The role of cognitive functions in merging manoeuvres during simulated highway driving

Jun KAWAHARA\textsuperscript{a,}, Toshihisa SATO\textsuperscript{b}, Masayoshi NAGAI\textsuperscript{b}, Takatsune KUMADA\textsuperscript{b},
Yuki SOMA\textsuperscript{b,c}, Hideaki NEMOTO\textsuperscript{d}, and Yukiko NISHIZAKI\textsuperscript{d}

\textsuperscript{a} Chukyo University, \textsuperscript{b} National Institute of Advanced Industrial Science and Technology (AIST),
\textsuperscript{c} Tsukuba University, \textsuperscript{d} Nissan Motor Company

The present study examined a model of the role of cognitive functions related to attention and decision making in merging manoeuvres during simulated highway driving. To test this model, we screened participants who scored high or low on two sets of tasks that were assumed to represent attentional function and decisiveness. We then conducted a driving simulation experiment in which attentional function and decisiveness were between-subject factors and task difficulty was varied as a within-subject factor. The results indicated that the attentional function was the primarily determinant of the swiftness and success of merging. The role of decisiveness was confined primarily to the activation of the turn signal. Thus, the present experiment suggests that attention is the cognitive function that determines performance during merging behaviour in the setting under examination. Exploratory multivariate analyses confirmed the measureable behaviour obtained from the simulation. The present results provided information about the cognitive functions for merging behaviour that may be useful to the automobile industry.

Key words: attention, driving simulator, merging manoeuvre, decisiveness, usability testing

Introduction

Almost all aspects of driving a car involve a high cognitive load. For example, individual cognitive abilities and internal cognitive states vary according to traffic conditions and thereby affect the efficiency of driving. Similarly, excessive demands on attention, one of the major cognitive functions, by dual tasking (e.g., cell-phone use during driving; Strayer \& Drews, 2007) have been shown to lead devastating consequences during driving. These examples suggest a direct link between cognitive functions and car-driving performance. In this study, we focused on the cognitive functions involved in merging manoeuvres on highway ramps. Such manoeuvres are known to be challenging for many drivers and many perform poorly in this situation (Nagai et al., 2012). Although the reasons of this difficulty remain to be clarified, it is obvious that merging is a dynamic and complex situation requiring both a high cognitive load and skilled motor control functions (Daamen, Loot, \& Hoogendoorn, 2010; Uechi, Morioka, Sasaki, Kosaka, \& Nishitani, 2007). Compared with other driving situations, one of the most important aspects of merging is speed control. In most driving circumstances, decreasing the speed of the vehicle leads to safety. However, decreasing one's speed on highway ramps may lead to conflict with other vehicles. Therefore, reducing speed is not an effective safety measure in the context of merging, which increase the cognitive demands of such manoeuvres.

The present approach: Screening participants by cognitive functions

We designed the present study to explore the cognitive factors responsible for merging manoeuvres on highway ramps during simulated driving. Compared with actal driving, driving simulations offer many benefits in terms of safety and the ease with which conditions can be controlled. Nonetheless, the number of trials that can be administered to one participant is limited relative to standard laboratory experiments. For this reason, previous studies have used certain characteristics of participants, such as age (e.g., de Waard, Dijksterhuis, \& Brookhuis, 2009), and driving experience (e.g., Underwood, Chapman, Brocklehurst, Underwood, \& Crundall, 2003) as independent variables to explain individual variations in driving behaviours.

These sorts of descriptive labels for participants have also

* Corresponding author. Department of Psychology, Chukyo University, 101-2 Yagoto, Showa, Nagoya 466-8666, Japan. E-mail: jkawa@lets.chukyo-u.ac.jp

Copyright 2013. The Japanese Psychonomic Society. All rights reserved.
been widely used in non-academic, industrial usability testing situations of commercial products. Variables such as age, sex, and frequency of use of, and past experience with a particular product have traditionally been treated as critical factors contributing to the usability of products. Engineers in the auto industry, for example, include number of years since receipt of a driving licence and the primary purpose of the car as well as the aforementioned characteristics of participants as independent variables. One reason for the frequent use of these simplistic descriptive labels in usability tests for commercial products is probably that such labels seem distinctive and salient for describing a group of participants. Another reason may be the ease of data collection.

However, distinctiveness and salience do not necessarily indicate the most representative behavioural characteristics of participants in academic and non-academic situations. Instead, such labels are too simplistic and are thus unable to predict complex human behaviours. This lack of predictive power causes serious problems for the usability tests performed in private industry. Specifically, usability tests and behavioural experiments using real or simulated settings, such as those involving a driving simulator, require substantial temporal and budgetary resources. Therefore, the number of participants available tends to be limited, and this shortage of participants severely undermines the resulting conclusions when researchers resort to the use of simplistic independent variables.

The present study does not rely on the demographic characteristics of participants, such as age, sex, and years since the license issuance, for interpreting driving performance because it is highly unlikely that such rigid and superficial characteristics directly relate to driving behaviour, as this behaviour requires adaptive actions to achieve goals such as parking in a narrow space or merging into busy highway traffic. Rather, we propose that the complex behaviours enacted in changing real-life environments are rooted in flexible cognitive functions. To explain a target behaviour (merging manoeuvres in the present study), we constructed a tentative cognitive model in which cognitive functions play critical roles in achieving a behavioural goal. We then screened participants based on scores on simplified tasks that supposedly to reflect the critical cognitive functions. Such screening of participants enabled factorial testing of the effects of selected cognitive functions on the target behaviour. Thus, this screening process was expected to increase the efficiency of the application testing of commercial products. Relative to the conventional approach, in which researchers extract potentially critical factors from data obtained via sub-optimally controlled experiments using superficial demographic labels, the present approach directly compares selected factors. A similar framework has been proposed in the domain of application studies of navigation in public places (Kitajima et al., 2008) and the use of information technology equipment (Suto & Kumada, 2010). The present study applied this cognitive-screening framework to driving simulations.

