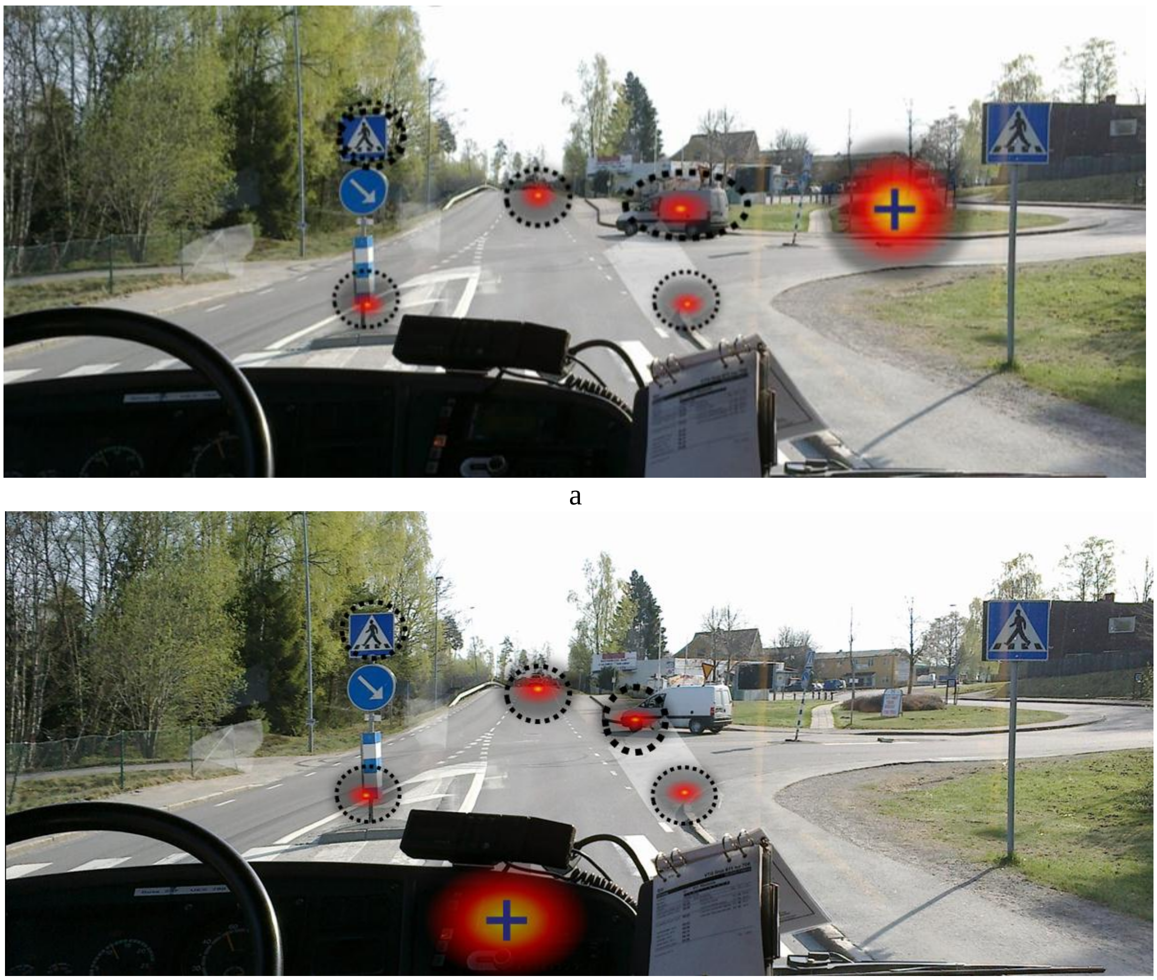
5.2.2 Driver distraction

This category refers to situations where *the driver allocates resources to a non-safety critical activity while the resources allocated to activities critical for safe driving do not match the demands of these activities*. In other words, the driver diverts attention away from activities critical for safe driving to one or more activities that are not critical for safe driving (Lee et al, 2009; Binder et al., 2011).

Examples

- The driver writes a text message on a hand-held phone and looks down towards the display, resulting in insufficient resources being allocated to the safety-critical activity of monitoring the headway to a lead vehicle.
- The driver is heavily engaged in a phone conversation resulting in insufficient resources allocated to the monitoring of traffic lights

Based on Treat et al. (1980) and Wallén-Warner et al., (2008), a further distinction could be made between vehicle-external and vehicle-internal distraction. Examples of these categories are given in Figure 10. In Figure 10a, the driver's visual attention and gaze is allocated towards a commercial sign on the lawn to the right (i.e., vehicle-external distraction). In Figure 10b, visual attention and gaze is focused on an in-vehicle display (i.e., vehicle-internal distraction).



a

b

Figure 10 Examples of attentional mismatches due to (a) vehicle-external and (b) vehicle-internal driver distraction.

