The Impact of Central Executive Function Loadings on Driving-Related Performance

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ABSTRACT
The study reported in this paper investigated the impact of individual ability, with respect to central executive (CE) functions, on performance of two driving-related tasks when distracted by CE loading secondary tasks. The two driving-related tasks used were visual target detection, and a one-dimensional pedal-tracking task designed to be an analogue of a vehicle following task. The three CE tasks were each designed to load mainly on just one of three different CE functions (inhibition, shifting, and updating, respectively) in both audio and visual conditions. An additional single key press secondary task was used to assess the impact of a non-CE loading secondary task. We hypothesized that people with a higher level of ability for a given CE function would do better, relative to those with lower ability, on the driving-related task when it was accompanied by a secondary task that loaded the corresponding CE function. 102 people participated in the screening portion of the study, and 34 of these participants were then selected to participate in the main experiment. We found that the impact of CE abilities on dual task performance is more complex than a simple tradeoff model would predict. Shifting ability generally improved primary task performance in the dual tasks, and inhibition ability tended to improve performance in the target detection task, while updating ability tended to improve performance in the pedal-tracking task.

Keywords
Driver distraction, Mental/cognitive workload, Central Executive, Individual differences, Inhibition, Shifting, Updating, In-Vehicle information device, User interface

1. INTRODUCTION
The long-term goal of this research is to identify interaction design requirements for minimizing the distracting effect of in-vehicle information systems on drivers. We focus in particular on the distraction and workload caused by tasks that place a load on the central executive (CE) functions. CE is one of the main components in the dominant model of working memory (e.g.,[1]). Extensive research has associated CE function activity with the prefrontal cortical region of the brain (e.g.,[16]).

Driver distraction caused by interaction with in-car information systems involves multi-tasking situations that likely comprise several types of workload, including perceptual (visual and audio), manual and cognitive workload involving central executive functions [18]. In the research reported here we focused on cognitive workload and investigated its effects on driving-related performance. We were particularly interested in using individual differences in cognitive ability (CE functions) as a way to identify when higher levels of CE function ability are needed to maintain adequate driving performance in the presence of distracting secondary tasks.

2. RELATED RESEARCH

2.1 Fractionated CE functions and Individual Differences
There has been considerable discussion around the issue of whether CE functioning should be understood as a unified system or as a fractionated system. The fractionated system view has mainly been supported by studies on individual difference in cognitive ability, which have been conducted with a variety of populations, such as normal young adults [17][9], normal elderly adults [13], brain-damaged adults [3], and children with neurocognitive pathologies [11]. These studies typically employed a battery of widely used executive tasks like the Wisconsin card sort test (WCST) and the n-back test, and examined how well these tasks correlated with one another by performing correlation/regression analysis and exploratory factor analysis (EFA). Many of these studies have shown low (not statistically significant) inter-correlations among different executive tasks, consistent with the fractionated system view.

Observations from neuropsychology have also supported the fractionated view of CE functioning. For example, Logie et al. examined the basis for a multiplicity of CE functions, showing that the function for multitasking could be selectively impaired in Alzheimer's disease (AD) patients group [12].

In the fractionated CE view, a variety of ways to classify executive functions have been proposed such as "mental set shifting", "inhibition", "flexibility", "updating", "monitoring", "planning", and "dual-tasking". In this research, we decided to start our exploratory study from the following three functions: "inhibition", "shifting", and "updating" based on Miyake et al's characterization [17], since the three functions, or analogous ones, are often seen in other classification systems (e.g., [19]). In addition, each of these three functions have been associated with tasks that can be used to measure the level of ability that a person has with respect to that function.

Some researchers have argued that these three functions differ in their degree of independence. For instance, Szmalec et al. argued that updating ability as measured by the n-back task includes an aspect of conflict solving that is related to inhibition [25]. While it is probably difficult, if not impossible, to develop "pure" tasks that load on only one CE function (since tasks will generally have shared perceptual, selective attention, and response selection components), it should still be possible to assess the impact of CE functions using "impure" tasks that tend to have high loadings on one CE function relative to the others.

2.2 Multiple resource model and multitasking performance

Wickens proposed a multiple resource model to describe cognitive (mental) workload [27]. In the multiple resource model there separable attentional resources (for example, visual and auditory in modalities, spatial and verbal in codes). In this research, we are interested in whether or not the multiple resource model should be extended to include the impact of different CE functions, and we are also interested in the impact of individual differences on those CE functions.

To measure cognitive workload, a dual-task procedure is often used. In the literature review on the use of secondary tasks in the assessment of workload, Ogden et al. found that there is no single best task or class of tasks for the measurement of workload [20] (also see [6], for a collection of chapters on the different approaches to measuring mental workload). Given the strong evidence for a multiplicity of CE functions, it is natural to ask what role, if any, they should have in models of mental workload and cognitive distraction. This question was the motivation for the research reported below.

2.3 CE functions and driving performance

While many researchers have tried to measure the levels of driver distraction caused by different secondary tasks (eg. [7][15][24]), relatively little research has focused on understanding the types of cognitive workload and their effects.