The screening procedure adopted in this study employed an extreme groups design, the advantages and disadvantages of which have been discussed elsewhere (e.g., Wherry, 1984). For example, Preacher, Rucker, MacCallum, and Nicewander (2005) argued that this design is a useful for improving the odds of detecting an effect, if it truly exists, when the resource for collecting data from a broad range of participants is limited with respect to time or money. They also suggested that this design warrants caution when predicting the behaviours of participants who were not included in the study. We discuss the validity of our approach in the General Discussion.

Cognitive functions involved in merging manoeuvres

We hypothesised that two cognitive functions, attention and decision making, would be involved in merging manoeuvres on highway ramps. We argue that the merging manoeuvre consists of two stages, accelerating and changing lanes. During the acceleration stage, a driver is required to accelerate sufficiently while monitoring speed, clearance in front and to the side, and termination of the acceleration lane. This demand for multi-tasking requires the driver to switch among tasks and frequently update working memory regarding traffic conditions. Therefore, we predicted that the cognitive functions of attention, including task switching, working memory, and executive control, would be involved. We recognise that attention is a broad term. For the purpose of the present study, we focus on a relatively higher level aspect of attentional functioning, such as working memory and executive processes. Therefore, sub-functions of attention, such as spatial localisation, inhibition, and priming, are beyond the focus of the present study.

The second stage of merging behaviour is changing lanes. During this stage, the driver finds a space in the inner lane, determines when to change lanes, and slides the vehicle into the space. This stage of merging reflects the effect of the decisiveness with which actions are executed. It should be noted that these two stages may not be strictly sequential. Rather,
drivers could monitor the inner lane while accelerating the vehicle. Nonetheless, it would be true that no drivers would start seeking opportunities to merge without any acceleration. Our intention of introducing this two stage model was to highlight the major behavioral components, acceleration and changing lanes, involved in the merging the manoeuvre at highway ramps. By this decomposition, we argue that attention and decision processes would be required to successful completion for smooth merging manoeuvres.

Given that these two factors, attention and decisiveness, are critical to merging manoeuvres, limitations in the abilities affected by these factors would be expected to impair driving performance. We hypothesised that similar patterns of results would be obtained even if cognitive capabilities were treated as traits. In other words, we hypothesised that participants with relatively low levels of attentional ability and/or decisiveness would demonstrate poor driving performance in merging manoeuvres. We tested this hypothesis in three steps. First, participants were screened according to their scores on cognitive tasks that reflect the attention and decisiveness involved in merging. Participants then engaged in test runs under controlled highway traffic conditions using a driving simulator. If our hypothesis regarding merging manoeuvres on highway ramps were confirmed, participants who scored high on the cognitive tasks would demonstrate more successful merging behaviour relative to those who scored low. As the third step, we conducted exploratory multivariate analyses to test the construct validity of our model of merging behaviour as well as our research strategy.

**Step 1: Screening experiment**

Our model of merging manoeuvres includes attentional and decision-making processes. Thus, to create two groups of participants for a two-level of between-subjects factor analysis of the results of the driving simulator experiment, we divided participants according to their scores on the cognitive tasks measuring these two processes. We used three tasks to measure attentional functions and three other tasks and two questionnaires to measure decisiveness. Participants were selected according to their scores on these tasks and questionnaires to enable a $2 \times 2$ (attention vs. decisiveness × high vs. low) between-subjects factor analysis of data collected in the simulator experiment for participants in the following groups: high attention and high decisiveness; high attention and low decisiveness; low attention and high decisiveness; and low attention and low decisiveness.

**Method**

**Participants.** We recruited 199 participants (range: 18–30 years, mean: 21.2 years, $SD=2.1$, 45 females) from the subject pool of the National Institute of Advanced Industrial Science and Technology. Participants were unaware of the purpose of the study and participated for pay. All participants were licensed drivers.

**Screening tasks.** We measured performance on task switching (Allport, Styles, & Hsieh, 1994), visual short-term memory (Luck & Vogel, 1997; Vogel, McCollough, & Machizawa, 2005), and the operation span (OSPA) function of working memory (Turner & Engle, 1989) to assess atten-tional function. To measure decisiveness, we used the symbol and coding tasks in the Wechsler Adult Intelligence Scale-Third Edition (WAIS-III), and a computerised task. The Regret and Maximization Scale-Japanese version (Isobe et al., 2008) and the Sports Clumsiness Scale (Furuta, 2008) were also included as indices of decisiveness.

Participants were individually tested. After signing the consent form, they completed these tasks in random order. Each task lasted approximately 5–15 min, yielding 90-minute sessions including brief breaks.

**Procedures.** Task switching: Participants discriminated either the shape (circle or square) or colour (green or red) of a geometric shape presented at the centre of a computer screen. At the beginning of a trial, a cue ("S" for shape or "C" for colour) was presented for 1 s to indicate the response category. After a 500-ms blank display, a critical item was presented at the centre of the screen. Participants were asked to respond as quickly and accurately as possible by touching one of the designated on-screen buttons with a response pen. The primary outcome of interest was the difference in reaction times between switching trials, in which two different response categories were cued in two consecutive trials, and non-switching trials, in which the same response categories were repeated.