5.3 Summary

The overall structure of the proposed taxonomy of driver inattention is summarised in Figure 11. To the left of the dashed line are the two general forms of inattention, insufficient attention and misdirected attention, related to the activation and selective aspects of attention, respectively. To the right is a categorisation of the more specific process that gives rise to inattention.

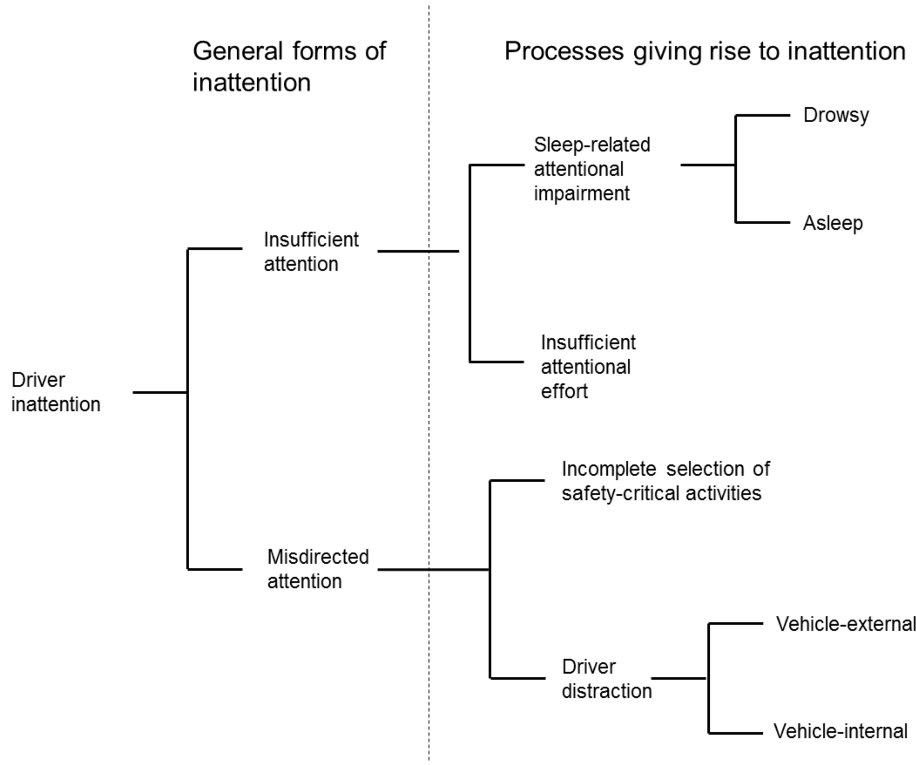


Figure 11 Graphical representation of the proposed driver inattention taxonomy

6 General summary and discussion

The objective of the present project was to develop a general taxonomy for driver inattention that could provide a common language for the study of safety-related driver inattention. The taxonomy is mainly intended to be applied in the context of driver behaviour and incident/accident analysis, the design of experimental studies and in the design and evaluation of vehicle systems. As discussed in Section 2, the term *taxonomy* here refers to the definition of key theoretical concepts and their mutual relationships, which should be distinguished from a *coding scheme*, which refers to detailed operational definitions of phenomena observable in the available data. A coding scheme should, however, be derived from the more general categories in the taxonomy (e.g., include the distinction between driver distraction and incomplete selection of safety-critical activities). On the other hand, the development of coding schemes may lead to identification of novel aspects that need to be included in the taxonomy. Thus, the future development of the taxonomy and specific coding schemes should shape each other in an iterative fashion.

A key starting point behind the present approach was that, in order to create a taxonomy of driver inattention, one first needs to be clear about what is meant by driver *attention*. To this end, a conceptual framework for driver attention was formulated in terms of a set of key principles. This framework proposes an action-oriented view of attention, where driver attention is generally viewed in terms of the allocation of resources to a set of activities (rather than just the selection of information). The distribution of resources over activities depends on two main aspects. The first relates to *activation* (*how much* of one or more resources is allocated) while the second relates to *selectivity* (the distribution of resources between activities).

