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Is the take-over paradigm a mere convenience?

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ABSTRACT

The last decade has seen a surge of driving simulator research on automation-to-manual take-overs. In this commentary, we argue that most research within the take-over paradigm bears little resemblance to real automated driving. Furthermore, we claim that results within this paradigm could already be known based on published research from the previous century. It is concluded that take-over studies have characteristics of a self-sustaining convenience. We end with recommendations for out-of-the-box take-over research that may contribute to the development of safer automated vehicles.

1. Introduction

In his work “The structure of scientific revolutions”, Thomas Kuhn argued that knowledge generation is not necessarily cumulative. He postulated that scientists operate within paradigms, defined as the theoretical frameworks and methods that a scientific discipline takes for granted. Within the constraints of the paradigm, scientists conduct ‘normal science’, i.e., puzzle-solving activities without questioning the paradigm’s validity. Kuhn’s philosophy of science offers a less honorable view of science than preceding views that regarded science as a rationally driven process towards absolute truth. According to Kuhn, scientific progress involves elements of irrationality.

In line with Kuhn’s philosophy of science, this commentary argues that a paradigm has entered the human factors literature during the past seven years: the take-over paradigm of automated driving. Our commentary on this paradigm is analogous to previous critiques of human factors research, particularly Dekker and Hollnagel (2004). They lamented that “the ease by which measurement tools can be developed does not necessarily reflect the significance or validity of that measurement” (p. 83). The present work is written in the form of critique to stimulate the exchange of thought and hopefully advance the field.

2. The take-over paradigm of automated driving

The take-over paradigm appears to have started with a paper by Gold et al. (2013), entitled “Take over! How long does it take to get the driver back into the loop?”. Gold et al. measured how quickly drivers, who were performing a visually demanding non-driving task, took control of an automated vehicle with time budgets of 5 and 7 s. To this day, Gold et al. accumulated 525 citations according to Google Scholar, indicating its significant impact.

A meta-analysis by Zhang et al. (2019) documented no fewer than 129 take-over studies published up until December 2018, 96% of which were conducted in a driving simulator. These studies included investigations into how quickly drivers took over control in take-over situations for different independent variables (time budget, take-over request modality, scenario complexity, etc.). We estimate that currently, at least 200 experiments have been published within the same paradigm. This lower estimate is based on the observation that in 2019 and 2020 alone, 71 “automated driving” records with the words “take over” in the title were found via Google Scholar.

It is remarkable that such a large number of studies have been published on the same take-over topic. In comparison, for other types of vehicle automation, such as cruise control, hardly any human factors studies are available at all (with Vollrath et al., 2011 being the only exception). This makes us wonder why so many researchers have jumped onto the take-over bandwagon and why they appear to consider this paradigm so attractive.

3. Is take-over research realistic?

First, it is important to ask the question of whether the assumptions of the take-over paradigm are realistic. Several critical remarks can be made about the realism of this paradigm.

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In current self-driving test vehicles in the United States, such as the vehicles of Waymo, there is a safety driver on-board. This safety driver, who is trained and supposed to be alert, has to intervene if the situation might turn dangerous. A recent paper by Boggs et al. (2020) illustrates that safety drivers have important roles. Their analysis of 159,840 disengagements showed that three-quarters of the disengagements were human-initiated rather than system-initiated. In other words, in current prototypes, human safety drivers intervene before the automation has recognized a discrepancy and a take-over request can be issued. Of course, the safety driver may err, as was demonstrated in the well-documented fatal Uber accident (Stanton et al., 2019). The meta-analysis of take-over times by Zhang et al. (2019) showed that for the majority (93%) of reported take-over times, the participants received a take-over request, usually in the form of an auditory and/or visual warning. Thus, the available simulator research appears to contradict actual practice, where no take-over requests are provided.

If current test vehicles require an alert and trained safety driver, how then can regular drivers be expected to drive an automated vehicle while performing a visually demanding secondary task? Such a vehicle would have to be able to provide take-over requests unfailingly. The most commonly studied time budget is 7 s (Eriksson & Stanton, 2017; Zhang et al., 2019), which means that the vehicle's radar should look 233 m ahead for an assumed driving speed of 120 km/h. It seems questionable whether automated driving systems will be equipped with a sensor system that can look that far ahead reliably. Besides, it can be argued that if the automated vehicle is so intelligent that it can reliably detect an object 233 m further down the road, then surely it must also be able to think of a resolution to this situation, such as through automated braking or steering. Why control should be handed over to the human driver in a potentially lethal situation is unclear.