However, Baumann et al. investigated the effect of CE load on driving performance (as assessed by time to collision and driving speed) [2]. They used simulated driving where participants were required to avoid obstacles while performing either an auditory monitoring task that should not load on the comprehension functions of the CE, or a running memory task that should heavily load on the CE involving comprehension and prediction function of situation awareness. They found that participants received less benefit from being provided with a warning signal when they had to perform the running memory task. The researchers concluded that the CE function is strongly involved in the construction of situation awareness.

Mäntylä et al. also examined the relationship between CE function and driving performance [14]. In their experiment, high school students completed a simulated driving task and six experimental tasks that tapped the three CE functions of inhibition, shifting, and updating. Their results showed that updating ability was a significant predictor of performance on a Lane Change Task (LCT) while doing simulated driving.

3. OUR RESEARCH INTEREST AND HYPOTHESIS

In the present study, we assumed that workload experienced by individuals is defined as the interaction between individual differences and task requirements. Figure 1 represents our approach, where workload is attributable to task loadings on the three CE functions of inhibition, shifting, and updating. The model makes the following three assumptions:

- Individual differences exist in the capacity of each CE function;

- Different tasks load the CE to varying extents as a function of both the nature of the task itself and the unique effect of the task on each individual.

- The cognitive workload that a person experiences while performing a task is determined by the direction and degree of mismatch between the person's abilities and the task requirements with respect to the CE functions.

If validated, this model provides for the profiling of tasks by measuring the CE ability of individuals and the subsequent cognitive workload they experience while performing those tasks. Tasks with unacceptably high loads on particular CE functions could then be identified and redesigned so as to reduce those loads to acceptable levels. Figure 1 summarizes this approach whereby cognitive demands by a task (pick bars on the left) combine with individual cognitive ability (green bars in the middle) and result in workload predictions across each of the three CE functions (blue circles on the right). For instance, participant 1 has low shifting ability and the task requires high shifting ability, meaning Participant 1's shifting workload is high for that task.

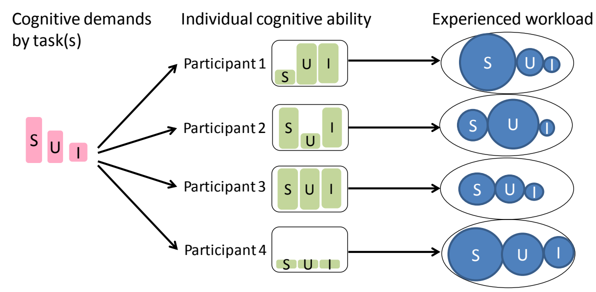

Figure 1. A model of cognitive workload based on the individual differences and different task requirements

In a driving task it seems that all three CE functions (inhibition, shifting, and updating) are required. Updating is likely required for keeping track of the position of one's vehicle relative to other vehicles in the road, and of keeping track of one's current location for navigation purposes. Inhibition would seem to be required to detect and respond to external events such as changing traffic signals or people who move into the path of one's vehicle. Finally, since driving often involves multi-tasking, shifting ability will be involving in managing the process of switching between the main driving task and other tasks. However, people with wide ranging cognitive abilities appear to perform well at driving. Thus it seems that the traditional driving task is not overloading CE function ability for most people.

What happens, though, when novel in-vehicle information technologies create demanding new secondary tasks? Could it be that some CE functions become overloaded with a corresponding decrement in driving performance and a decrease in safety? In order to test whether this is a far-fetched concern or not, we designed the experiment below to examine the impact of CE function ability on driving performance when CE loading tasks are involved. Should concerns about CE loading prove to be justified, the methodology used in this paper (assessing the impact of CE abilities on driving in the context of CE loading secondary tasks) may help to find problems relating to CE function loading in in-vehicle interfaces.

We developed the following hypotheses to test in the experiment:

1. Effect of Cognitive workload

An individual's ability on a particular CE function will be significantly related to primary task (driving-related task) performance when also performing a secondary task loading on that CE function. To test this we used a series of regression analyses with performance on the primary task (either pedal tracking or target detection) as the criterion, and measured levels of individual ability (inhibition, updating, and shifting) as the predictor variables. Forward and backward stepwise analyses were run with one pair of analyses for each combination of primary task complexity (block 1 was lower complexity, block 2 was higher complexity), modality (auditory or visual) and type of loading on the secondary task (inhibition, shifting, or updating).

We expected that the overall pattern of results in the regression analyses would tell us the extent to which CE function ability was driving primary task performance, and in what contexts. If a particular CE function ability was only a significant predictor of primary task performance when the secondary task loaded on that same CE function, then that would show that the secondary task was harming primary task performance because of its loading on that function.

Alternatively, if the presence of the secondary task in itself was making loading on the primary task more critical, then we might expect to see different CE abilities affecting performance on the two primary tasks, regardless of which CE function loaded the secondary task. Specifically, we would predict in this case that performance on the pedal tracking task would be significantly related to updating ability, while performance on the target detection task would be significantly related to inhibition ability. In addition, to the extent that shifting is related to task switching we would expect it to be significantly related to primary task performance in all the dual task conditions.

2. Effect of Perceptual workload

Overall experienced workload is a combination of visual (or perceptual), manual and cognitive workloads. Since both the main and CE tasks involve visual processing, we would expect overall workload to be higher when the information in the secondary task is presented visually due to the resulting high load on visual attentional resources (cf. [27]). However, it could also be hypothesized that mental workload could rise, rather than fall when an audio secondary task was used due to the fact that auditory information tends to require more storage in working memory.