Driver *inattention* was then defined in terms of a mismatch between the driver's current resource allocation and that demanded by *activities critical for safe driving*. Activities critical for safe driving were broadly defined as those activities *required for the control of safety margins*[9], where safety margin control may be performed at the operational, tactical as well as strategic levels of the driving task.
Thus, more precisely, *inattention occurs when the driver's allocation of resources to activities does not match the demands of activities required for the control of safety margins*. Attentional mismatches may be broadly divided into (1) insufficient attention and (2) misdirected attention. For each of these two main inattention categories, a set of sub-processes giving rising to them were defined.

As reviewed in Section 3, most existing inattention taxonomies are based on surface-level categories derived from the analysis of crash data, thus lacking a theoretical basis in a conceptualization of attention. Thus, according to the distinctions outlined in Section 2, they can be regarded as classifications rather than taxonomies. This was also suggested as the main reason for the existing diversity of definitions and sub-categorisations of driver inattention. The present project has attempted to take a step further by grounding the proposed taxonomy in a conceptual framework of driver attention. As stated in Section 2, a taxonomy represents a model of what is being classified and, to be a useful tool for communication and application to diverse issues, a taxonomy should make explicit the underlying model. The model behind the proposed taxonomy is explicitly defined by the principles outlined in Section 4 and the proposed sub-categories in the taxonomy can be traced back to these principles.

The idea of conceptualizing inattention in terms of mismatches between the resources allocated and those demanded by safety critical activities (Lee, Young and Regan, 2009), rather than in terms of driver "failures", helps to work around conceptual problems related to hindsight bias and the attribution of blame. The present framework addresses these issues by suggesting a blame-neutral, systemic, perspective where inattention is viewed as a breakdown in the driver-vehicle-environment system as a whole, not as a failure attributed to the driver. Thus, at any point in time during the evolution of a driving scenario one can, in theory, ask whether the allocated resources match those demanded by activities critical for safe driving. If not, the driver is inattentive at that particular moment. Hence, inattention, as defined here, can, in principle, be ascribed independently of outcomes and without considerations of blame. While this should, in theory, minimize the influence of hindsight bias it may be difficult to directly observe all activities to which the driver allocates attention (in particular covert activities such as daydreaming), or the attentional demands associated with activities critical for safe driving at that point in time. Thus, it may still sometimes be necessary in practice to infer previous attentional states from behavioural outcomes, with the risk of introducing hindsight bias.

When related to the existing definitions and taxonomies of inattention reviewed in Section 3, the present taxonomy is in line with Petitt et al. (2005), Wallén-Warner et al. (2008) and Regan et al. (2011) in viewing inattention as an umbrella term that subsumes driver distraction as well as other sub-categories, but differs from e.g., Treat et al. (1980) and Hoel et al. (2010) who view inattention as a separate category distinct from driver distraction. More specifically, the present approach adopts the view of Pettitt et al. (2005) and Regan et al. (2011), where inattention is sub-categorized in terms of processes giving rise to it. The conceptualization of inattention in terms of the inappropriate selection of activities rather than information is consistent with Hoel et al. (2010) and Regan et al. (2011). Moreover, in line with Klauer et al. (2006) and Regan et al. (2011), sleep-related impairment is included as a specific process giving rise to

[9] Other definitions of the set of *activities critical for safe driving* may be used without affecting the overall structure and logic of the taxonomy. However, this would critically determine in what situations the driver should be categorised as inattentive as well as the categorisation of different forms of misdirected attention (incomplete selection of safety-critical activities vs. driver distraction).

inattention, which can be motivated by the fact that sleep-regulation processes operate directly on the brain's attentional activation system. Finally, in line with most existing taxonomies, the present taxonomy distinguishes driver distraction from situations where attentional mismatches occur due to distribution of resources between safety-critical activities (here conceptualised as incomplete selection of safety-critical activities). The proposed definition of driver distraction is also consistent with those proposed by Lee et al. (2009) and the US-EU Driver Distraction and HMI Working Group (Binder et al., 2011). However, compared to existing approaches, the present taxonomy additionally introduces the systemic perspective and the mismatch concept to deal with hindsight bias and offers scientific grounding in the proposed conceptual framework of driver attention.