The fact that drivers can take control in about 1 to 4 s (Zhang et al., 2019) is not necessarily reassuring. With a time budget of 7 s, these take-over times will, in most cases, prevent an accident; that much is true. However, given that response time distributions are right-tailed, a significant proportion of drivers will still crash, as was also previously argued by Eriksson and Stanton (2017). The purpose of their study was to demonstrate the distribution of response times, with and without a distraction, as the emphasis in human factors research is to design for the range of performance and not just the mean, median, and mode. As Eriksson and Stanton (2017) confirmed, time budgets of 5 or 7 s are not sufficient, yet it is unclear why dozens of research papers continue to use the same time budgets.

Another issue is that experiments on driving behavior usually last less than an hour per participant. More specifically, our analysis of the take-over experiments included in the meta-analysis of Zhang et al. (2019) showed that the mean driving time (including practice trials) was 50.9 min (median = 36.0 min; SD = 38.6; n = 91; see supplementary material). Often, the experiment involved multiple take-overs per participant. This means that there is limited opportunity for participants to get drowsy or fatigued, and the aforementioned average take-over times of 1 to 4 s may be too optimistic. As early as 1999, Farber commented on a simulator-based study that involved taking over control while driving on an automated highway system (AHS): "How quickly drivers would respond to such situations in an actual system would depend on their state of arousal and attention … there is simply no rational basis for assuming any relationship between the arousal states of participants in an AHS simulator and that of actual drivers in an actual AHS" (Farber, 1999; p. 84; commentary on a simulator experiment by De Waard et al., 1999).

We doubt whether an IRB would permit a take-over study, such as the one of Gold et al. (2013), in a real vehicle, unless extreme safety precautions are taken such as 'balloon obstacles' (see Frison et al., 2019). If take-over experiments with real hazards are not permitted, why would such vehicles be sold on the market to be used by the general public?

4. What have we learned from the take-over paradigm?

Because a large number of take-over studies have been carried out, a substantial amount of knowledge has been gained within this paradigm. Example findings are that take-over times depend on traffic density, time budget, the type of take-over request, and the type of non-driving task the participant is performing (Zhang et al., 2019). However, it may be questioned whether this knowledge could only have been acquired within the take-over paradigm. The same knowledge may already be available within analogous paradigms.

Before the automated driving era, a large series of studies were conducted into brake response times. This work has been summarized in several articles, including Green's (2000) "How long does it take to stop? Methodological analysis of driver perception-brake times" (cited 963 times as of today). This review concerns a similar paradigm but applies to manual driving instead of automated driving. There are several differences, such as the fact that the driver in the automated vehicle performs a non-driving task, which causes extra time to intervene, but the results and principles of take-over studies appear similar to the brake-reaction-time paradigm. For example, Green reviewed the effects of expectancy/anticipatability, driver age, urgency, cognitive load, and the type of response required (braking versus steering) on response times. Each of these categories has been studied in the take-over paradigm as well (Zhang et al., 2019). However, from the 119 references (i.e., unique papers, reports, chapters) included in Zhang et al., only 5 cite the work of Green (2000).

Levitan et al. (1998) summarized the results of several pioneering take-over studies in the context of an automated highway system. This work has been cited 'only' 22 times, suggesting that scientists do not often dig up old literature and accumulate knowledge but are prone to the availability heuristic. Furthermore, a search using Google Scholar reveals numerous studies that bear relevance to the take-over paradigm. For example, a wealth of research exists into the effects of mobile phone use and other secondary tasks on brake response times (e.g., Consiglio et al., 2003; Young & Stanton, 2007), a topic that bears relevance to take-over times of distracted drivers in automated vehicles.

Research into brake response times goes back an even longer way. Early studies measured brake response times to a single light or sound in real vehicles (Moss & Allen, 1925) or mockups (Fig. 1, and see Greenshields (1937) for a survey of such studies). This type of research was soon extended to different driving tasks and conditions. Literature reviews that show that drivers' average reaction times increase with task complexity have already been available for as long as 60–85 years (Forbes, 1960; Forbes & Katz, 1957; Massachusetts Institute of Technology, 1935; Olmstead, 1936). These early literature reviews show that drivers, on average, are able to release the accelerator in 0.25 s in stationary conditions but take up to 1.65 s to respond in more demanding and distracting conditions.

In fact, relevant research on reaction time and distraction can be traced back to the beginnings of scientific psychology (e.g., Cattell, 1886). Evans (1916) surveyed the "history of reaction-time with relation to distraction", whereas Greenshields (1936) noted that "certain facts of reaction time have already been established" (p. 355), including the fact that "distractions increase the time of all reactions except the reflex" (p. 356).