4. SCREENING TEST

Prior to the experiment, we conducted a screening test to select people who cover a range of different cognitive profiles with respect to the three CE functions considered in this research.

4.1 Method

4.1.1 Participants

102 people participated in the screening test. Participants were recruited through recruiting firms, emails to distribution lists and from notices posted on University of Toronto campus bulletin boards. The participants consists of 53 males and 49 females, aged from 16 to 64 years old (*M*=42.3, *SD*=13.4). All of the participants were English speakers living in the Toronto area with normal vision and hearing.

4.1.2 Tasks

We selected three cognitive tests to measure each participant's CE ability based on Miyake et al.'s findings concerning the mappings between tasks and CE functions [17].

(1) Stroop test (Inhibition): Six color words ('black', 'white', 'yellow', 'orange', 'purple', and 'green') were presented in one of the six same font colors individually and at random. There were 36 possible word-font color combinations. On each trial, three color names (response alternatives) were presented in black at the bottom of the display. The participant's task was to respond with the color in which the stimulus word was written, by pressing a corresponding key. The three response alternatives were mapped to the left arrow key, down arrow key, and right arrow key, respectively.

(2) Color monitoring test （Updating task): Participants were shown blue, yellow and red circles (8cm in diameter) one at a time for 500ms in randomized order with an inter-stimulus interval of 2500ms. The task was to respond when the third instance of each circle color was presented (e.g., after seeing the third blue circle, or the third yellow circle), which required participants to monitor and keep track of the number of times each color had been presented. For example, if the sequence was ''blue, red, yellow, yellow, red, blue, *yellow, blue, red*'' then the participant should have responded to the third blue, yellow and red circle (italicized). In order for momentary mental lapses to have less impact on task performance, the circle count for each color was automatically reset to 0 if the participant made a key press for that color, and participants were informed of this feature before starting the task. Prior to completing the trial blocks, participants received a practice session, which continued until they made 3 correct responses.

(3) Wisconsin Card Sort Test (WCST; Shifting task): In this task, four stimulus cards were presented to participants. The objects on the cards could differ in color, quantity, and shape. The participants were then given an additional card and were asked to choose which one of the four original cards conformed to the same category as the additional card. As the classification rule was not provided to the participants, they had to guess the rule. They did this based on the pattern of feedback provided to them ("correct" or "incorrect"), after they chose one of the four cards to match with the additional card. In this experiment, the classification rule changed after 10 correct responses under the rule. The task was finished when a participant completed 8 different rules or 128 trials, whichever came earlier. We used the number of perseveration errors as the performance measure based on previous research [17].

4.1.3 Results

Data from six of the participants was removed from the analysis because of problems in collecting their data (e.g., failing to follow instructions). The skill levels of the remaining 96 participants were then assigned into three categories on each of the three executive functions (inhibition, updating, and shifting) using the following method. Measures obtained on the experimental tasks that corresponded to each of the three executive functions were characterized as low (-1), medium (0) and high (1) by segmenting the standardized (z-) scores obtained on each measure across the entire sample of participants. A z-score of less than -1 was interpreted as low ability (relative to the rest of the sample), a z-score between -1 and 1 was interpreted as medium ability, and a z-score of greater than +1 was interpreted as high ability. This created three variables that represented the three skill levels (high, medium, and low).

Table 1 CE ability patterns

	CE ability			Number of participants		
Group	Inhibition	Shifting	Updating	screening test	main experiment	
average	0	0	0	33	7	
high inhibition	1	0	0	6	5	
low inhibition	-1	0	0	2	0	
high shifting	0	1	0	12	7	
low shifting	0	-1	0	5	3	
high updating	0	0	1	4	3	
low updating	0	0	-1	4	2	
mixed	-1	-1	0	30	7	(4)
	0	-1	1			(1)
	1	-1	1			(1)
	-1	-1	1			(1)
			Total	96	34	

Table 1 shows the results of CE ability patterns and the number of participants who are classified into the patterns.

5. EXPERIMENT

5.1 Method

5.1.1 Participant

Thirty-four people were selected from the screening sample for the main experiment . The people selected represented a variety of different profiles in terms of shifting, updating, and inhibition ability (however, one limitation was that neither of the two "low inhibition" people could participate in the main test). The people who participated in the main experiment consisted of 20 males and 14 females, aged from 17 to 64 years old (M=42.9, SD=13.2). The numbers of each cognitive pattern are shown in Table 1.

5.1.2 Primary tasks (driving-related tasks)

We selected two types of tasks, which we assume to be related to fundamental aspects of driving.

(1) Detect-respond task

This target detection task was designed to simulate a situation to detect a particular road sign or sudden obstacles while driving and to respond to it. The task consists of two blocks. In the first block (easy block), either a red, down-pointing triangle (r=20 pixels) or a gray circle was presented on the main display for 1500 ms (Figure 2). Participants were instructed to tap a pedal with their right foot immediately after (and not until) they saw a red triangle. The study used six different inter-trial time intervals (750, 1250, 1750, 2250, 2750, 3250 ms) between the end of one trial (when the participant pushed the foot pedal to make his or her response) and the display of the stimulus for the next trial. Both the length of inter-trial intervals and the position that objects appeared in were varied randomly across trials. There was a 1/2 chance on each trial of getting either stimulus (a red triangle or gray circle) and a 1/6 chance of being assigned a specific inter-trial interval. In the second (more difficult) block, stimuli included a red triangle, red circle, gray triangle or gray circle (i.e., there were three distractors, and the target was defined by the conjunction of two features).