Visual working memory: Participants viewed two sequential displays, each of which consisted of four, six, or eight coloured squares with a blank display and then indicated whether one of the squares had changed colour between the two displays (Luck & Vogel, 1997). The working memory score $K$ for the set size $n$ was calculated using the following equation (Cowan, 2001; Pashler, 1988): $K_i = \text{number of squares} \times (\text{hits}−\text{false alarms})$.  


Operation span (OSPAR) function of working memory: This task was adopted from the study conducted by Bleckley, Durso, Crutchfield, Engle, and Khanna’s (2003) and Minamoto, Osaka, and Osaka (2010). Participants viewed an equation–word pair (e.g., \((4 \div 2) + 4 = 8\) ～奇特), verbally indicated whether the equation was true or false, and read the word aloud. After viewing and reporting to one list consisting of several equation–word pairs, participants were asked to recall the words. The number of correct words recalled was recorded as the participant’s OSPAN score.

Decisiveness tasks: Scores on the WAIS-III symbol and code tasks were calculated and treated as representative of participants’ general processing speed. Additionally, the grand mean reaction time for correct responses in the task-switching experiment, regardless of switching condition, was calculated for each participant as another index of general processing speed. General clumsiness was measured by performance on the “Assembly Task” of the computer game Rhythm Tengoku for Nintendo DS (NTR-P-YLZ), Nintendo). The experimenter recorded a score that was automatically calculated and displayed on screen upon completion of this task. Participants also completed the Regret and Maximization Scale-Japanese version (Isebe et al., 2008) consisted of 16 items and the Sports Clumsiness Scale (Furuta, 2008). The former consisted of 16 items intending to assess the tendency to experience regret, and individual differences in the desire to maximize or to satisfy. The latter consisted of 8 items designed to measure subjective perception of respondents’ own physical abilities for sports activities.

Results

Figure 1 presents a histogram showing the normalized scores on each cognitive task and questionnaire. Scores on these tasks and questionnaires were calculated and summarised as a set of single values representing each participant’s attention function and decisiveness. Specifically, we defined the attentional function as the cost of task-switching (in ms), the size of visual working memory as \(k\), and the working memory span as the OSPAN score. Similarly, we defined decisiveness as the scores on the two WAIS-III tasks (in points), the score on the timing game (in points), the general reaction time (in ms), and the scores on the two questionnaires. To convert these scores into two representative values (i.e., attentional function and decisiveness), we used the following strategy. First, participants were categorised by each dependent measure and ranked so that the top 35 participants received graded points. For example, participants with the highest \(k\) value on the test of visual working memory earned the highest number of points (35) and the second-place participant received the second-highest number of points (34). In this way, the top 35 participants earned positive scores. Similarly, negative scores were given to the lowest 35 participants: the participant with the lowest \(k\) was assigned \(-35\) points, and the participant with the second-lowest score received \(-34\) points. The value of 35 was determined arbitrarily. We chose this value because we initially intended to analyse the top and bot-

![Histogram showing the normalized scores on Attentional tasks (left) and Decisiveness tasks (right).](image-url)
tom quartiles of 140 participants on each dimension (attention and decisiveness) and implemented the screening procedure accordingly. However, we were able to collect data from more participants due to improvements in the efficiency of data collection, and we decided to add participants while maintaining the screening scheme.

Figure 2 represents the distribution of participants with the attentional function plotted on the abscissa and decisiveness plotted on the ordinate. The resulting four quadrants enabled us to divide participants into four categories based on high/low scores in the attentional and decisiveness domains. Specifically, participants in the top-right quadrant received high scores for attention and decisiveness, those in the top-left demonstrated low attention but high decisiveness, and those in bottom-right demonstrated high attention but low decisiveness. Finally, those in bottom-left received low scores for both attention and decisiveness.

We used these categories to create factorial groups of participants for the driving simulation study. We contacted those participants whose scores were farthest from the centre of the plot to participate in the next experiment.

Discussion

Our primary aim in this screening study was to select participants based on their abilities in two cognitive domains: attention and decision making. As seen in Figure 2, the scores of the four groups of participants were widely distributed along the axes representing attention and decisiveness. Thus, we were able to recruit different types of participants for the driving simulation experiment and treat these group differences as between-subject variables measuring attention and decision making.

However, the preset screening scheme was not the only method by which we could have assigned participants to different groups. For example, we might have applied a factor analysis to combine several scores on the screening tasks. In fact, the two axes, attention and decisiveness, were not completely independent, and a weak but significant correlation between the two variables was found ($r = 0.19, p < .01$). Therefore, one of the possible directions for future studies involve elaboration of the screening criteria.

Step 2: Driving simulation experiment

The factors of attention and decisiveness were combined to create a $2 \times 2$ grouping of participants (both scores high; attention high and decisiveness low; attention low and decisiveness high; both scores low). Participants recruited based on the screening scheme engaged in a simulated scenario in which their vehicle was supposed to merge into the inner lane from the acceleration lane at Gotemba Higashi interchange of eastbound Tomei Highway.

We predicted that attention and decisiveness would exert different effects on driving performance. Specifically, our model of merging behaviour predicted that the acceleration stage would rely primarily on the attentional function. Therefore, participants with high levels of attentional ability would be able to efficiently execute manoeuvres during this stage, resulting in their merging early during the process of acceleration. We predicted that participants scoring low on decisiveness would take more time to make the relevant decision and thus fail to merge appropriately.

