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Heikoop, Daniël; de Winter, JCF; van Arem, B; Stanton, NA

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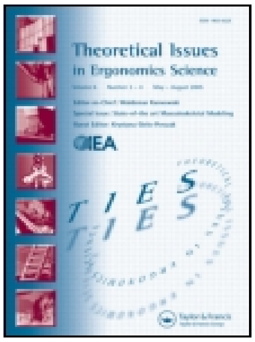

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Psychological constructs in driving automation: a consensus model and critical comment on construct proliferation

Daniël D. Heikoop[a], Joost C.F. de Winter [b], Bart van Arem[c] and Neville A. Stanton[a]

[a]Civil, Maritime, Environmental Engineering and Science, Faculty of Engineering and the Environment, University of Southampton, Southampton, Hampshire, UK; [b]Department of BioMechanical Engineering, Faculty of Mechanical, Maritime and Materials Engineering, Delft University of Technology, Delft, the Netherlands; [c]Department Transport & Planning, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, the Netherlands

ABSTRACT
As automation in vehicles becomes more prevalent, the call for understanding the behaviour of the driver while driving an automated vehicle becomes more salient. Although a variety of driver behaviour models exist, and various psychological constructs have been said to be influenced by automation, an empirically testable psychological model of automated driving has yet to be developed. Building upon Stanton and Young's model of driving automation, this article presents an updated model of interrelated psychological constructs. The proposed model was created based upon a systematic literature search of driving automation papers and a subsequent quantification of the number of reported links between a selected set of psychological constructs. A secondary aim of this article is to reach consensus in the use of psychological constructs regarding driving automation. Henceforth special attention is paid to resolving the issue of construct proliferation.

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Psychological constructs; driving automation; driver model; construct proliferation

Relevance to human factors/ergonomics theory

Much has been said about human factors constructs such as workload and situation awareness, and various models have been created that describe the interaction between human and automation as a function of such constructs. The present study was undertaken from a novel point of view, namely by investigating the prevalence of human factors constructs in the scientific literature. We focused our literature searches on the topic of automated car driving, a task that is both a safety critical task and of great societal importance. Accordingly, this article proposes a consensus-based psychological model of automated driving. Moreover, this article aims to critically discuss and resolve the issue of construct proliferation. In more practical terms, our work may provide impetus for the design of future empirical research on human factors of automated driving.

CONTACT Daniël D. Heikoop d.d.heikoop@soton.ac.uk

Introduction

Automation in vehicles is becoming increasingly prevalent. Defined as the execution by a machine agent (usually a computer) of a function that was previously carried out by a human (Parasuraman and Riley 1997), automation now has a major role in car driving. Present automation systems in cars range from ultrasonic or electromagnetic parking sensors that can inform the driver, to technology that can take over all longitudinal and lateral control tasks. Keeping in mind that the majority of vehicle accidents are caused by humans (e.g., Klauer et al. 2006; Treat et al. 1977), it is argued that automation serves as a potential solution for driver safety.

Automating certain driver tasks might increase driver safety on the assumption that human operations are replaced with an infallible machine. However, due to risk compensation (also called behavioural adaptation; for overviews, see Elvik 2006; Martens and Jenssen 2012; Wilde 1998), drivers may use automation in such a way that their behaviour changes (e.g., increasing speed, reducing headway, engaging in non-driving related tasks, etc.). Hence, more automation does not necessarily imply more safety. Another issue is that automation may result in mental overload in unforeseen circumstances (e.g., when automation fails and manual take-over is required), while mental underload is likely to occur during routine situations (Stanton and Marsden 1996; Young and Stanton 2002). A related concern is the lack of salient feedback from automation systems (Norman 1990; Saffarian, De Winter, and Happee 2012; Sarter, Woods, and Billings 1997). Humans are notoriously bad at sustaining attention for prolonged periods of time while supervising rare signals (e.g., Mackworth 1948; Molloy and Parasuraman 1996), yet, paradoxically, this is exactly what drivers of automated vehicles are required to do. Such examples are just the tip of the iceberg when it comes to understanding human factors and ergonomics (HF/E) issues in automated driving. The field would benefit from a model that can explain how drivers interact with their automated vehicles.

Thirty years ago, Michon (1985) performed a critical review of driver behaviour models, and distinguished four categories of models along two dimensions (behavioural vs. psychological, and taxonomic vs. functional). Michon argued that taxonomic-behavioural task analysis models do not account for the dynamic and complex environment of the driving task, and are therefore inadequate for modelling driver behaviour (Michon 1985; Ranney 1994). Alternatively, De Winter and Happee (2012) argued taxonomic-psychological (i.e., trait) models are a promising type of model, if developed through multivariate statistical approaches such as exploratory factor analysis (EFA) or structural equation modelling (SEM). Functional−behavioural models such as information flow control and adaptive control models focus on the physical motion of vehicles, without much consideration of drivers' motivations and cognitive processes. Hence, such models are less useful for understanding *why* drivers behave the way they do. Furthermore, most adaptive control models tend to be mathematically intricate, with limited generalizability (De Winter and Happee 2012; see also Sheridan 2004). The final category in Michon's (1985) overview contains functional−psychological models, focusing on driver motivation (e.g., Wilde 1998) or cognitive processes (e.g., Bellet, Bailly-Asuni, Mayenobe, and Banet 2009). Motivational models have a long history in the field of traffic psychology (Vaa 2007), and describe the products of cognitive functions, such as beliefs and emotions (Michon 1985). Although valuable, motivational models lack specificity and are therefore considered inadequate for modelling driver behaviour (De Winter and Happee 2012). The cognitive process approach is considered by Michon (1985) to be an important approach in driver modelling, with the Adaptive Control of Thought–Rational (ACT-R) being one of the more popular methods (Anderson and Lebiere 1998; Salvucci 2006).