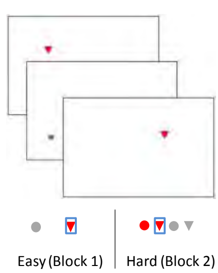

Figure 2 Detect-respond task

(2) Pedal tracking task

This task was designed to simulate performance of keeping inter-vehicle distance. We chose this task based on a pedal tracking task used by [26]. Our implementation of the task was designed to function like an inter-vehicle distance keeping task. A target rectangle in blue (corresponds to a car in front) and a frame-shaped area in yellow were displayed on the main display (Figure 3). The participants' goal was to keep the outer edge of the target rectangle inside the yellow area by controlling a foot pedal.

To simulate adjust inter-vehicle distance controlling an acceleration pedal, The size (side length) of the target rectangle (D) was defined by the equation (1).

$$\boldsymbol{D} = \boldsymbol{D_0} + \left(\boldsymbol{V_0} + \left(\boldsymbol{S_f} - \boldsymbol{L_T}\right)\boldsymbol{dt}\right)\boldsymbol{dt} \qquad (1)$$

Initially D_0 was equal to half the width of the acceptable area (yellow area), V_0 equaled 0 km/h and dt was 0.1sec. S_f represented the fluctuating signal while L_t was a percentage of the first order lag of the throttle opening. D was the second-order integral of the difference between the fluctuating signal (corresponding to the acceleration of the car in front) and the control signal (corresponding to the acceleration of one's own car; the first order lag of the throttle opening %). The fluctuation signal was generated from a mixture of four sine waves.

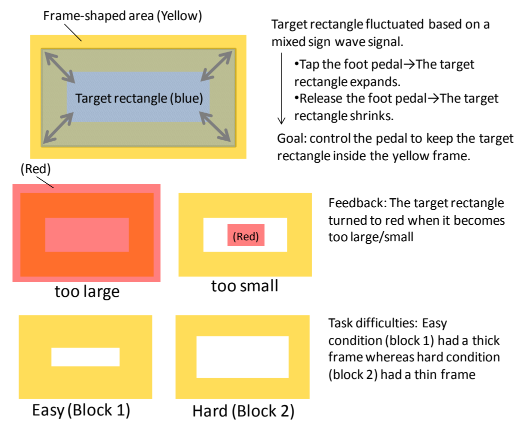

Figure 3 Pedal tracking task

5.1.2.1 Secondary tasks (CE tasks)

We developed inhibition, shifting, and updating tasks in both visual and audio conditions. We also prepared a simple key press task as a control condition (Table 2).

(1) Visual Inhibition (VI)

We used the Stroop task from the screening test as a visual inhibition task. Accuracy and RT were used as the performance measures.

(2) Audio Inhibition (AS)

We used a modified auditory Stroop task based on previous research [5][19][22]. Three different words ("High", "Day", "Low") were presented individually in two pitches (High pitch: 290Hz, Low pitch: 110 Hz) with semi-random word-pitch combinations (the numbers of each combination of word-pitch was balanced). The participant's task was to indicate the pitch by pressing a corresponding key (low = left arrow, high = right arrow).

(3) Visual Shifting (VS)

We wanted to have equivalent shifting tasks in both visual and audio conditions. However, since it was difficult to utilize the WCST in an audio condition, we developed a new task that required rule shifting.

A single digit number (the target number, varying between 1 and 8) was presented on a display with three single digit numbers (the option numbers, between 0 and 9) underneath it. The option numbers represented (a) the sum of the target number plus 1, (b) the decrement of the target number minus 1, and (c) the same number as the target number (i.e., plus 0). Participants were expected to apply one of the rules (+1, -1, 0) to the target number, and then indicate the result by pressing a key that corresponded with the position of the desired option number (the right arrow for the option displayed on the right, the left arrow for the option on the left, and the down arrow for the option presented in the middle. The horizontal ordering of potential responses (-1, 0, +1) presented along the bottom of the screen changed randomly between trials. At the start of the task participants were told to simply guess the rule. After the system provided subsequent feedback as to whether the rule they applied was the correct (expected) one or not (a red "X" for incorrect responses), participants were instructed to find the expected rule as quickly as possible and to apply the same rule until it changed. After eight consecutive correct responses, the program changed the rule.

(4) Audio Shifting (AS)

The procedure in this task was equivalent to the Visual Shifting task except that all the stimuli were presented in audio; A single digit number (1-8; the target number) was presented in a high-pitched voice (290Hz) followed by three single digit number (0-9) in low-pitch voice (110Hz) as options. Feedback to an incorrect response was given using a beep sound. The three option numbers corresponded to the left, down and right arrow keys, in that order.