To create a variety of levels of difficulty in merging manoeuvres, we introduced two parameters (time to contact, TTC) and relationship between speed of one’s own and other vehicles) that defined the behaviour of the computer-generated vehicles in the inner and outer lanes in the driving simulation. Thus, in addition to the two between-subjects factors mentioned above, two within-subject factors were included in the present study: TTC (3.5, 6.0, 9.0, or 13.0 s) and inter-vehicle speed difference (relative or absolute). Thus, the present study consisted of a mixed design involving four factors (two
between- and two within-subject factors).

**Method**

*Participants.* We invited individuals to participate in the study based on their scores on the cognitive tasks in Step 1. The sample consisted of eight participants with high scores for both attention and decisiveness (4 males; Mean age 22.6, SD = 3.6; 2.3 years of driving experience), 10 with low scores on both dimensions (9 males; Mean age 21.1, SD = 1.4; 2.0 years of driving experience), five with high scores on attention and low scores on decisiveness (4 males; Mean age 20.8, SD = 3.3; 2.2 years of driving experience), and eight with low scores on attention and high scores on decisiveness (6 males; Mean age 23.3, SD = 1.1; 2.2 years of driving experience). All had earned non-professional drivers’ licenses for vehicles up to 4500 kg (gross vehicle weight).

*Apparatus.* A custom-made driving simulator was used. This system consisted of a cabin removed from a commercially available vehicle, a computer projection subsystem to achieve a view of 300 deg, a motion platform with six-axis actuators, and eight speakers controlled by host computers (Aka- matsu & Onuki, 2007). This system sampled and recorded various parameters, such as speed, acceleration, location of itself and of other vehicles, heading direction, steering orientation, strokes of gas and brake pedals, status of console meters and electric equipment, and time at a rate of 60 Hz.

*Experimental manipulations.* One primary factor, TTC, was defined as the time to contact with an inner-lane vehicle approaching from behind (distractor vehicle) if the participant’s vehicle maintained its present speed at arrival at the critical location (the end of the striped marking on the road, 130 m from the initial location at which a trial started). For example, a 10.0-s of TTC means that participant’s vehicle will collide with the distractor vehicle in 10.0 s if the participant maintains the present speed. This outcome was produced when the distractor vehicle appeared to approach the participant’s vehicle when it was approximately 19, 33, 56, and 72 m behind the participant’s vehicle upon the latter’s arrival at the end of the striped marking. We chose these TTC values to introduce a wide range of difficulties. The TTC 3.5 condition was meant to create a circumstance in which most drivers yield to let other vehicles pass. On the contrary, most drivers change the lane ahead of other vehicles under the TTC 10.0 condition. The TTC 6.0 was meant to create a midway condition in which most drivers should waver in their judgments.

These values were derived from experience in parameter settings during driving-simulator experiments.

The second factor, inter-vehicle speed difference, was introduced to manipulate the difficulty of the merging task. Specifically, under the absolute-speed condition, the distractor vehicle matched the speed at which the participant’s vehicle arrived at the critical location. Under the relative-speed condition, the simulator was programmed so that the distractor vehicle accelerated/decelerated on every 0.02 s to maintain the relative speed difference at the critical location. Under this condition, the speed of the distractor vehicle was, in principle, faster than that of the participant’s vehicle. Therefore, the merging manoeuvre under this condition was more difficult than it was under the absolute condition because participants were unable to enter the inner lane ahead of the distractor vehicle without additional acceleration. In other words, the relative condition is a difficult condition because the distractor vehicle followed the participant’s vehicle by adjusting speed (in this sense “relative”), whereas the absolute condition was an easy condition because the distractor vehicle maintained a speed at which participant’s vehicle arrived at a critical location (in this sense “absolute”).

*Procedure.* To familiarise themselves with driving in the simulator, participants participated in 5-minute scenario on local roads that included merging traffic: this was followed by two (or three, at the request of participants) test runs using a highway scenario that was identical to the one used in the experiment except that no other vehicles were involved. The experimental trials consisted of three trials under each of eight conditions (four levels of TTC × two levels of speed difference), resulting in a total of 24 trials. The order of these trials was randomised across participants.

At the beginnings of both the familiarisation trials involving the highway scenario and the experimental trials, participants were instructed to merge from the acceleration lane to the inner lane, as they usually do, by accelerating up to approximately 60 km/h before reaching the striped marking and then up to approximately 80 km/h upon arrival at the critical location. They were asked to drive in the inner lane for a few hundred meters after merging.

*Results*

*Analyses of simulator records.* The location at which the merging manoeuvre was initiated was determined based on simulator record. Figure 3 presents an example of the record of
the steering angle (solid line), deviation from the centre of the acceleration lane (dashed line), inter-vehicle distance (dotted line), and status of the turn signal (thick line). The driver activated the turn signal at Point A. The sharp rise in the dotted line represents the appearance of the distractor vehicle. The wavy solid line from 400 to point C on the abscissa represents minor adjustments during acceleration. Inflection point B indicates that the distractor vehicle passed in the inner lane. The sharp turn of the steering angle at Point C and the subsequent increase in the deviation from the centre of the acceleration lane indicated that the merging manoeuvre was initiated at that point. Point D indicates that the turn signal was automatically deactivated once the steering wheel returned to the normal heading angle. Individual data were analysed in the same way and the X-axis point indicating the location at which the merging manoeuvre was initiated was determined. Vehicle speed, strokes of the gas pedal, and location at which the turn signal was activated were also identified and analysed. Specifically, the analyses discussed below were performed to examine the effects of cognitive functions (attention and decisiveness) and traffic conditions (TTC and speed difference) on the merging manoeuvres in terms of the location, mean speed, speed at which the merging manoeuvre was initiated, and outcome of the merge. We also examined the effect of decisiveness on the activation of the turn signal. Briefly, the merging manoeuvres were affected primarily by attention and TTC. Although we conducted an analysis of variance (ANOVA) on the dependent variables identified above, the two between-subjects factors (attention (high vs. low) and decisiveness (high vs. low)), the two within-subjects factors (TTC (3.5, 6.0, 10.0, and 13.0 s) and speed difference (absolute vs. relative)), decisiveness had a significant effect on only activation of the turn signal. Therefore, with the exception of the analysis involving this dependent measure, the factor of decisiveness was collapsed to plot the results.