In order to understand and predict how people behave while driving automated vehicles, it is important to develop psychological models of driving with automation (Michon 1993; Stanton and Young 2000). Michon's (1985) categorization of driver behaviour models is concerned with non-automated vehicles. A few previous attempts have been made to develop psychological models for driving automation (e.g., Boer and Hoedemaeker 1998; Stanton and Young 2000), but despite rapid advances in vehicle automation technology and user uptake over the last two decades, an updated psychological model of driving automation is lacking.

Outside the domain of driving, several psychological models of human–automation interaction exist. Most of these models either describe automation psychology in general, thereby not addressing specific characteristics of the car driving task (e.g., Dzindolet et al. 2001; Parasuraman, Sheridan, and Wickens 2000; Riley 1989; Sanchez 2009), and/or have a narrow scope as they address only a small number of psychological constructs (e.g., Endsley 1995; Lee and See 2004; Muir 1994; Parasuraman and Manzey 2010). For example, a model by Wickens, Lee, Liu, and Gordon-Becker (2004) qualitatively described the relationships between the psychological constructs trust and complacency in relation to automation use and automation reliability. This is a useful approach, but ignores other relevant constructs, such as mental workload and situation awareness.

This article is based upon a psychological model of driving automation developed by Stanton and Young (2000; Figure 1). When placing it into Michon's (1985) framework,

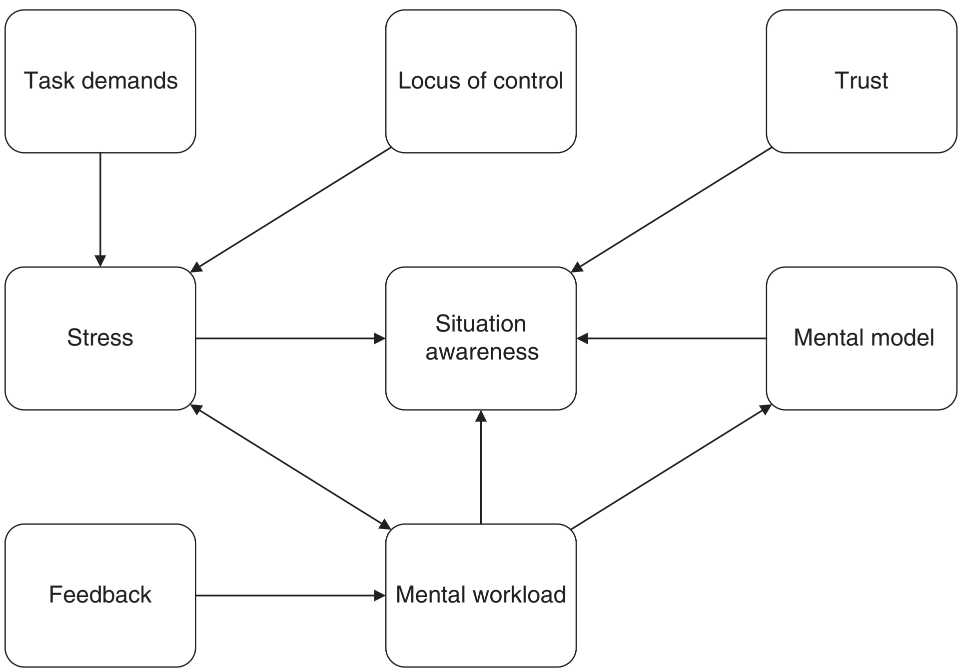

Figure 1. A proposed psychological model of driving automation (from Stanton and Young 2000).

the model of Stanton and Young (2000) can be categorised as a functional−psychological model, as it contains psychological constructs from both a cognitive (e.g., mental workload) and motivational (e.g., locus of control) perspective. One could also argue that it resembles a trait model approach, as their model also covers psychological constructs that were considered by some as psychological traits, for instance trust (e.g., Lee and See 2004). The psychological constructs of the Stanton and Young (2000) model were used as a basis for a literature search, with the aim of developing an updated psychological model of driving automation.

Stanton and Young (2000) used a theoretically oriented approach for the development of their model, using prominent literature of the time that presented results and discussions concerning the influences of automation on certain psychological constructs. Specifically, based on an earlier review by Stanton and Marsden (1996), Stanton and Young (2000) followed a deductive train of thought to identify psychological issues with vehicle automation, on which they built their psychological model of driving automation. Stanton and Young (2000) also provided a narrative review of these key psychological constructs, and correctly predicted that vehicular automation would have a major impact in the years to come. However, although Stanton and Young (2000) described the constructs used in their article in much detail with respect to their interrelationships, the model they proposed does not depict whether these interrelationships are causal or correlational, and whether the signs of the effects are positive or negative. Implementation of this type of information would be a welcome addition to such a model.