(5) Visual Updating (VU)

The procedure in this task was similar to that used in the updating task during the screening study. However, in this condition we used two colored circles instead of 3, and the participants were instructed to respond to the second blue and second yellow circle. This visual version of the task was equivalent to the Audio Updating task except that all stimuli were presented visually.

(6) Audio Updating (AU)

For this task we used the modified procedure based on Miyake et al. [17] which was modeled on the Mental Counters task developed by Larson et al. [10]. Participants were presented with high-pitched tones (880Hz) and low-pitched tones (220Hz) for 500ms, with an inter-stimulus interval of 2500ms. This procedure was essentially a repetition of the visual updating tasks used in screening and in the VU condition except that two tones were used in place of two colored circles: Participants responded to the second occurrence of any given tone.

(7) Simple key press task (SK, control condition)

In this task, one of the words "Left", "Down" or "Right" was presented on the secondary display. The participant's task was to press the key that corresponded to the word (Left = left arrow, Down = down arrow, right = right arrow). This task was designed to require roughly equivalent visual and manual workload to the other CE tasks, so that the effect of cognitive workload could be assessed.

Table 2 CE task conditions

	Inhibition	Shifting	Updating	Simple Key press (Control)
Visual	(VI) Stroop task	(VS) Number calculation rule task	(VU) Color monitoring task	(SK) Press left, down or right arrow key corresponding to the instructed direction.
Audio	(AI) Auditory stroop task "High" "Low""Day"in high/low pitch	(AS) Auditory number calculation rule task	(AU) Tone monitoring task	

5.1.3 Apparatus

The main and CE task programs were run on the same computer, and were shown on the main display and secondary display correspondingly. Experimental equipment was set up as shown in Figure 4. Table 3 shows information concerning the manufacturers and models of the equipment.

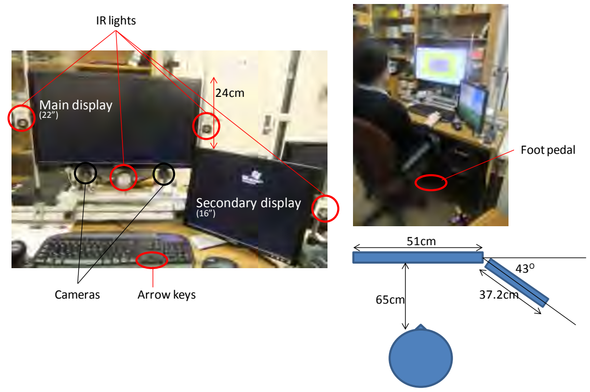

Figure 4 Experiment settings

To measure the participants' eye gaze information, a two-camera Remote Eye-Gaze Estimation (REGT) system (VISION 2020-RB, El-MAR Inc., [4]) was used. The system consists of two cameras (1624 x 1224 pixels) and four infrared light-emitting diodes (LEDs) mounted to either side of the camera (Figure 4).

Table 3 Equipment used in the experiment

		Manufacturer/model
Main display (23" LCD)		Acer/ 23"/58cm Wide LCD Monitor, S231HL
Secondary display (17" TFT)		Dell/ E177FPf TFT, E177FPf
Foot pedal		Logitech/ Driving Force GT
PC	OS	Microsoft/ Windows XP Professional
	Motherboard	Gigabyte Technology Co., Ltd./ X58A-UD3R

5.1.4 Procedure

All experimental sessions were conducted at the University of Toronto from January through March 2012. Participants participated in the experiment individually.

The participants performed one of the two driving-related tasks as a single task. They then performed the driving-related task and CE tasks as dual tasks. The CE tasks consisted of the six CE function conditions (AI, VI, AS, VS, AU, VU) and a Simple Key press (SK) condition. The order of the CE task was varied among participants in order to avoid order effects. After a 5-10 minute break following the first driving-related task condition (performed as a dual task with each of the CE tasks), participants then performed the second driving-related task condition with the same seven CE tasks. Each participant was exposed to all 14 dual task conditions (one CE task at a time), with approximately two minutes' worth of trials per condition. Ordering of conditions was counterbalanced between participants. Participants were instructed to respond as quickly and accurately as they could, and to allocate their attention in such a manner as to perform as well as they could on both of the tasks. Participants were paid for their participation and signed a consent form before participating, in accordance with a research protocol that was approved by the University of Toronto Ethics Review Board.

5.2 Results

5.2.1 *The effect of CE ability on the primary task performance under a particular CE loading condition*

(1) Detect-respond task

We calculated the median correct response times by participant and condition, and compared them between different CE ability groups. Medians, rather than means, were used as measures of central location as they are robust to the effects of positive skew that typically occur in distributions of response time measures, and that was also present in our data. Regression analyses were then carried out to assess the degree to which high CE workload affected detect-respond response times in the presence of CE loading tasks. Both backward and forward methods of entry were used on all the regression analyses reported below. However, since the results for forward and backward entry were similar in all cases, only the backward entry results are reported below.

For analysis of the detect-respond task data, seven backward entry stepwise regression analyses were carried out with response time on the detect-respond task as the dependent measure. One analysis was carried out for the SK condition, and three analyses each were carried out for the inhibition and shifting conditions respectively. These three analyses consisted of one for block one, one for block two, and one where the slowing in detect-respond time between block1 and block2 was used as the dependent measure. The predictor variables in each of these analyses were six measures of CE ability measured in the screening test. The variables and results are summarized in Table 4.