However, one potential problem with the present attempt to obtain a scientific conceptualization of driver attention and inattention is that it may deviate from the laypersons' view of the phenomena. In daily language, "attention" typically refers to the effortful, deliberate and conscious concentration of higher mental resources, which is also reflected in the dictionary definition quoted in Section 3. For example, we say that we should *pay attention* to driving. This general view of attention is also found in several mainstream scientific accounts of attention (e.g., Posner and Petersen, 1990). It is also evident in several of the definitions of inattention reviewed in Section 3, for example the one proposed by Wallén Warner et al. (2008): "Any condition, state or event that causes the driver to pay less attention than required for the driving task" (Wallén Warner, et al., 2008, p.12). In terms of the present framework, this refers to the activation aspect of attention, and specifically to the deployment of cognitive control. However, driving is a largely automatized task and, according to the present framework, this applies also to attention allocation. Thus, the traditional view would seem to exclude such automatized resource allocation from the concept of attention. Indeed, from a layperson's (and probably many scientists') perspective, it may seem strange to say that you could attend to something that you are not aware of. However, if automatized resource allocation is not included in the concept of "attention", we would lack a term for characterising this form of effortless resource allocation which is critical in natural, overlearned, tasks such as driving. Thus, we strongly suggest, in line with Trick et al. (2004), that a technical definition of driver attention also should cover automatized resource allocation.

Another, potentially more serious, deviation between the proposed framework and the layperson's view concerns the conceptualization of *inattention*. As discussed above, the term driver inattention, as used in daily language, is strongly associated with negligence and blame. This is also reflected in the dictionary definition quoted in Section 3. However, our conceptualization is deliberately intended to be blame neutral, characterising inattention strictly in terms of mismatches in the driver-vehicle-environment system as a whole. Thus, according to the present taxonomy, a driver with the right of way that collides with another vehicle suddenly crossing his path at an intersection may be labelled inattentive, even if our driver was not judged to be at fault (and hence is not blamed for the crash). This use of the term inattention may indeed seem odd to the layperson, as well as to policy makers. However, the alternative would be to assess inattention against some normative standard, but that would necessarily introduce some degree of arbitrariness and subjective judgement. A possible way out of this dilemma could be to introduce a different term, such as, e.g., "attentional mismatch", for the more technical meaning of inattention proposed here. However, we leave this as an issue for future consideration.

Finally, how can the proposed taxonomy be applied in practice to the three main application areas identified above? The first intended application was the definition of coding schemes for crash/near-crash analysis, including on-site, in-depth, crash analysis as well as naturalistic driving studies. As outlined in Section 2, such coding schemes need to be developed based on the purpose of the analysis and what is observable in the available data. The general idea is that the present taxonomy could serve as the conceptual basis for defining categories in the coding scheme related to driver inattention. Thus, for example, the present taxonomy suggests that insufficient attention should be distinguished from misdirected attention, and that driver distraction should be coded differently from other forms of misdirected attention that does not involve a diversion of attention away from safety-critical activities (i.e., incomplete selection of safety critical activities). However, the detailed operational definitions of the categories need to be defined in the specific coding scheme, depending on what's observable in the available data. Moreover, it should be emphasised that the present taxonomy in itself is of course not sufficient as the sole basis for the development of an entire coding scheme for incident/accident analysis, as it only covers aspects related to driver inattention.

The second intended application area was the design and interpretation of experimental studies addressing driver inattention, where the present taxonomy may help to conceptualise key constructs such as driver distraction and cognitive load, thus potentially enabling more precise experimental hypotheses. Moreover, it may facilitate more consistent interpretations of experimental results. The taxonomy could also be used in the context of standardisation of methods for measuring driver distraction. Finally, the taxonomy could aid the design and evaluation of vehicle systems intended to support attentive driving, such as, for example, collision warning, lane keeping support, drowsiness warning and distraction mitigation (see Engström and Victor, 2007; Victor, 2011). A key benefit here is that the taxonomy, and the underlying conceptual framework, allows for more precise characterisation of the attention-related problems that these systems and functions are intended to address. This should also help to define criteria for their evaluation.

The proposed taxonomy will be put to test when used for these practical applications. Indeed, it is foreseen that the taxonomy will need be iteratively updated based on feedback obtained from its application in various specific domains. Future versions of the taxonomy may also include more fine-grained categories. Moreover, as mentioned in Section 2, the taxonomy needs to evolve with technological and scientific advances. For example, the neuroscientific understanding of attention as well as techniques for measuring attention in the laboratory or in the field is moving forward rapidly today. Moreover, automated driving technologies are changing the nature of the driving task. Thus, the present taxonomy needs to be subject to future iterative refinement and modification based on how well it fares in capturing real-world phenomena.

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