The aim of the present review was to create an updated, testable version of the model developed by Stanton and Young (2000). The unique aspect of our approach is that it is descriptive and atheoretical. Meaning we measured how frequently key psychological constructs, as well as pairs of constructs, are reported in the scientific literature on automated driving. Based on this numeric information, we devised a model describing the interrelationships between the constructs. Hence, our approach offers a consensual description of the literature on the psychology of automated driving.

Method

In their model (Figure 1), Stanton and Young (2000) used eight psychological constructs that were considered to have a critical impact upon behaviour when driving with automation: (1) Situation Awareness, (2) Mental Workload, (3) Mental Model, (4) Feedback, (5) Locus of Control, (6) Stress, (7) Task Demands and (8) Trust. The following seven extra constructs were also selected for the literature search: (9) Attention, (10) Vigilance, (11) Satisfaction, (12) Acceptance, (13) Arousal, (14) Complacency and (15) Fatigue. As opposed to the constructs used in the model of Stanton and Young (2000), which are primarily involved with short-term effects on driving psychology in automation, the seven extra psychological constructs serve to address the long-term effects (i.e., minutes to hours) on driving psychology in automation. We reasoned that the seven extra constructs are a welcome supplement, because it is likely that automated driving will be first deployed on highways (e.g., Bishop 2005), where long-term use of automation is expected.

The eight constructs used in the Stanton and Young model (2000), together with the seven supplementary constructs, were submitted to Google Scholar using Harzing's 'Publish or Perish' software (version 4.10.1.5395; 8 October 2014). The use of Google Scholar over other academic search engines is advantageous, because Google Scholar is the only major academic search engine providing full text search (cf. Web of Science and Scopus, which only search abstracts). Furthermore, Google Scholar provides a substantially wider coverage of the scientific literature than other academic search engines (De Winter, Zadpoor, and Dodou 2014; Gehanno, Rollin, and Darmoni 2013; Shariff et al. 2013). As a result Google Scholar also includes articles of lesser quality. To overcome the issue of literature quality a manual filtering method was applied and is described below.

Together with three domain-specific search terms (i.e., 'Driving Automation', 'Driver Automation' and 'Automated Driving') all possible unique combinations of the aforementioned constructs were used as search queries (a search query was for example: 'Driving Automation' AND 'Situation Awareness' AND 'Feedback'). With 3 domain-specific terms and 15 psychological constructs, $3^*((15^*14)/2)$ unique combinations were possible, which yielded a total of 315 searches.

To make a distinction between articles of better quality and of lesser quality, a filter of a minimum of 10 citations per article was used as a threshold. These results were then filtered for duplicates, which resulted in a total of 224 unique articles containing any combination of two different constructs within the three domain-specific terms, henceforth referred to as driving automation. Patents and 'citations' (i.e., results that were displayed as either a patent or a citation in Google Scholar) were manually removed, as well as some obvious false positives (i.e., articles that were not about driving automation) and duplicates (i.e., articles that were dissimilar according to the results of the search tool, but after examination appeared to be similar).

Of the resulting articles, the abstracts were read. Once an abstract of an article referred to either a link between constructs, or to an investigation of two or more constructs, thereby showing a possibility of mentioning a link between constructs, the entire article was read. Whenever a link between constructs was mentioned, this link was noted down. A link could entail (1) the results of empirical or theoretical studies, (2) inferences made by authors based on previous (empirical or theoretical) studies, or (3) references to previous articles. This last option was seen as an acknowledgement of the existence and viability of this link by the author(s), thus reinforcing the link. The above process resulted in 43 unique articles mentioning a link between at least 2 of the 15 constructs.

In order to create an interpretable and parsimonious model, certain decisions had to be made as to whether or not to include each construct in the model. A simple counting scree plot (Figure 2) was used to assess the prevalence of each construct within the retrieved literature.

The constructs after the *cut-off point* (i.e., Arousal, Complacency, Vigilance, Locus of Control, Acceptance and Satisfaction) are henceforth left out of the model. A brief description of the psychological constructs used in our model is provided in Table 1. These definitions and descriptions were selected from the field of HF/E.

The construct with the widest variety of definitions was Mental Workload. The definition provided by Hart and Staveland (1988) is used in this article, as this definition applies best to the way the construct is being seen and used in this review, that is, Mental Workload being a human-centred construct rather than task-centred (Hart and Staveland 1988). As for the construct of Feedback, one has to take into account that feedback is usually considered as automation-induced (e.g., visual or auditory signals), but can also be from the driving environment (e.g., seeing a car approaching, or hearing the engine is in