**Distance required to initiate merging manoeuvre.** An ANOVA with the four factors as independent variables was performed on the location at which the merging manoeuvre was initiated (Figure 4). The distance from the start location to this location reflects how long it took for participants to initiate the merging manoeuvre; longer distances mean that it was more difficult for participants to make this move. The analysis revealed a main effect of TTC \(F(3, 81) = 65.7, p < .001\). Significant the two-way interactions between attention and TTC \(F(3, 81) = 2.76, p < .05\) and between speed difference and TTC \(F(3, 81) = 2.80, p < .05\) were also obtained. Multiple comparisons using Ryan’s method of the main effect of TTC revealed significant differences between all combinations except the TTCs pairs between 3.5 vs. 6.0, and 10.0 vs. 13.0 \(t(81) > 9.38, p < .001\). These differences correspond to a downward trend to the right and indicate that merging behaviour was initiated earlier during acceleration when TTC
was long. In other words, participants merged more quickly into the inner lane when the distractor vehicle was separated by longer distances. More importantly, the interaction between attention and TTC indicates that participants who scored low on the attentional tasks required more distance to initiate the merging manoeuvre when TTC was longer than did those who scored high. Thus, in Figure 4, at longer TTCs, data for low-attention participants (filled symbols) are plotted above those for high-attention participants (open symbols), indicating that low-attention participants required more time to initiate the merging manoeuvre.

**Mean vehicle speed.** We analyzed mean vehicle speed because we believe that this speed is practically a handy index to characterize the properties involving in driving behavior. The same four-factor ANOVA on the mean vehicle speed from the beginning of the trial to the moment at which the merging manoeuvre occurred revealed significant main effects of attention \([F(1, 27) = 9.62, p < .005]\), speed difference \([F(1, 27) = 4.61, p < .05]\), and TTC \([F(3, 81) = 45.22, p < .001]\). The interaction between attention and TTC was also significant \([F(3, 81) = 2.77, p < .05]\). Figure 5, which presents the plot of these relationships, shows that mean merging speed of the high-attention participants was lower than that of the low-attention participants, indicating that the former group initiated the merging manoeuvre at an early stage of acceleration, resulting in a relatively low mean speed during merging. However, this does not mean that the high-attention participants entered the inner lane at a low speed. A subsidiary four-factor ANOVA on the speed at the moment of merging indicated that only the main effect of TTC was significant \([F(3, 81) = 13.78, p < .001]\). The speed at each TTC was 75.70, 76.72, 83.06, and 84.42 km/h for TTC 3.5, 6.0, 10.0, and 13.0 s, respectively. This result suggests that high-attention participants accelerated immediately before engaging in the merging manoeuvre.

**Failure to merge.** In the present study, a failure trial was defined as one in which the merging manoeuvre occurred beyond the point at which the acceleration lane became narrower than the width of the vehicle or the participants vehicle collided with the distractor vehicle or the roadside fence. The four-factor ANOVA on the rate of unsuccessful merging manoeuvres revealed a significant main effect of TTC \([F(3, 81) = 9.24, p < .001]\). The interactions between attention and speed difference and between speed difference and TTC were also significant \([F(1, 27) = 7.22, p < .05; F(3, 81) = 10.95, p < .001, \text{ respectively}]\). As shown in Figure 6, the main effect of TTC is reflected in the downward trend to the right. The interaction between attention and speed difference corresponds to the

![Figure 5](image1.png)  
Figure 5. Mean vehicle speed as a function of TTC for high and low attention conditions at relative and absolute speed conditions. Error bars indicate standard errors.

![Figure 6](image2.png)  
Figure 6. The rate of the failure to merge as a function of TTC for high and low attention conditions at relative and absolute speed conditions. Error bars indicate standard errors.
trend whereby low-attention participants failed to merge under the relative-speed condition. The failure to merge increased under the relative-speed condition at shorter two TTC conditions as compared to the longer two TTC conditions \( F(3, 108) > 12.6, p < .001 \).

**Turn signal.** A four-factor ANOVA was conducted on the location at which the turn signal was activated. The results revealed a significant main effect of TTC \( F(3, 72) = 10.71, p < .001 \) and an interaction between decisiveness and TTC \( F(3, 72) = 2.78, p < .05 \). Further analysis revealed that participants low in decisiveness were affected by TTC \( F(3, 72) = 11.19, p < .001 \), whereas no such effect was observed among high-decisiveness participants. Multiple comparisons regarding this simple main effect revealed that low-decisive participants delayed in activating the turn signal \( F(72) > 2.6, p < .05 \). The downward trend to the right in Figure 7 reflects the main effect of TTC. The results for the low-decisive participants (filled symbols) show the downward trend to the right, whereas those for the high-decisive participants (open symbols) show no such trend, reflecting the interaction.

