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Overall Effects of Non-Driving Related Activities' Characteristics on Takeover Performance in the Context of SAE Level 3: A Meta-Analysis

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ABSTRACT

Since users of Level 3 driving automation systems may engage in non-driving related activities, it is of interest to investigate effects of non-driving related activities on traffic safety. The current meta-analysis aims at estimating non-driving related activities' effects on takeover behavior based on theory and empirical findings on task switching and modality shifting. Results indicate that takeover time increases after non-driving related activities that (1) physically require the user to free his/her hands from the respective activity before takeover, (2) obstruct concurrent visual perception of the driving environment, (3) are dissimilar to the driving task in terms of required cognitive processing modules.

Keywords: Driving automation, Non-driving related tasks, Takeover, Traffic safety

INTRODUCTION

Effects of non-driving related tasks (NDRTs) on takeover performance in the context of SAE Level 3 have been investigated in multiple studies. These have been summarized by – to our knowledge – three meta-analyses: First, Zhang et al. (2019) focused on takeover time at SAE Levels 2 and 3, and looked for factors influencing takeover time after either a request to intervene or a critical event. They find many situational variables that impact the duration of takeover (e.g. situation's urgency, modalities of the request to intervene), but also some factors that can be influenced by the user (e.g. experience with takeover situations, specifics of the non-driving related activity) (Zhang et al. 2019). Second, Soares et al. (2021) report a meta-analysis on simulator studies and used *k*-medoids clustering to answer the question how primary studies' experimental conditions may have influenced the measured outcomes (e.g. takeover time). Based on the described search procedures and study coding, it can be assumed that Soares et al. looked at driving automation systems of Level 2 and higher levels, similar to Zhang et al. (2019). Third, Weaver and DeLucia (2020) conducted a meta-analysis to examine whether (1) time budget, (2) engagement in NDRTs and (3) information provided to

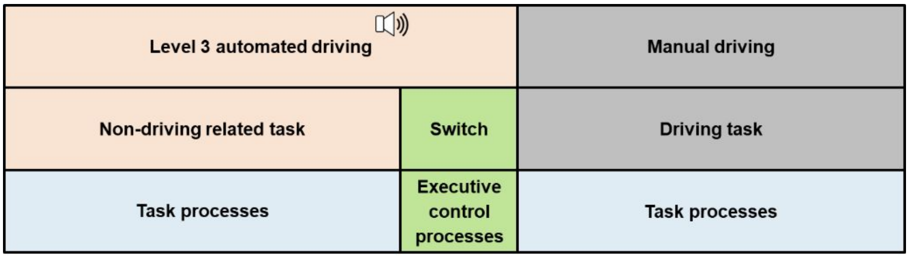

Figure 1: Takeover situation in Level 3 from the perspective of Rubinstein et al.'s task switching theory (2001). Speaker symbol indicates system's request to intervene.

the driver in the takeover situation influences takeover performance. In contrast to the former two meta-analyses, Weaver and DeLucia focused on SAE Level 3 exclusively because of the distinctive role of the fallback-ready user. The meta-analysis at hand adds to the former by focusing on existing empirical research on effects of NDRTs in SAE Level 3 from the perspective of task switching and modality shifting known from psychological basic research (Rubinstein et al. 2001, Spence et al. 2001). Thereby, we investigate a theoretical basis to differentiate non-driving related activities' effects on traffic safety based on their respective characteristics.

SAE Level 3 Automation from a Switching and Shifting Perspective

Sustained driving automation systems (Shi et al. 2020) of SAE Level 3 (SAE International/ISO 2021) perform the entire dynamic driving task within its system limits, thereby releasing and relieving in-vehicle human user from the driver role. S/He may engage in other non-driving related activities. Beyond its limits, the Level 3 system cannot perform the dynamic driving task on a sustained basis. When a system limit is approached, the system issues a request to intervene expecting the in-vehicle human user to respond by taking over the driving task.

Upon onset of the request to intervene, the user needs to physically and mentally switch from a potential non-driving related activity to the driving task. Regarding physical switching, the user might need to free her/his hands from the respective non-driving related activity (e.g. smartphone, laptop). If physical adjustments are necessary, they will by nature prolong takeover time compared to when physical adjustments are not required. The mental switching to the driving task will be described in the following by first applying Rubinstein et al.'s stage model of executive control for task switching (2001) and second, by applying the modality shifting effect (Spence et al. 2001).