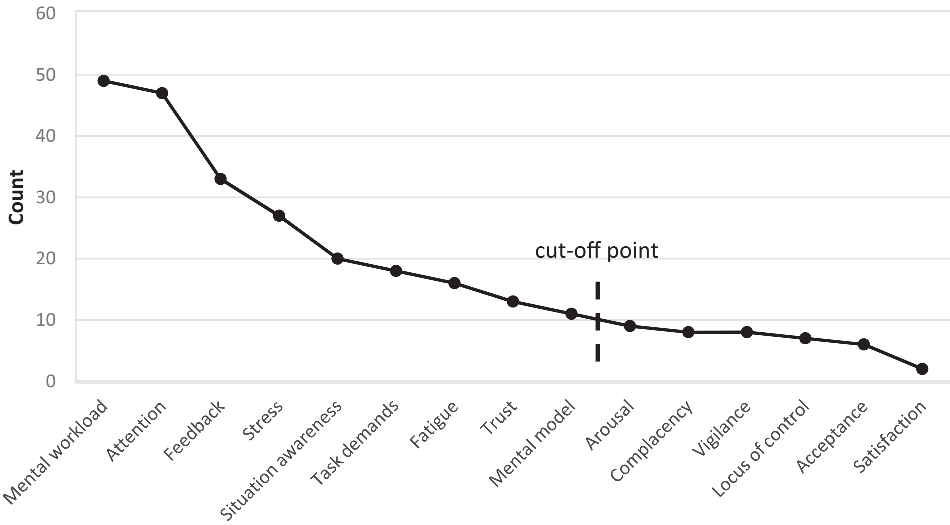

Figure 2. Scree plot of the constructs used for the development of the psychological model of driving automation, derived from the 43 unique articles that resulted from the literature search. The count represents the number of times the construct was used in reference to a link with another construct viable for use in the model, that is, including a direction (which construct influences which construct?) and sign of the effect (does the one construct have a positive or negative relationship with the other construct?). The cut-off point was set at 10 counts.

the wrong gear). In this review, the articles used in the development of the model only refer to feedback as a form of automation-induced feedback.

Results

The results of the literature search are shown in Table 2. The aim of this literature search was to determine causal links between constructs. Therefore, any mention of a link between constructs with a specific direction is thought to be causal. The constructs on the left hand side are the starters of a causal link towards the constructs on the top. This link is either a positive (1/0) or negative causal link (0/1). Table 2 does not show links mentioned or inferred in the articles without either a direction or a sign of effect. As this research is concerned with a psychological model of driving automation which can be empirically tested, it has a need for directions and signs of effect of links.

Table 2 clearly identifies two standout links; the positive causal links from Mental Workload and Task Demands to Attention (13 and 7 counts, respectively). Furthermore, Feedback appears to have a causal link towards Situation Awareness, Mental Workload, and Attention. There does not seem to be a consensus on the sign of the effect, which can be explained by the type of Feedback (i.e., proper or improper) used in the research. For example, Coughlin, Reimer, and Mehler (2009) suggested that Feedback can be either distracting or attracting Attention depending on the form of Feedback.

Our psychological model on driving automation is shown in Figure 3, and consists of the constructs mentioned above, with their inferred relation to each other. During the development of this model certain inevitable subjective decisions had to be made, and various

Table 1. The nine psychological constructs used in the development of the updated model of driver psychology in automation, including definitions and references to key sources. In quotation marks are proper definitions given by their corresponding reference, whereas text without quotation marks are descriptions based on our inferred consensus in the literature.

Construct name	Definition/key description	Source
Situation awareness	'… the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future.''… knowing what's going on so you can figure out what to do'	Endsley (1988) Adam (1993)
Mental workload	A generally accepted definition does not exist, because of its applicability in a wide array of fields. 'A hypothetical construct that represents the cost incurred by a human operator to achieve a particular level of performance.'	Young et al. (2014) Hart and Staveland (1988)
Mental model	A mental model (MM) is a dynamic representation of the world. The concept dates back to 1943 where Craik mentioned a 'small-scale model' of the external reality. 'In interaction with the environment, with others, and with the artefacts of technology, people form internal, mental models of themselves and of the things with which they are interacting.'	Johnson-Laird (1980) Norman (1983)
Feedback	A definition of feedback is usually dimensionalised, as it can be either quantitative or qualitative, as well as informational or motivational.	Norman (1990)
Stress	'Everyone knows what stress is, but nobody really knows.' 'Stress is the nonspecific response of the body to any demand made upon it.' In this field it is thought to be part of a group of conceptually similar constructs in which these are influenced by disturbances the traffic environment causes.	Selye (1973) Matthews (2002)
Task demands	'The external demand, the goals that have to be reached, …'	De Waard (1996)
Trust	Various approaches towards defining trust exist, ranging from it being an attitude or expectation, an intention or willingness to a behavioural result or vulnerable state.	Lee and See (2004)
Attention	'There are two kinds of attention. Selective attention determines our ability to focus on certain sources of information and ignore others: … Divided attention determines our ability to do more than one thing at once, …'	Proctor and Van Zandt (2011)
Fatigue	'Physiological fatigue is a loss of maximal force-generating capacity during muscular activity or a failure of the functional organ. … Psychological fatigue … has been defined as a state of weariness related to reduced motivation.'	Shen, Barbera, and Shapiro (2006)

alternative hypotheses had to be considered. The detailed description of the steps that follows will help the reader understand and replicate the decisions made during this process.