By calculating the distance between the location at which the turn signal was activated and that at which the actual merging manoeuvre occurred, we observed how long in advance participants explicitly indicated their intention to merge. Figure 8 shows this distance under each speed-difference condition as a function of TTC. The four-factor ANOVA on this distance revealed significant main effects of speed difference \( F(1, 24) = 4.36, p < .05 \) and TTC \( F(3, 72) = 24.73, p < .001 \). The two-way interaction between attention and speed difference was also significant \( F(1, 24) = 7.19, p < .05 \), as was the three-way interaction among decisiveness, speed difference, and TTC \( F(3, 72) = 5.09, p < .005 \). The interaction between attention and speed difference means that low-attention participants activated the turn signal later under the relative-speed condition. This effect is reflected in Figure 8, where the disks, representing the low-attention participants, are above the triangles, representing the high-attention partic-

![Figure 7. The location were the turn signal was activated as a function of TTC for high and low decisiveness conditions. Error bars indicate standard errors.](image)

![Figure 8. Distances in which turn signal was activated (meter) as a function of TTC. Error bars indicate standard errors.](image)
participants. This pattern indicates that the low-attention participants took longer than the high-attention participants to active the signal. This trend was prominent when TTC was long, reflecting the three-way interaction. Interestingly, the participants who were high in attention but low in decisiveness activated the turn signal after the distance required to initiate the merging manoeuvre at long TTC conditions, plotted as negative values in triangles in the left panel. This result, in conjunction with the data showing that high-attention participants initiated the merge at an early stage in acceleration and that low-decisiveness participants activated the turn signal at a later stage, indicates the reason for the temporal proximity of those two events. Thus the turn signal could be activated after the merging manoeuvre was initiated.

**Step 3: Exploring the relationships between cognitive functions and driving behaviour via multivariate analyses**

The results discussed thus far suggest that attentional functioning greatly affects various aspects of merging-related behaviours, including distance required to initiate a merging manoeuvre, mean vehicle speed, and failure to merge, whereas decisiveness exerts a very limited effect, confined to activation of the turn signal. However, we must consider the arbitrariness of the independent and dependent variables before reaching conclusions. Specifically, the independent variables were arbitrarily determined in the present study in that we used the sum of the weighted scores on measures of two cognitive functions (i.e., attention and decisiveness) to represent these variables; as a result, participants who performed better received higher scores. Similarly, there were no specific or well-established dependent variables to represent merging behaviour on highways. For example, excellence in merging was defined in terms of the aggregate of the more elemental parameters measured during the simulation. Thus, it is necessary to confirm the construct validity of the present research strategy with regard to the selection of independent and dependent variables. To this end, we assessed whether the scores on some (or all) of the individual cognitive tasks would be correlated with the values of the elemental dependent variables (e.g., accelerator pedal strokes) recorded during the simulation if attentional function and decisiveness made substantial contribution to merging manoeuvres.

**Multivariate analyses**

First, we grouped dependent measures with similar pattern of results because there were too many dependent measures to evaluate each of them independently. Specifically, we used the following values: vehicle location (X coordinate on the simulator map; L hereafter), stroke of the gas pedal at the moment of merging (gas), velocity at the moment of merging (V), mean velocity during driving trials ($V_a$), and risk factor at the moment of merging (RF; Kondoh, Yamamura, Kitazaki, Kuge, & Boer, 2007); these were calculated using the following equations:

\[
TTC = \frac{\text{relative distance from the distractor vehicle}}{\text{relative velocity to the distractor vehicle}}
\]

\[
\text{Time Head Way (THW)} = \frac{\text{relative distance from the distractor vehicle}}{\text{velocity of the distractor vehicle}}
\]

\[
RF = \frac{5}{TTC} + \frac{1}{THW}
\]

We calculated the correlations between the values for each level of TTC (i.e., 3.5, 6.0, 10.0, and 13.0) under the relative- and absolute-speed conditions separately. The values that indicated strong correlations (0.7 < |r| < 1.0) were averaged, resulting in the 19 dependent variables listed in Table 1. We conducted simple linear regression analyses, treating the test scores related to attentional functioning or decisiveness as explanatory variables and these 19 variables as response variables. Regarding the (OSPA) score, which was included under the attentional function, the values of $V_a$ ($\beta = -0.39$) and gas at TTC 3.5 ($\beta = 0.38$) under the relative TTC condition and the $V_a$ ($\beta = -0.46$) and RF values at a TTC of 13.0 ($\beta = 0.36$) were significantly correlated ($p < 0.05$). The scores for task switching and the RF value were also significantly correlated ($\beta = 0.36, p < 0.05$). Regarding decisiveness, score on the symbol task were significantly related to the V value under the absolute TTC condition ($\beta = -0.37, p < 0.05$). Additionally, the general reaction time was correlated with the gas value ($\beta = 0.41, p < 0.05$). These results are summarised in Table 2, which indicates significant positive and negative correlations with white and black cells, respectively. Note that dependent vari-

---

1 Of course simulator experiments can be followed by multivariate analyses on the basis of pre-measurements of cognitive functions. Ideally, such an order of systematic investigations would be preferable given sufficient temporal and budgetary resources were available, which lacked in the present study, unfortunately.
Table 1
Combined dependent variables on the basis of the results of correlation analyses.