In summary, it may be questioned whether the large amount of resources spent on take-over studies have been worth it and whether

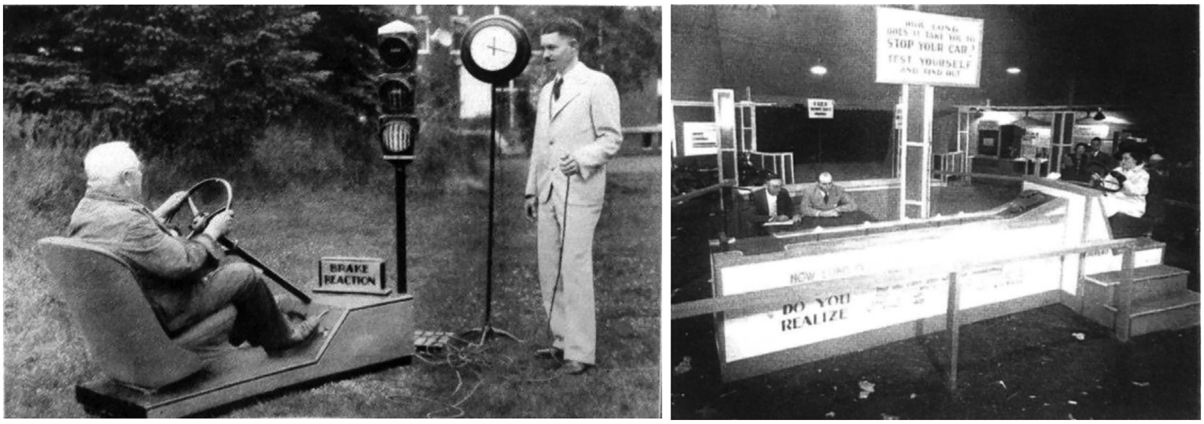

Fig. 1. Apparatus used by De Silva (1936) and Greenshields (1936) for measuring brake response times.

the conclusions could not have been deduced, if only in part, from the literature already available.

5. Conclusions and recommendations

In this work, we criticized the take-over paradigm within human factors science as unrealistic and providing limited new insights. Incidentally, Kuhn's model of science indicates that at some point, people will step up who criticize the prevailing paradigm and contribute to a paradigm shift (and see Stanton et al., 2017). We hope this commentary can contribute to such a paradigm shift, where the next paradigm is hopefully more grounded in real-life problems.

Why don't researchers deviate from the existing paradigm by examining more realistic scenarios? One reason may be that most universities do not have the resources to test with an actual vehicle or reproduce a realistically behaving automated vehicle in a simulator. More typically, experiments at universities are conducted with low-fidelity simulators and student populations, as previously noted by Zhang et al. (2019). Another reason is that, if performing an experiment within the familiar take-over paradigm, the researchers are guaranteed to acquire data that can be reduced into metrics such as brake response time and steering response time, which can then easily be processed statistically. This approach, in turn, offers excellent ingredients for an empirical research paper. Of note, a time budget of 5 to 7 s seems about perfect for academic purposes: it requires the participant to perform an 'exciting' yet doable corrective maneuver. In comparison, a shorter time budget will cause a portion of participants to crash, and therefore yield unusable or heterogeneous data; a long time budget, on the other hand, will mean that take-over times will be long and varied, which is inconvenient for examining variations in experimental conditions. In summary, the risk is that performing a standard take-over study is a matter of convenience and academic productivity rather than having the aim of realism and meaningfulness.

We wish to clarify that unless a vehicle is wholly automated–which seems unfeasible at the current state of technology–human drivers will occasionally have to take over control. So, we do not suggest that take-overs as a whole will never take place on the road; take-overs will take place (see Boggs et al., 2020). However, it is remarkable that such a vast number of similar take-over studies have been conducted so far. We would like to encourage scientists to ask questions that make sense in a practical or theoretical sense, not just because they fall within the prevailing paradigm and therefore offer convenient ways of acquiring data and writing papers.

A possible way forward is to collaborate more with vehicle manufacturers and use their automated driving algorithms, vehicle models, and scenarios. In such a way, it can hopefully be stimulated that experiments have more direct value in the design of automated driving systems. Another recommendation is that experiment design choices need to be motivated. For example, if researchers decide to use take-over requests combined with a short time budget of 5 or 7 s, they would need to explain what sensor systems would be involved if it were a real automated vehicle. Alternatively, the researchers could explain that they are studying a 'what if' scenario, aiming to investigate driving skills in a condition that would be extremely rare in reality. Suppose the critical event concerns, for example, upcoming roadworks or a highway exit. In that case, such information may already be known via GPS and HD maps, and there is no need to rely on radar or lidar. In such a case, longer time budgets such as 20 s or longer might just as well be used, and there is no particular reason to adopt a short time budget.