Takeover Situation at SAE Level 3 in Terms of Task Switching

Considering the Level 3 takeover situation as an example for the task switching paradigm is not new (e.g. Zeeb et al. 2017). We apply Rubinstein et al.'s task switching theory (2001) to differentiate NDRTs' effects on takeover behavior. In their stage model of executive control for task switching, Rubinstein et al. (2001) assume task processes and executive control processes, with executive control processes being specific to task switching, and task processes taking place whenever working on a task. *Task processes* include stimulus identification, response selection and movement production related to the respective task at hand. *Executive control processes* include goal shifting and rule activation required when switching from one task to another. Rubinstein et al. explicitly assume that goal shifting may take place before stimulus identification of the following task started (Rubinstein et al. 2001, p. 771). Transferred to the takeover situation at SAE Level 3, we estimate effect sizes comparing NDRTs that allow for executive control processes and task processes of the subsequent driving task to take place earlier compared to tasks that do not allow so. For instance, if the NDRT does not involve the visual modality (e.g. listening to music), the visual modality can be used to observe the traffic situation which is part of the subsequent driving task. In terms of the described task switching theory, the NDRT "listening to music" allows for task processes related to the subsequent task to take place earlier compared to another NDRT "playing Tetris".

Modality Shifting Effect in the Takeover Situation at SAE Level 3

Task processes such as stimulus identification might be influenced by the so-called modality shifting effect which refers to the relative costs in reaction time and error rates when the modality in which a target is presented, differs from the modality of a previous stimulus compared to when both modalities match. Since NDRTs and takeover situations occur in real traffic, differentiation of NDRTs by sensory input modality is less practical than in the laboratory experiments (e.g. as long as the user does not close his/her eyes, there will always be visual input. Since sleeping violates the fallback-ready user's responsibilities at Level 3, it is unlikely that the user would close his/her eyes for a longer period of time). We therefore make use of the modality specific cognitive processing modules to describe the similarity between NDRTs and the driving task. Based on Baddeley's working memory model (Repovs and Baddeley 2006), the processing modules required for each task (NDRTs, driving task) were evaluated first, and then compared. The similarity of the tasks' demand profiles serve as an indicator for the two tasks' similarity.

We considered empirical evidence suggesting the visuo-spatial sketchpad to consist of two separate subsystems instead of one combining visual and spatial features (e.g. Klauer and Zhao 2004). Moreover, most everyday tasks, including driving and NDRTs, need to be deemed "episodic". To allow for differentiation, we deviated from the episodic buffer's original focus, and chose deliberate long-term memory retrieval as the criterion, e.g. in case of quiz tasks when knowledge needs to be actively retrieved. Consequently, the following cognitive processing modules were coded: phonological loop, visual system, spatial system, central executive, deliberate long-term memory retrieval. For example, the driving task requires the visual, spatial system and the central executive, but does not require deliberate long-term memory retrieval or the phonological loop. The similarity between driving task and playing Tetris (requires the visual, spatial system, central executive to align action to input, but no deliberate long-term memory retrieval) is thus higher than between driving task and listening to music (requires the phonological loop, but not the visual, spatial system, central executive or deliberate long-term memory retrieval). According to Rubinstein et al. (2001), however, listening to music allows task and executive control processes related to both switching and the subsequent driving task to take place earlier compared to playing Tetris.

Aim and Hypotheses

Starting from the outlined theoretical basis, we investigate the following overall effect sizes on takeover times: (1) overall effect size of monitoring task vs. active NDRT, (2) overall effect size of required vs. not required visual sensory system for active NDRTs, (3) overall effect of physical need vs. no need to free hands before takeover, (4) overall effect size of similarity between NDRTs.

METHODS

Search Procedure

Articles were searched for in following databases (for the last time in January 2020): IEEE Xplore, Web of Science and APA PsycArticles. Search terms were "non-driving related task AND automated driving" and "non-driving related activities AND automated driving". Additionally, the reference list of a catalogue on non-driving related activities developed in the German Ko-HAF project (Hohm et al. 2018) was screened.

Inclusion Criteria

The following criteria were applied to select studies for this meta-analysis: (1) articles had to be full-text reports of a quantitative study written in English or German language, (2) the implemented SAE Level 3 driving automation function had to fulfill all criteria as defined by SAE Standard J3016, (3) the Level 3 function was active until takeover by the in-vehicle human driver, (4) a manual driving phase of SAE Level 0 had to follow the Level 3 driving automation phase, (5) the ride had to take place in a passenger car, (6) articles had to include either a control group or another NDRT condition to allow for calculation of an effect size, and (7) articles had to include a takeover time measure.

Coding of Studies

Effect Size Calculation

Cohen's d of the difference in takeover time between two NDRTs was preferably directly derived from the primary study, or calculated based on reported means and standard deviations using formulas by Borenstein et al. (2009). If these data were not reported, effect sizes were either calculated using reported test statistics (t- or F-statistic) provided the numerator's degrees of freedom was 1, or converted from other reported effect size measures. For effect sizes based on within-subject designs the correlation r is needed. If it was neither reported nor could be provided, $r = .50$ was assumed.