Intermediate steps between psychological constructs

As many articles focus on different aspects of driver psychology, certain intermediate steps are prone to be overseen, resulting in a wide spread of interrelations. For example, one article may have mentioned a link between Situation Awareness and Mental Workload, and another article between Situation Awareness and Attention. Both articles may be correct, but one link may be an intermediate step within the other (e.g., Mental Workload → Attention → Situation Awareness). This aspect must be taken into consideration when developing a psychological model on driving automation. The results of this consideration are to be seen when comparing Table 2 with Figure 3. In the model shown in Figure 3, Task Demands are not directly linked to Attention, whereas Table 2 shows seven articles mentioning a direct positive causal link. However, after examination of these articles, most articles mentioned a task or construct that involves some form of Mental Workload in between Task Demands and Attention. As Mental Workload is composed of three elements, called (1) cognitive, (2) perceptual (i.e., visual, auditory, etc.), and (3) psychomotor workload (McCracken and Aldrich 1984), tasks or constructs mentioned in those articles can often be considered as an element of Mental Workload. For example, Beede and Kass (2006) reported that using a phone and making decisions are examples of (cognitively) demanding tasks, whereas Collet, Guillot, and Petit (2010) referred to motor actions which can be seen as an aspect of (psychomotor) Mental Workload, and Stanley (2006) used a combination of both physical movement (looking over one's shoulder) and Mental Workload (remembering letters on a card). In summary, authors have often stated

Table 2. Causation table between psychological constructs in driving automation. Each count represents an article mentioning a link between two constructs. The constructs on the left influence the constructs on the top either positively (1/0) or negatively (0/1).

	Situation awareness	Mental workload	Mental model	Feedback	Stress	Task demands	Trust	Attention	Fatigue
Situation awareness			1/0						
Mental workload	2/4				5/0			13/1	2/3
Mental model	3/0						2/0	1/0	
Feedback	2/2	3/4	1/0		0/2		0/2	3/5	0/1
Stress	0/1	1/0						0/3	
Task demands		3/0			4/0			7/0	0/3
Trust	0/1				0/1			0/1	
Attention	4/0	3/0	1/0						
Fatigue					5/0			0/1	

Note. For example, if an article mentions that Stress increases when Trust decreases, it would indicate that Trust has a negative causal influence on Stress. This would be displayed here as (0/1) in the table that joins Trust at the horizontal plane and Stress at the vertical plane.

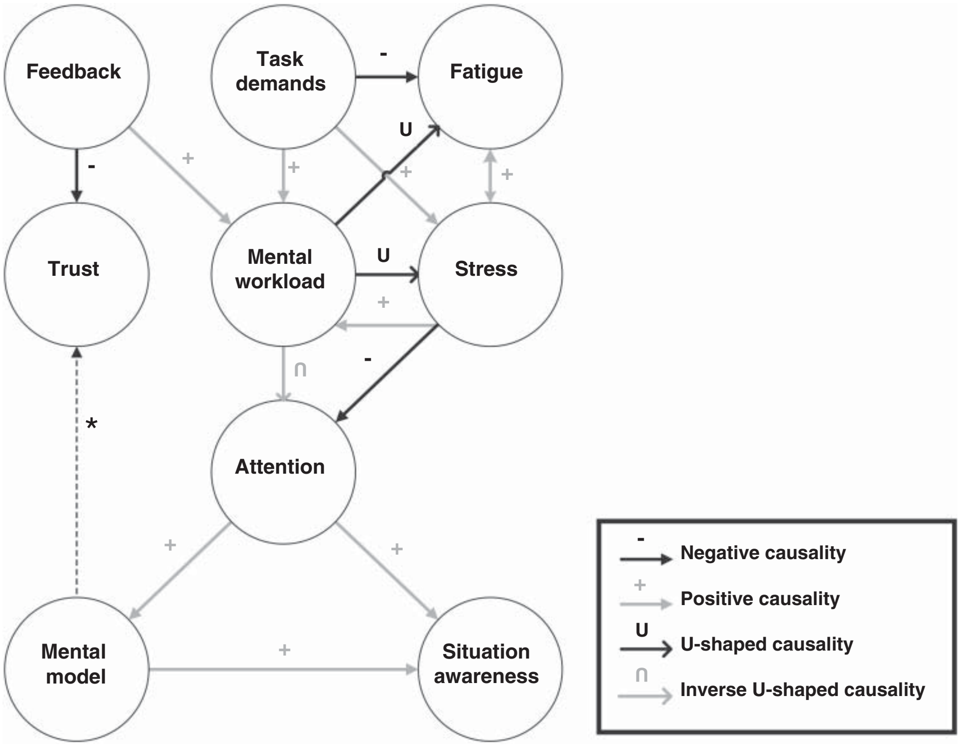

Figure 3. The proposed updated psychological model of driving automation. It incorporates the interconnectedness of the constructs, similar to the model of Stanton and Young (2000), but adds a flow-like type to it for testability purposes. A black solid arrow indicates a negative causal link (e.g., when less Task Demands are being requested from the driver, more Fatigue is considered to be experienced by the driver). A grey solid arrow indicates a positive causal link. A black open arrow indicates a U-shaped causal link (e.g., both low and high Mental Workload evoke Stress), and, conversely, a grey open arrow indicates an inversed U-shaped causal link. *The development of a Mental Model can recalibrate the trust towards the automation over time.

that they gave the participants a task (Task Demands) which in turn influenced Attention. What they did not explicitly mention is that these tasks were also cognitively/perceptually/psychomotorically demanding, as in requiring (some form of) Mental Workload. Hence, the conclusion was drawn that Task Demands influence Mental Workload, which in turn influences Attention.

Another feature of the model in Figure 3 is the absence of a direct link between Mental Workload and Situation Awareness. Stanton and Young (2005) concluded that Mental Workload influences Situation Awareness, but explained that Situation Awareness is comprised of various types of Attention. The relations between Attention, Situation Awareness, and Mental Workload have also been described in other articles (Matthews 2002; Stanton and Young 1998; Vahidi and Eskandarian 2003). Furthermore, Stanton and Young (2000) discussed the construct Attention, but did not include it in their model.