For the block 1 in AI condition, the best fitting model ($p<.01$) contained one predictor variable (inhibition correct RT) that explained 25% ($r=.503$) of the variance in detect-respond response time. The best fitting model for the block 2 ($p<.05$) was also inhibition correct RT as a single predictor, in this case explaining 16% of the variance ($r=.401$). No model was found that predicted the slowing (due to the added difficulty of two extra distractors in the detect-respond task) between block 1 and 2.

For the block 1 in AS condition, the best fitting model ($p<.05$) contained inhibition correct RT and WCST perseveration errors, which jointly explained 22% ($r=.466$) of the variance in detect-respond response time. The best fitting model for the block 2 in AS ($p<.05$) was a single measure of shifting ability, WCST rules completed, in this case explaining 30% of the variance ($r=.544$). No model was found that predicted the slowing between block 1 and block 2 of the detect respond task.

For the block 1 in AU condition, the best fitting model ($p<.05$) contained inhibition correct RT, inhibition accuracy and WCST perseveration errors, which jointly explained 28% ($r=.524$) of the variance in detect-respond response time. There was no significant predictive model for the block 2 data. However, a single variable model involving inhibition accuracy significantly predicted ($p<.05$) the slowing between block 1 and block 2 of the detect respond task, explaining 14% of the variance ($r=.367$).

For the SK task the best fitting model ($p<.05$) again contained only the inhibition correct RT measure, which explained 13% ($r=.366$) of the variance in detect-respond response time.

For the block 1 in VI task the best fitting model ($p<.001$) contained four predictor variables (the two measures of inhibition CE ability plus the two measures of shifting CE ability) that jointly explained 85% ($r=.919$) of the variance in detect-respond response time. The best fitting model for the block 2 in VI ($p<.001$) included three predictors (the two measures of inhibition CE ability, plus the number of WCST perseveration errors), which explained 54% of the variance ($r=.734$). No model was found that predicted the slowing between block 1 and block 2 with the visual inhibition CE task.

For the block 1 in VS task the best fitting model ($p<.001$) contained three predictor variables representing each of the three CE abilities (inhibition correct RT, updating accuracy, and WCST perseveration errors) that explained 58% ($r=.76$) of the variance in detect-respond response time. The best fitting model for the block 2 in VS ($p<.005$) contained the same three predictors as had been found for block 1, in this case explaining 39% of the variance ($r=.62$). No model was found that predicted the slowing between block 1 and block 2.

For the VU task none of the predictive models were statistically significant either for block one or for block two data. As in most of the other CE task conditions, no model was found that significantly predicted the slowing between block 1 and block 2. The preceding results are summarized in the first two columns of Table 4, where each cell represents a regression analysis. Note that no significant predictors were found for the block 2 updating analyses.

Table 4 Significant Predictors of the Primary Task Performance by type of CE task CE Function loading

Secondary task \ Primary task		Detect-Respond Task: Block 1	Detect-Respond Task: Block 2	Pedal Tracking (No significant differences between blocks)
Auditory	Inhibition	I	I	U
	Shifting	I, S	S	I, S, U
	Updating	I, S		S, U
Visual	Inhibition	I, S	I, S	U
	Shifting	I, S, U	I, S, U	S, U
	Updating			S, U

●dependent variables
detect-respond task: reponse time (RT)
pedal tracking task: error rates (the proportion of the time that the target rectangle was out of the yellow allowable area)
●predictor variables (based on the screening test results)
inhibition (I) : correct RT and accuracy in Stroop test
shifting (S) : prseveration error rate and the number of rules completed in WCST
updating (U) : correct RT and accuracy in color monitoring test

(2) Pedal tracking task

We calculated the mean error rates (the proportion of the time that the target rectangle was out of the yellow allowable area) by participant and condition, and investigated which CE functions can be predictor of the error rates. As with the detect-respond task we ran a series of backward stepwise regression analyses examining which of the CE abilities predicted pedal tracking accuracy in the presence of the different CE task conditions. The results are summarized in the right-most column of Table 4. Note that the pedal tracking regression analyses were carried out with pooled data across both blocks because no significant differences were found between the blocks.

For tracking accuracy during the AI task as a secondary task, updating total accuracy was the only significant predictor ($p<.005$) explaining 30% of the variance ($r=.547$).

In the AS condition, tracking accuracy was predicted ($p<.001$) by a combination of the three CE abilities (inhibition accuracy, WCST completed, and updating total accuracy), with 48% of the variance explained ($r=.689$).

In the AU condition, only two of the CE abilities were represented in the best fitting ($p<.005$) model (WCST completed rules, and updating total accuracy), accounting for 38% of the variance in pedal tracking accuracy ($r=.613$).

In the SK condition, updating total accuracy ($p<.001$) was the sole predictor in the selected model explaining 34% of the variance ($r=.583$).

In the VI condition, updating total accuracy significantly predicted pedal tracking accuracy ($p<.001$), explaining 40% of the variance ($r=.632$).

In the VS condition, updating total accuracy and WCST jointly predicted the pedal tracking accuracy ($p<.005$), accounting for 38% of the variance ($r=.614$).