<table>
<thead>
<tr>
<th>Relative TTC condition</th>
<th>Absolute TTC condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Loc (Loc values averaged over at TTC of 6.0, 10.0, and 13.0)</td>
<td>Mean Loc (Loc values averaged over at TTC of 10.0 and 13.0)</td>
</tr>
<tr>
<td>Mean Gas (Gas values averaged over at TTC of 10.0 and 13.0)</td>
<td>Mean Gas (Gas values averaged over at TTC of 6.0, 10.0, and 13.0)</td>
</tr>
<tr>
<td>Mean V (V values averaged over at TTC of 3.5, 6.0, and 10.0)</td>
<td>Mean V (V values averaged over at TTC of 3.5, 6.0, 10.0, and 13.0)</td>
</tr>
<tr>
<td>Mean V_a (V_a values averaged over at TTC of 3.5, 6.0, 10.0, and 13.0)</td>
<td>Mean V_a (V_a values averaged over at TTC of 3.5, 6.0, 10.0, and 13.0)</td>
</tr>
<tr>
<td>Mean RF (RF values averaged over at TTC of 6.0, 10.0, and 13.0)</td>
<td>Mean RF (RF values averaged over at TTC of 3.5, 6.0, and 10.0)</td>
</tr>
<tr>
<td>Loc at TTC of 3.5</td>
<td>Loc at TTC of 3.5</td>
</tr>
<tr>
<td>Gas at TTC of 3.5</td>
<td>Gas at TTC of 6.0</td>
</tr>
<tr>
<td>Gas at TTC of 6.0</td>
<td>RF at TTC of 13.0</td>
</tr>
<tr>
<td>V at TTC of 13.0</td>
<td></td>
</tr>
<tr>
<td>RF at TTC of 3.5</td>
<td></td>
</tr>
</tbody>
</table>

Table 2
Summary of correlation analyses between attentional function and decisiveness vs. 19 dependent variables derived from the simulator records. □ and ■ indicate significant positive and negative correlations ($p < .05$)

<table>
<thead>
<tr>
<th>Relative TTC</th>
<th>Absolute TTC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean V_a</td>
</tr>
<tr>
<td>Attentional function</td>
<td></td>
</tr>
<tr>
<td>OSPAN</td>
<td>■</td>
</tr>
<tr>
<td>VSTM</td>
<td></td>
</tr>
<tr>
<td>Task Sw.</td>
<td></td>
</tr>
<tr>
<td>Decisiveness</td>
<td></td>
</tr>
<tr>
<td>Symbol</td>
<td></td>
</tr>
<tr>
<td>Code</td>
<td></td>
</tr>
<tr>
<td>Timing</td>
<td></td>
</tr>
<tr>
<td>Sports</td>
<td></td>
</tr>
<tr>
<td>Decisiveness questionnaire</td>
<td></td>
</tr>
<tr>
<td>Gen. RT</td>
<td></td>
</tr>
</tbody>
</table>

ables without significant associations according to simulator records were omitted from this table. As can be seen, attentional function was negatively related to mean vehicle velocity, indicating that participants with low attentional functioning (i.e., small OSPAN capacity) drove faster than did those with high attentional functioning. This is in concordance with the analysis of the mean vehicle speed (Figure 5). This result is in concordance with finding that participants with low attentional functioning travelled longer distance before merging because they required a longer time to complete this manoeuvre, resulting in a more distant merging location and faster vehicle speed at the end of the acceleration lane. These results are also consistent with the finding that a greater proportion of participants with low attentional functioning than with high attentional functioning failed to merge because high speed near the end of the acceleration lane left fewer degrees of freedom for merging manoeuvres.

It is notable that visual short-term memory was not correlated with any dependent variable. The effect of decisiveness on the dependent variables was also weak. Instead, OSPAN and task switching were related to a wide range of variables. Thus, we suggest that the cognitive functions involved in the merging behaviour measured in the present context were primarily to the executive component of attention.
Table 3

<table>
<thead>
<tr>
<th>Factor loadings and accounted (cumulative) percentage of variance under the relative TTC condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Merging at a high speed</td>
</tr>
<tr>
<td>-------------------------</td>
</tr>
<tr>
<td>V at TTC of 13.0</td>
</tr>
<tr>
<td>Mean V</td>
</tr>
<tr>
<td>Gas at TTC of 3.5</td>
</tr>
<tr>
<td>Mean V</td>
</tr>
<tr>
<td>Mean RF</td>
</tr>
<tr>
<td>Loc at TTC of 3.5</td>
</tr>
<tr>
<td>RF at TTC of 3.5</td>
</tr>
<tr>
<td>Gas at TTC of 6.0</td>
</tr>
<tr>
<td>Mean Loc</td>
</tr>
<tr>
<td>Mean gas</td>
</tr>
<tr>
<td>Eigenvalues</td>
</tr>
<tr>
<td>% of variance</td>
</tr>
<tr>
<td>Cumulative % of variance</td>
</tr>
</tbody>
</table>

To further examine the components of merging behaviour in the present context, we conducted an exploratory factor analysis using the least square method to separately standardise the scores under the relative and absolute TTC conditions. This analysis, using varimax rotation, delineated four independent factors under the relative TTC condition (Table 3). The first factor, accounting for 20.7% of the variance, consisted of five items and was labelled "merging at a high speed." The second factor, accounting for 16.8% of the variance, consisted of three items and was labelled "behaviour at TTC of 3.5." The third and fourth factors, accounting for 16.0% and 12.9% of the variance, respectively, consisted of two and one items, respectively, and were labelled "acceleration at early stage" and "acceleration," respectively. A similar analysis was conducted under the absolute TTC condition, and the results revealed a three-factor solution (Table 4). The first factor, accounting for 23.1% of the variance, consisted of four items and was labelled "merging at a high speed." The second factor, accounting for 20.8% of the variance, consisted of five items and was labelled "taking time in merging." The final factor, accounting for 18.1% of the variance, consisted of two items and was labelled "risky merging." If the cognitive functions examined (attention and decisiveness) underpinned the merging behaviour in the present context, these functions would be correlated with some of the factors identified in the factor analysis. The results indicate the following significant correlations (p < .05). OSPAN scores were negatively correlated with the factor loading of merging at a high speed under the relative (r = -.39) and absolute (r = -.43) TTC conditions. Task switching scores were positively correlated with the factor loading of merging at a high speed under the relative TTC condition (r = .31). Under the absolute TTC condition, scores on the symbol scale were also negatively correlated with the factor loading of merging at a high speed (r = -.32). The score for the general reaction time was positively correlated with the factor loading of taking time in merging (r = .41). No other significant correlations between pairs of cognitive functions and factor loadings were found.
Discussion