Similarly, a closer examination of the articles that mentioned a link between Feedback and Situation Awareness led us to believe no direct relation exists, but rather that Mental Workload acts as a mediator variable, which influences Attention to establish Situation

Awareness, as explained by Stanton and Young (2005). This is also supported by Endsley (1995, 2000, 2015) who discussed how automation influences the attention requirements that are important for developing Situation Awareness.

Also, Stress and Fatigue have been represented differently in Figure 3 than in Table 2. This is largely due to the fact that Stress and Fatigue are very much related (Desmond and Matthews 2009; Matthews 2002; Saxby, Matthews, Hitchcock, and Warm 2007) and therefore have similar characteristics (Desmond and Matthews 2009).

Construct proliferation

Another issue encountered during the development of our driver model is the phenomenon of construct proliferation. That is, researchers may mistakenly assume that two highly correlated variables are unique constructs, while in reality they are one and the same construct. A review with examples on construct proliferation in psychology was performed by Schmidt (2010), in which he explained researchers often postulate new constructs, giving a false sense of differentiation. Ironically, the literature about this phenomenon suffers from construct proliferation itself, also coining terms such as construct redundancy (e.g., Le, Schmidt, Harter, and Lauver 2010; Singh 1991).

In the field of driving automation psychology the most prevalent occurrence of construct proliferation is with the construct Mental Workload. We encountered terms such as driver workload (Carsten and Nilsson 2001; Flemisch et al. 2008; Funke, Matthews, Warm, and Emo 2007; Schieben, Damböck, Kelsch, Rausch, and Flemisch 2008), mental (over-/under-)load (Funke et al. 2007; Stanton, Dunoyer, and Leatherland 2011; Young and Stanton 1997), cognitive load (Carsten and Nilsson 2001), or just simply over- (Coughlin, Reimer, and Mehler 2009; Matthews et al. 1999; Stanton, Dunoyer, and Leatherland 2011; Young and Stanton 1997) or underload (Navarro, Mars, and Young 2011; Young and Stanton 1997). This is just a selection of different uses which in fact can all be put under the same construct, in this article called Mental Workload (for further read, see McCracken and Aldrich 1984). An overview of the varieties of psychological constructs used in this review is shown in Table 3.

Table 3. List of psychological constructs from Figure 2 with corresponding varieties and references to their use. Corresponding references are shown between brackets in the reference list.

Original construct	Varieties	References
Situation awareness	Situation awareness	[3,6,18,24,25,33,34,35,36,37,38,40]
	Situational awareness	[3]
	Awareness of the status	[20,32,38]
	Aware	[35]
Mental workload	Mental workload	[12,13,16,33,39,40,41,42]
	(visual) perception	[1]
	Mental/cognitive processing	[1]
	(driver) work/mental/cognitive/over-/underload	[1,6,10,12,14,15,17,18,20,23,24,26,30,32,34,35,38,39,40,41,43]
	(mental) demand(s)	[8,31,35]
	… decision making …	[2,3,36]
	Cognitive resources	[3]
	Cognitive activity/task	[9,25]

(*continued*)

Table 3. (*Continued*)

Original construct	Varieties	References
	Listening to the radio (auditory)	[9]
	(demands on) supervisory management	[18]
	Mentally capable	[21]
	Working memory	[23,36]
	Monitoring (demands)	[24,35,42]
Mental model	Mental model	[3,20,22,29,33,34,36,40]
	Mental representation	[3]
	Conceptual model	[17]
	Mental theory	[37]
	knowing how something behaves	[40]
Feedback	Feedback	[10,14,17,26,30,33,34,35,39,40]
	In-vehicle systems (e.g., ADAS)	[1,6,12,26,29,35,38,40]
	Provision of information	[5,21,22]
	Alerting methods (e.g., haptics)	[10]
	(False) Alarms/warnings	[17,20,26,27,31]
Locus of control	Locus of control	[19,26,29,33,37,40]
	'Externals'/'Internals'	[34]
Stress	Stress	[5,10,12,15,23,24,26,32,33,34,35,40,41]
	Over arousal	[10]
	Distress	[12,15,23,24,43]
	Tenseness	[37]
Task demands	Task demands	[11,15,23,24,33,35,39,41]
	Tasks that require …	[1]
	… in demanding … situations …/ … demand(s)	[2,12,28,39]
	The … task/ … tasks	[9,11,18,23,31,32,34]
	Workload	[40]
Trust	Trust	[4,16,17,19,20,22,23,26,29,31,33,40]
Attention	Attention	[1,2,3,5,7,9,10,13,15,17,18,20,21,22,24,25,26,29, 31,32,33,36,37,38,39,40,41,42]
	Attentional resources/processes	[3,9,16,17,25,26,35]
	(distracting)	[10]
	(attentional deficit)	[17]
	(attentional shrinkage)	[26]
Vigilance	Vigilance	[5,7,9,18,23,25,28,33,35,39,41]
	Attentive	[34,37]
	(…)mobilization	[11]
Satisfaction	Satisfaction	[13,27,40]
	Acceptance	[27]
Acceptance	Acceptance	[5,10,13,14,17,20,27,31]
	Accepted	[13]
	Satisfaction	[27]
Arousal	Arousal	[7,8,10,18,28,33,41]
	Alerting stimulation	[10]
	Activation	[41]
Complacency	Complacency	[11,16,17,23,24,29,33]
	Abdicate	[4]
	Reliance	[6]
	Misplaced trust/overtrust	[40]
Fatigue	Fatigue	[10,11,12,15,18,23,24,26,28,32,34,35,42,43]