Finally, in the VU condition, updating total accuracy and WCST jointly predicted ($p<.001$ 43% of the variance in pedal tracking accuracy ($r=.658$).

5.2.2 The effect of modality and task types

Based on the eye tracking data, we calculated the proportion of the time that participants viewed the main vs. the secondary task display (main display gaze rate). Figure 6 shows the main display gaze rate and detect-respond task performance (difference of correct response time between single and dual task; diffMedianHitRT).

In general, the main display gaze rate was higher in the audio vs. visual secondary task conditions (i.e., there was less visual distraction in the audio conditions). However, the VU condition showed a higher gaze rate on the main display (lower visual distraction) as compared to the other visual conditions. This may be because the task could be performed using peripheral vision, as was reported by some of the participants.

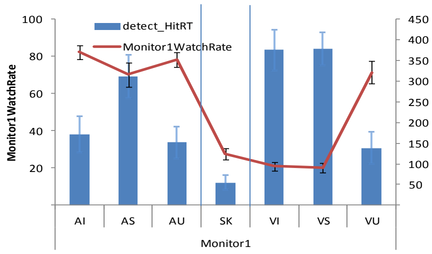

Figure 6. Main display gaze rate and the driving-related task performance (detect-respond task)

As shown in Figure 6, driving-related task performance was not impaired as much with the audio secondary tasks. The VI and VS conditions were visually distracting and results in a slowing of primary task performance. On the other hand, the VU secondary task resulted in less visual distraction and relatively little slowing in primary task performance relative to the single task condition. One other feature in Figure 6 is that the slowing in primary task performance with the AS secondary task was much higher than the other audio conditions and almost comparable with the VI and VS slowing. This suggests that the AS task was more cognitively distracting than the other audio secondary tasks.

5.3 Discussion

5.3.1 Individual CE abilities and driving-related task performance while performing the particular CE task as a secondary task

The results of the regression analysis did not support our hypothesis that the match between CE Function loading on a CE task and individual ability on that CE function predicts task performance on the driving-related task in a dual task setting. In other words, we could not find evidence that CE ability can be a predictor of the driving-related task performance under a particular CE loading condition.

On the contrary, we found (unexpectedly) a fairly consistent relationship between CE ability and primary task performance, regardless of which CE function was loaded by the secondary task.. The results showed that better inhibition and shifting abilities helped people perform better in the target detection task whereas in the pedal-tracking task, it was higher shifting and updating ability that led to better performance (Table 4).

These results suggest that shifting ability aids in managing dual tasks, whereas inhibition is required to deal with distraction in the detect-respond task. Additionally updating appears necessary to deal with distraction in the pedal tracking task.

The overall pattern of results showed a strong influence of cognitive distraction on the target detection and pedal tracking tasks, as indicated by the fact that people who had higher abilities on specific CE functions were able to perform better on the driving-related task when it was carried out in a dual task setting.

Why wasn't the relationship between ability on a particular CE function and primary task performance affected by a secondary task that loaded on that function? Two possible explanations are suggested below.

1. CE functioning changed in the dual task setting

Some previous research studies have argued that dual-task coordination is a separate component of CE function. When a task is performed in a dual-task setting, the function of dual-task coordination may become the most relevant, and strongly loaded, function. This might explain why shifting ability significantly predicted primary task performance in almost of all the dual task settings that we examined.

2. The secondary tasks we designed might not have been pure enough measures of the CE functions that we were trying to characterize.

In order to provide a equivalent rule-shifting task in both visual and audio conditions, we created a new shifting task based on the WCST. However, we observed that participants often needed to retain or retrieve the target number while performing this task. Thus it is likely that the task did not purely load on shifting function, but also loaded on memory retention/retrieval. Similar concerns might be raised about the updating and inhibition secondary tasks that were used in this study.

Thus it is possible that expected secondary task CE function loadings did not interact with ability on those function because participants were loaded on several CE functions during the dual-task, and not only the CE function targeted by the secondary task.

5.3.2 The effect of visual and cognitive workload

Comparison between visual and audio conditions showed that participants generally looked away from the main display for longer periods of time in visual vs. audio conditions, except for the VU condition, where participants seemed to use their peripheral vision. However, comparison between SK and other audio conditions showed that audio tasks with high cognitive loads had been slowed down more. This suggests that "audio UI with high cognitive load could be more distracting than visual UI with low cognitive load" . In this research, we used a single test to estimate each CE ability. However, due to the well-known test impurity problem (e.g. [21]), no test completely represents a particular CE ability. Thus it is recommended for further research to use multiple test batteries for each CE function to assess the common factors among the tasks.

6. CONCLUSIONS

We had expected that cognitive ability would affect the ability to perform a driving-related task in the presence of secondary tasks that loaded on activities requiring CE abilities and this was found to be generally true. With some exceptions people with higher cognitive abilities tended to have better performance, both on pedal tracking, and on the detect-respond task, in the presence of the CE loading secondary tasks. However, this affect of CE ability was more notable in the easier conditions of the detect-respond task, and generally did not affect the slowing that occurred when the detect-respond task was made more difficult in the second block through the addition of more distractors. Thus it appears that the benefits of higher cognitive ability are stronger in simpler versions of a primary task when performed in the presence of distracting tasks that load cognitive abilities. We also found evidence of a fair amount of interplay between the CE functions highlighted by the previous research [17] with performance in the presence of a distracting task representing one function sometimes being predicted by a combination of the CE abilities, or in some cases by a different CE ability.