Similarity of Tasks

Similarity of tasks was coded based on the cognitive processes they require (as outlined in the introductory section on the *Modality shifting effect* in the takeover situation at SAE Level 3). Following criteria were coded for each NDRT: phonological loop, visual system, spatial system, central executive, deliberate long-term memory retrieval. For each pair of compared NDRTs, the similarity of their resulting demand profiles was calculated.

Meta-Analytic Procedure and Analyses

The meta-analytic procedure followed the guidelines proposed by Field and Gillett (2010) and was conducted using R version 4.1.0 and the robumeta package (Fisher and Tipton 2015). Meta-regression models were estimated using robust variance estimation methods and a correlated effects model with small sample correction. Robust variance estimation methods were used because of the complex data structure that includes multiple effect size estimates drawn from the same or overlapping samples, which violates the traditional meta-analysis' assumption of independent effect sizes. We deliberately did not reduce data to one effect size estimate per study (by either averaging effect size estimates or selecting one effect size per primary study) since this would imply loss of information. Due to unknown covariance structure underlying the effect sizes, we decided against conducting a multivariate meta-analysis. A multilevel meta-analysis was not chosen because the hierarchical effects model assumes independent sampling errors within clusters, which can be assumed to be not given in our effect size sample where part of the effect size estimates are based on overlapping participant samples. Robust variance estimation methods are not intended to be used for calculating variance parameter estimates or testing null hypotheses on heterogeneity parameters, but more suitable for calculating meta-regression coefficients and mean effect sizes (Tanner-Smith et al. 2016) which is suitable for our aims and hypothesis. Average effect sizes were calculated by meta-regression using an intercept-only model. For the within-study effect size correlation, rho, the default value of .80 was used.

RESULTS

Table 1 shows a summary of average effect size estimates, reported separately in the following.

DISCUSSION

Our meta-analysis indicates that engagement in a NDRT increases takeover time. Activities that occupy users' hands prolong takeover times compared to activities that do not occupy their hands. This attribute has the strongest effect on takeover times. Next, the visual distraction accompanying non-driving related activities prolongs takeover time. And lastly, dissimilarity to the driving task in terms of involved cognitive processes prolong takeover time. Practical relevance can be deducted from the absolute size of the estimated effect sizes. Regarding theoretical implications, the meta-analysis

Table 1. Summary of average effect sizes.

Comparison	No. of studies / outcomes	Average effect size	*t*-statistics
Engagement in an active task compared to monitoring	12 / 54	$d = .663$	$t(10.7) = 3.28, p < .01$
Need to put away task	11 / 47	$d = .625$,	$t(9.89) = 4.34, p < .01$
Visual task compared to non-visual task	9 / 36	$d = .326$	$t(7.8) = 2.64, p < .05$
Similarity of cognitive processing modules	22 / 129	$d = .096$,	$t(10.4) = 2.31, p < .05$.

provides first indication that task switching and modality shifting might be suitable to differentiate between NDRTs' effects on takeover behavior.

Implications for Theory

Acknowledging that the Level 3 driving automation is accompanied by a paradigm shift away from dual-task (from Level 0 to Level 2) towards task switching (e.g. Zeeb et al. 2017, Weaver and DeLucia 2020) is not new. By merging task switching and modality shifting, we contribute to founding a theoretical basis for differentiating NDRTs regarding their effects on take-over. Differentiation thereby considers both the Level 3 automated driving context and the diverse physical and cognitive demands an activity puts on the human user. The resulting overall effect size estimates are in accordance to our prior theoretical assumptions, indicating that the hypothesized processes of task switching and modality shifting seem to contribute to variance in takeover time.

Implications for Practice

The absolute size of the overall effect size estimates indicates the practical relevance of the respective factors. The need to put away a task and the engagement in an active task compared to monitoring influence takeover time strongest. In practice, for instance the effect of the necessity to put away a task can be used in multiple regards. First, the probably most obvious inference is to either render taking up remote devices unnecessary (suitable for activities involving electronic devices, such as smartphones and tablets) or create possibilities to quickly store or place items upon request to intervene (suitable for activities such as reading books or eating and drinking). Second, it is possible to constrain the range of possible non-driving related activities for a given system.

It should be noted that our meta-analysis refers to Level 3 driving automation only. Inferences on other driving automation levels cannot be drawn from our analysis. Next, generally, conclusions about takeover quality must not be drawn since we focused on takeover time only. Unfortunately, numerous studies report only reaction times but not takeover performance in a systematic way. This means our results cannot suggest any better or worse takeover depending on NDRTs' characteristics. Our results rather indicate that absolute takeover times will be systematically underestimated when only considering situations in which the user has previously engaged in a passive monitoring task. This situation can be also assumed to be unrealistic as most users name non-driving related activities as one of the major advantages of automated driving.

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