Note: Please see online supplemental file for the references cited in this table

Discussion

Limitations of the consensus model

During the development of our model of driving automation, it has become clear that a descriptive literature-based approach is challenging for several reasons. First of all, during the literature search, the issue of construct proliferation arose. The development of the model required some subjective decisions, particularly due to the fact that the included articles had different scopes. Hence, certain assessments had to be made concerning interpretation of terms and phrases shown in Table 3. The authors acknowledge that the phenomenon of construct proliferation could have led to misinterpretation of results or inferences made in this review.

A second limitation is that we set a cut-off mark at 10 counts of links (Figure 2), which may be seen as a somewhat arbitrary decision. However, we argue that in *any* statistical model a trade-off has to be made between model complexity (i.e., number of constructs included) and model comprehensiveness (i.e., representativeness of the literature). This situation is the same in EFA where deciding on the number of factors to retain is essentially a model selection problem (Preacher, Zhang, Kim, and Mels 2013). There has been considerable debate in the statistical literature about how to interpret scree plots and how to create appropriate cut-off criteria (e.g., Fabrigar, Wegener, MacCallum, and Strahan 1999). In summary, the cut-off mark we selected should be seen as an appropriate solution, not necessarily the only valid solution.

As a third limitation, we acknowledge that the interpretations made in this review of the links inferred in the articles are subject to the risk of inferring causality from correlation. However, the emphasis within the review was on developing a model based on causal relations. Therefore, only relationships that were regarded as causal have been used for the development of the model, whereas correlations have been disregarded, as correlation does not imply causality. The links used for the model were based on either empirical, theoretical, or deductive evidence. Some of the relationships were more ambiguously described than others, which increased the risk of misinterpretation.

A final limitation is that consensus does not imply 'truth' or 'most appropriate', because what researchers do in their experiments and report in their articles may be much influenced by the availability heuristic. For example, it is possible that some constructs are highly used by researchers for the simple reason that others have also used them, thereby contributing to self-reinforcing behaviour, or the 'Matthew effect' (Merton 1968). It is also possible that some constructs are used more than others for the reason that they can be more easily observed and measured (Dekker and Hollnagel 2004). For example, Stress can be determined using a user-friendly self-report questionnaire such as the Dundee Stress State Questionnaire (DSSQ; Matthews et al. 1999), whereas other types of constructs, such as Attention, may require the application of cumbersome and expensive techniques, such as eye-tracking systems. Furthermore, since driving automation is a relatively new domain, newly arising constructs might be underrepresented compared to well-established constructs. Relatedly, the 10-citations threshold may be disputed as a means of filtering article quality. It is acknowledged that this threshold discriminates against recent and poorly accessible articles (e.g., articles that are not available online, or articles that are not published in open-access journals). However, recently published articles are not yet well-established, so by definition they do not belong in a consensual model.

Despite these limitations, the clear strength of our review is its descriptive 'consensual' approach, rather than it being based on personal theorizing. In other words, the exact aim of our research was to determine how psychological constructs *are* used, and not to determine how they *ought* to be used. Our approach to this review may be regarded as unusual in the sense of theory building and critical analysis. However, since our approach is relatively atheoretical, the insights this may bring should serve as a complement to the many existing theoretically oriented driver models (e.g., Michon 1985; Ranney 1994), and might therefore be important to the scientific community. Furthermore, the validity of the updated model is supported by the fact that it contains certain well-known relationships, such as Mental Workload and Task Demands having a positive causal link with Attention. With this in mind, it should be repeated that the updated model is not a definite statement, but rather a proposal based on what the literature infers regarding the intricate psychology of driving an automated vehicle.

Characteristics of the consensus model

Despite the issues mentioned above it was possible to develop an updated psychological model of driving automation that provides interesting insights as well as new directions towards future research. For instance, although the Stanton and Young (2000) model was proposed fifteen years ago and not based on a systematic literature search, their model and ours show a high degree of similarity regarding their structure. Although many similarities appear, our updated model contains more detail concerning the interrelations of the psychological constructs within the model. Primarily, the implementation of directions and signs of effect to the links between the psychological constructs in the model might serve as a welcome addition in comparison to the Stanton and Young (2000) model, as this gives direction to future empirical research as to how these psychological constructs relate to each other.

Many types of psychological models of driving behaviour exist (Michon 1985). The same applies to psychological models of automation (e.g., Dzindolet et al. 2001; Endsley 1995; Lee and See 2004; Muir 1994; Parasuraman and Manzey 2010; Parasuraman, Sheridan, and Wickens 2000; Riley 1989; Wickens et al. 2004). However, models that link psychological constructs in the driving automation domain are rare. Stanton and Young (2000) proposed a psychological model of driving automation based on the existing literature, a model that formed the foundations of the present article. By means of a thorough literature review, we developed a new model of driving automation (Figure 3), in an attempt to validate and expand the proposed model of Stanton and Young (2000). Our review attempted to describe a general consensus amongst researchers, concerning the interplay between psychological constructs in driving automation. However, it was not expected that the results, definitions and use of the constructs would be as widespread as they appear to be. In light of the issue of construct proliferation, it must be stressed, as was previously by Schmidt (2010) that the use and misuse of constructs may lead to inconsistent or even false data. Future research could try to tackle the problem of construct proliferation, for example by assessing convergent and divergent validity using the multitrait-multimethod matrix approach (Campbell and Fiske 1959).