In many take-over scenarios, however, it may be unrealistic to expect a take-over request at all (Boggs et al., 2020). Looking at accidents with the Tesla Autopilot, for example, the automation failed to detect the hazard, and no take-over request was provided (Banks et al., 2018). This suggests that more research is needed into so-called silent take-overs, a currently understudied topic (but see Louw et al., 2019). There is ample out-of-the-box research that can be conducted, including, for example, the effects of take-overs on other traffic, such as vehicles driving behind, the role of vulnerable road users in take-overs, etc.

If, on the other hand, one is interested in answering basic research questions, such as regarding the effect of warning sounds on reaction times, then it may be more appropriate not to conduct an (expensive) driving simulator study but use psychophysics methods instead (cf. Bazilinskyy & De Winter, 2018). In other words, we suggest that the choice of the research method should correspond as closely as possible to the problem one wants to solve and the question one tries to answer, and not be based on convenience or the prevailing paradigm.

As a limitation, we would like to point out that this commentary article might suffer from hindsight bias. We too participated enthusiastically in the take-over paradigm and only after several years were able to reflect on it deeply and realize there are more interesting aspects of automated driving (Tabone et al., 2021). It may be difficult for a scientist to face the fact that the paradigm in which one operates may not be realistic. It must also be said that the concerns expressed in this commentary are not necessarily limited to the human factors discipline but presumably a concern for psychological research as a whole. Meehl (1978) lamented that certain psychological research topics rise, become popular, and then fade away without having advanced cumulative knowledge.

Finally, we note that reviewers and colleagues alike have offered insightful potential counterarguments to some statements made in this paper. We synthesize these in Table 1, together with our reply. It is

Table 1
Possible counterarguments to our commentary, and our reply.