The present analysis was intended to reinforce the findings from Step 2 of this study. Specifically, we assumed that if attentional function and decisiveness made essential contributions to merging manoeuvres, then scores on the individual cognitive tasks would be correlated with those on the elemental dependent variables recorded by the simulator. The results from the correlation and factor analyses are consistent with this view. The finding that participants who scored highest on the OSPAN task merged at a low mean speed is consistent with the results of the analyses in Step 2. The consistently significant correlations between scores on the OSPAN task and the dependent measures reflecting vehicle speed suggest that this task reflected a skill that is a major determinant of manoeuvres during merging the context of simulated highway driving.

It should be noted that the participants in the present study were university students who were relatively less experienced drivers. Therefore, the results may not be applicable for other groups of drivers (e.g., senior drivers, experienced and/or professional drivers). Further examination regarding the effect of driving skill should be required. The number of the participants was also limited and thus the interpretation of the factor analyses should be cautious.

General Discussion

The present study examined a cognitive model of merging manoeuvres enacted in a simulated highway driving scenario. Our model hypothesised that attention and decision making are involved in the merging manoeuvres performed on highway ramps, in such contexts, acceleration and lane changing are required for a successful merging. It was assumed that attentional ability plays a critical role in this situation given that dividing one's attention among monitoring forward clearance, speed, and traffic in other lanes is required. Additionally, maintaining and updating working-memory and task-switching are also necessary. Therefore, we predicted that the cognitive functions of attention, including task switching, working memory and executive control, would be involved in merging manoeuvres. Moreover, decision making is required once the driver finds a space at which to enter the inner lane. Thus we assumed that decisiveness with regard to action would also contribute to driving performance.

To test this model, we first conducted a screening study in which participants who scored high or low on two sets of tasks were assumed to represent attentional functioning and decisiveness were identified (Step 1). We then conducted a simulator experiment with the individuals identified in Step 1 in which attentional functioning and decisiveness were included as between-subject factors (Step 2). The results of the simulator experiment indicated that attentional functioning was the primary determinant of the swiftness (reflected in the distance required to initiate the merging manoeuvre and the mean vehicle speed) and success of the merging behaviour. Decisiveness was involved only in terms of activating the turn signal.

Thus, based on the results of the current study, we suggest that the cognitive function that primarily determines performance during merging behaviour in the settings tested is attention. To confirm the construct validity of the cognitive functions used as the independent variables and their relationships with the particular behaviours measured in the simulator and used as the dependent variables, we conducted exploratory multivariate analyses. The results were consistent with those in the factorially designed experiment.

The present results provide useful information with which the automobile industry can identify the cognitive functions required for merging behaviour. Specifically, we demonstrated that the component of working memory as indexed by the OSPAN task critically involved in the merging behaviour during simulated driving. Therefore, further investigation focusing on this aspect would be fruitful in developing supporting equipment. The same approach to identify critical a cognitive function in a target behaviour would be applicable to any other domains for research and development related to human technology. Indeed, the usability of individual pieces of equipment, such as instrument panels, has been frequently and intensively tested within the domain of application studies. Nonetheless, researchers sometimes lack a conceptual framework for understanding relatively complex behaviours, such as the merging tested in the present study. Although it was plausible that attentional functioning would be involved in merging manoeuvres, as far as we know, no systematic attempts have been made to explore the subcomponents of attention involved in merging behaviour. The present study clearly indicates that the attentional function is involved in merging manoeuvres. Moreover, the exploratory multivariate analyses revealed that the operation span of working memory, as indexed by the OSPAN task, and executive function, as indexed by task-switching cost, are major subcomponents of the attentional ability required for this behaviour. In this sense, the
model that we described in the Introduction should be revised to de-emphasise the decision-making component.

It is notable that visual working memory (Luck & Vogel, 1997; Vogel, McCollough, & Machizawa, 2005) did not explain any of the variance in the dependent measures recorded by the driving simulator. This pattern, which became evident in the exploratory multivariate analysis, was somewhat counter-intuitive because visual working memory has been shown to be critical to a variety of cognitive tasks. For example, low capacity with poor visual working memory experienced visual distraction related to current behavioural goal (Fukuda & Vogel, 2009, 2011). Such low-capacity participants were also inefficient in object selection (Vogel et al., 2005). We suggest that the present task did not depend critically on visual working memory, although this function would seem clearly necessary for any visual task.

The exploratory multivariate analysis was also helpful in confirming the construct validity of the independent and dependent variables used in the present study (Step 3). This approach is useful when only a limited number of participants is available, as in the present study. Specifically, identifying critical cognitive functions (e.g., working memory in the present study) by screening participants would simplify research designs and would clarify the ways for further examination (e.g., development of assisting systems for highway driving). Ideally, studies exploring the cognitive mechanisms that potentially underpin in the use of specific commercial product (e.g., passenger vehicles) should carefully select critical independent and dependent variables based on ample and rigorous supporting evidence. However, time and budgetary considerations may not permit such considerations. Thus, the present strategy for confirming construct validity using exploratory multivariate analysis should help to bolster relevant research.

References


—Received Dec. 16, 2012; Accepted Apr. 24, 2013—