Recommendations for future research

The model proposed in this review was developed based on existing literature and hence not empirically tested. Furthermore, this model was designed to fit specifically within the domain of driving automation. An extension of the model with important non-psychological constructs (e.g., ability, authority) and legal issues such as responsibility might increase its applicability.

Observable measures such as performance, behaviour, and safety (i.e., incidents and accidents) were not included in the model either. We argue that the psychological status of the driver is at the root of the causal tree. By this we mean that a driver's psychological status in the automated vehicle (e.g., the driver's level of Situation Awareness) will likely determine how effectively he/she will perform in a take-over scenario, which in turn determines the risk of collisions. We decided to not model such effects, but believe that our model could in principle be extended and thereby become a potential predictor of performance, behaviour, and safety.

Additionally, future research might investigate whether the model can be adjusted for application to other domains, such as aviation. However, caution should be taken with this approach. For example, the field of aviation (with professional pilots performing highly procedural work) is fundamentally different from the automotive domain (with high degrees of freedom for drivers who usually have received only basic training; see e.g., Wheeler and Trigs 1996).

In an attempt to test our newly proposed psychological model of driving automation, each part of the model could be assessed through empirical investigations. These investigations may take the form of using driving simulator technology with self-report questionnaires and psychophysiological measurements, such as eye trackers (e.g., Merat, Jamson, Lai, and Carsten 2012; Jamson, Merat, Carsten, and Lai 2013) or heart rate measurements (e.g., Brookhuis and de Waard 2010), and assess two or more of the psychological constructs to determine their interrelations.

For example, it is possible to change the level of automation (in the likes of Jamson, Merat, Carsten, and Lai 2013) or to alter the characteristics of a platoon (cf. Skottke, Debus, Wang, and Huestegge 2014), and to investigate the impact this has on the psychological constructs. Banks, Stanton and Harvey (2014) emphasised several concerns regarding the changing role of the driver due to increasing amounts of subsystems within automated vehicles. These authors pointed out that driving automation may entail a change or increase of the monitoring environment for the driver. Hence, it is acknowledged that not only the degree of automation, but also the number of subsystems to interact with, is an important subject to take into account.

Experiments could also investigate the impact of different types of secondary tasks (e.g., verbal vs. spatial tasks; see Young and Stanton 2007) on the correlations between a set of psychological constructs. Proposals to variations in experimental manipulations are thus plentiful, but one cannot ignore variations in individual differences, which may be as plentiful and important to understand (Cronbach 1957).

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Supplemental data

Supplemental data for this article can be accessed here.

About the authors

Daniël D. Heikoop received his MSc degree in applied cognitive psychology from Utrecht University in 2012. He is currently a PhD candidate at the Delft University of Technology, Delft, the Netherlands, and working at the University of Southampton, being involved in the Marie Curie Initial Training Network funded project HF-AUTO. Within this project, he focuses on human psychology and behaviour in highly automated platoons, using psychophysiology to assess interrelationships between psychological constructs in that domain.

Joost C. F. de Winter received his MSc degree in aerospace engineering and PhD degree (cum laude) from the Delft University of Technology, Delft, the Netherlands, in 2004 and 2009, respectively. He is currently an assistant professor at the Department of Mechanical Engineering, Delft University of Technology. His research interests include human factors and statistical modelling, including the study of individual differences, driver behaviour modelling, multivariate statistics, and research methodology.

Bart van Arem received his MSc and PhD degrees in applied mathematics, specialising on queuing theory from the University of Twente, Enschede, the Netherlands, in 1986 and 1990, respectively. From 1992 to 2009, he was a researcher and a programme manager with TNO, working on intelligent transport systems, in which he has been active in various national and international projects. Since 2009, he has been a full professor of transport modelling with the Department of Transport and Planning, Delft University of Technology, Delft, the Netherlands, focusing on the impact of intelligent transport systems on mobility, in particular cooperative and automated driving.

Neville Stanton, PhD, DSc, is both a chartered psychologist and a chartered engineer and holds the Chair in Human Factors in the Faculty of Engineering and the Environment at the University of Southampton. He has degrees in psychology, applied psychology, and human factors engineering. His research interests include modelling, predicting, and analysing human performance in transport systems as well as designing interfaces between humans and technology. Prof. Stanton has been working on cockpit design in automobiles and aircraft over the past 25 years, in a variety of automation projects. He has published over 30 books and 240 journal papers on ergonomics and human factors, and is currently an editor of the peer-reviewed journal Ergonomics. The Institution of Ergonomics and Human Factors awarded him The Otto Edholm Medal in 2001, The President's Medal in 2008, and The Sir Frederic Bartlett Medal in 2012 for his contribution to basic and applied ergonomics research. The Royal Aeronautical Society awarded him and his colleagues the Hodgson Prize and Bronze Medal in 2006 for research on the design-induced flight-deck error.

ORCID

Joost C.F. de Winter http://orcid.org/0000-0002-1281-8200

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