Counterargument / comment	Our reply
Take-over studies involve more than just the measurement of take-over time: Take-over studies have looked at many other dependent variables, including eye movements, response sequences, user acceptance, etc.	This is true, but the original Gold et al. (2013) paper already examined response sequences, including gaze reaction time, hands-on time, intervention time, as well as take-over quality (braking, steering, trajectory). Hence, it can be argued that subsequent studies offer little originality. Furthermore, for these extra dependent variables as well, there is a lot to learn from the literature. McGee, Hooper, Hughes, and Benson (1983, p. 36), using a literature analysis, provided predictions for eye-movement latency, recognition time, decision time, and brake response time. As early as 1937, De Silva and Forbes (1937) distinguished between perception time and movement time in emergency braking tasks with and without a secondary task (braking or braking & steering combined). We also note that many of the dependent variables are causally related. For example, if the take-over time is long, then less time budget is remaining, and take-over quality is necessarily worse. Hence, doing more measurements does not necessarily offer more insight.
Take-over studies are much richer than what the present commentary seems to suggest. For example, studies have evaluated different human–machine interfaces, different scenarios, and different traffic complexity levels.	It is true that dozens of different experimental variations have been tested. However, these variations mostly fall within the same unrealistic take-over paradigm, where a driver is transported in the automated vehicle, and is then surprised by a take-over request with a time budget of 5 to 7 s. The testing of different variations is what Kuhn called ‘normal science’, in which science is a puzzle-solving activity. Researchers appear to conduct their puzzle-solving activities within the take-over paradigm, without much recognition of their predecessors. Regarding the independent variable ‘task complexity’, for example, Forbes and Katz (1957), Forbes (1960), and predecessors already showed a clear monotonic relationship between task complexity and brake response times.
This commentary argues that scientists should cooperate more with car manufacturers. However, many of the ‘take-over researchers’ did cooperate with car manufacturers.	We are aware that collaborations with car manufacturers are ongoing. For example, several take-over researchers have used the driving simulator facilities of the car manufacturer to conduct their experiments. Still, it is our impression that these researchers tend to stick to the academic take-over paradigm without connecting their research to the challenges the car manufacturer may be facing, such as derived from scenarios the automated vehicle has encountered in field tests.
It is true that sensors cannot look 233 m ahead. But not all take-over studies were conducted at a driving speed of 120 km/h. Perhaps speeds in other experiments were lower and therefore would require a smaller sensor range.	The Gold et al. (2013) study used a speed of 120 km/h. Most take-over research involves highway scenarios. In fact, a literature search using Google Scholar reveals that many other take-over studies used an even higher speed of 130 km/h (e.g., Braunagel et al., 2017), which is a speed that is typical on the German Autobahn.
This paper makes a comparison with test drives of automated vehicles (Boggs et al., 2020) as well as accidents involving automated vehicles, such as the Tesla accident (Banks et al., 2018). These studies indeed reveal that take-overs can be ‘silent’, but this does not mean that future cars will not feature take-over requests. If technology keeps improving, then take-over requests can be issued more often.	Automated vehicles (including Tesla’s Autopilot) indeed produce take-over requests. Our point is that drivers cannot rely on their automated vehicle if take-over requests are not produced perfectly. Silent take-overs are a safety issue in SAE level 3 automation, but surprisingly little research is available on this topic. Also, it can be argued that if automated vehicles provide take-over requests unfailingly, then the driving task could just as well be fully automated.
It is true that the majority of take-over research has been conducted with time budgets of 5 to 7 s, but this does not imply that this research is invalid or useless. Isn’t it good to know what time budget is sufficient for taking over control?	What is surprising is that so many researchers have used 5 to 7 s time budgets. The Zhang et al. (2019) meta-analysis showed that only a handful of studies used time budgets above 15 s, even though long time budgets are realistic and probably required. There is also very little research on voluntary or other types of driver-initiated transitions of control. The same point was made by Lu et al. (2016).
It is true that there is insufficient research on the effect of drowsiness and fatigue on take-over performance. This means that *more* take-over research is required, not less, as this commentary seems to suggest.	While there have been several take-over studies that involved 1.5 to 3 h of driving to make participants fatigued (Feldhütter et al., 2018; Kreuzmair et al., 2017; Schmidt, 2018; Weinbeer et al., 2017), this seems about the maximum experiment duration observed (see supplementary material). These studies show that drivers become fatigued but can still take over quickly, even after several hours. An issue is that participants show faster take-over times as the experiment progresses due to learning and the formation of expectations. This trend runs counter to the potential consequences of fatigue (Kreuzmair et al., 2017). Research on the etiology of fatigue-related accidents may require a fundamentally different paradigm, such as naturalistic driving studies.
It is not true that many of the take-over findings could have been deduced from old academic literature. Results are always context-dependent, and findings from manual driving research cannot be translated to automated driving.	There appears to be a fundamental problem that science is not cumulative. For example, in several take-over studies, researchers used a mentally demanding task (*N*-back) and found no strong effects on take-over times. In fact, about one-quarter of take-over studies involved a mentally demanding non-driving task (Zhang et al., 2019). There is a rich and apparently forgotten history on this topic, starting with Cattell (1886), who measured reaction times with and without a mental arithmetic task. Our critique is equivalent to Evans (2004), who made a critical remark on the development of an expensive driving simulator: “*Although the research literature documents 1733 papers on alcohol and skill, the first sentence of justification for the $50 million expenditure is The effects of alcohol, drugs, visual impairments and aging on driving will all be safely studied using the new research tool.*” In other words, there is a lot to learn from old literature. If results are as context-sensitive as claimed, real automated vehicles should be used, not driving simulators.
Human factors research is indispensable to inform the policy and design of technological systems. We need more human factors studies, not less.	This is true, but practical recommendations made by human factors scientists should be grounded in realism, and not be made for the sake of academic convenience.
It is not true that take-over studies have not advanced our knowledge. A lot has been learned.	We agree that much knowledge has been gained. Each of the 200+ studies on the topic has contributed its share to Kuhnian puzzle-solving. Our point is that this knowledge falls within the bounds of the take-over paradigm, where a paradigm is the research method that researchers appear to take for granted. It is remarkable that comparatively little human factors research is available on very long or very short time budgets, other types of transitions in automated driving, and other types of automation (cruise control, automated evasive steering, automated emergency braking, electronic stability control, human factors of SAE levels 4 and 5 automation, take-overs in low-speed automated shuttles, etc.).
Are you saying that all the take-over research should not have been conducted at all?	It seems unreasonable to criticize individual researchers. The problem of noncumulative science is broader and may apply to science as a whole, as we pointed out. Our work is meant to stimulate critical thinking and hopefully advance knowledge and allow other researchers to generate new hypotheses. Concretely, we see room for out-of-the-box and realistic research in the area of human factors of automated driving.

hoped that the content of Table 1 facilitates further thinking on the topic of human factors of automated driving.

CRediT authorship contribution statement

Joost de Winter: Conceptualization, Writing - original draft, Writing - review & editing. **Neville Stanton:** Writing - review & editing. **Yke Bauke Eisma:** Writing - review & editing.

Supplementary Materials

Supplementary material, including an appraisal of Olmstead (1936) and the driving times of 129 take-over studies, are available online: https://doi.org/10.4121/14370572.v1.

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