Overall these results indicate that there is a role for detailed evaluation of CE abilities and their impact on distracted driving. However, the present results suggest that CE abilities play a larger role in simpler versions of primary tasks and that the mapping between the impact of CE abilities and the CE functions required in the distracting CE task is not a simple one.

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8. REFERENCES

[1] Baddeley, A.D. (1986) Working Memory. Oxford: Clarendon Press.

[2] Baumann, M. R. K, Petzoldt, T., Hogema, J. & Krems, J. F. (2008). The effect of cognitive tasks on predicting events in traffic. *In Proceedings of the European Conference on Human Centred Design for Intelligent Transport Systems.* Lyon, France, 2008, 3-11.

[3] Burgess, P. W. (1997). Theory and methodology in executive function research. In P. Rabbitt (Ed.), Methodology of frontal and executive function (81–116). Hove, UK: Psychology

[4] Press.Guestrin, E. D. & Eizenman, M. (2007). Remote point-of-gaze estimation with free head movements requiring a single-point calibration, *Proceedings of Engineering in Medicine and Biology Society 2007,* 4556 - 4560.

[5] Hamers, J. E, & Lambert, W. E. (1972). Bilingual interdependencies in auditory perception. *Journal of Verbal Learning and Verbal Behavior*, 11, 303-310.

[6] Hancock, P. & Meshkati, N. (Eds.), Human Mental Workload. Amsterdam: North Holland.

[7] Hurts, K., Angell, L. S., and Perez, M.A. (2011). The Distracted Driver: Mechanisms, Models, and Measurement. In P. De Lucia (Ed.), *Reviews of Human Factors and Ergonomics*, Vol. 7, 3-57.

[8] Kass, S. J., Cole, K. S., & Stanny, C. J. (2007). Effects of distraction and experience on situation awareness and simulated driving. *Transportation Research Part F: Traffic Psychology and Behaviour,* 10 (4), 321-329.

[9] Lehto, J. (1996). Are Executive Function Tests Dependent on Working Memory Capacity? *The Quarterly Journal of Experimental Psychology,* Section A, 49:1, 29-50

[10] Larson, G. E., Merritt,C. R. & Williams, S. E., Information processing and intelligence: Some implications of task, *Intelligence*, Volume 12(2), 131–147

[11] Levin, H. S., Fletcher, J. M., Kufera, J. A., Harward, H., Lilly, M. A., Mendelsohn, D., Bruce, D., & Eisenberg, H. M. (1996). Dimensions of cognition measured by the Tower of London and other cognitive tasks in head-injured children and adolescents. *Developmental Neuropsychology*, 12, 17–34.

[12] Logie, R. H., Cocchini, G., Della Sala, S., & Baddeley, A. (2004). Is there a specific executive capacity for dual task co-ordination? Evidence from Alzheimer's disease. *Neuropsychology*, 18, 504–513.

[13] Lowe, C., & Rabbitt, P. (1997). Cognitive models of aging and frontal lobe deficits. In P. Rabbitt (Ed.), Methodology of frontal and executive functions, 39–59. Hove, UK: Psychology Press.

[14] Mäntylä, T., Karlsson, M., & Marklund, M. (2009). Executive control functions in simulated driving. *Applied Neuropsychology*, 16, 11-18.

[15] Matthews, R., Legg, S., and Charlton S. (2003). Distraction, driving, multiple-task, workload, performance, *Accident analysis and prevention,* 35 (4), 451-457.

[16] Miller E.K., & Cohen J.D. (2001). An integrative theory of prefrontal cortex function. *Annual Review of Neuroscience*, 24 (1): 167–202.

[17] Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H. & Howerter A. (2000). The unity and diversity of executive functions and their contributions to complex ''Frontal Lobe'' tasks: A latent variable analysis. *Cognitive Psychology*, 41, 49–100.

[18] Mizobuchi, S., Chignell, M., Suzuki, J., Koga, K. & Nawa, K. (2011) Central Executive Functions Likely Mediate the Impact of Device Operation When Driving, *Proceeding of the third conference on automotive user interface and interactive vehicular applications 2011,* 129-136.

[19] Morgan, A. (1989) An auditory Stroop effect for pitch, loudness, and time, *Brain and Language*, 36 (4), 592-603.

[20] Ogden, G.D., Levine, I.M., & Eisner, E.J., (1979). Measurement of workload by secondary tasks, *Human Factors,* 21, 529-548.

[21] Rabbitt, P. (1997). Introduction: Methodologies and models in the study of executive function. In P. Rabbitt (Ed.), Methodology of frontal and executive function, 1–38. Hove, UK: Psychology Press.

[22] Roberts K. L. & Hall D. A. (2008). Examining a supramodal network for conflict processing: a systematic review and novel functional magnetic resonance imaging data for related visual and auditory Stroop tasks. *Journal of Cognitive Neuroscience.* 20, 1063–1078

[23] Strayer, D. L., Cooper, J. M., & Drews, F. A. (2004). What do drivers fail to see when conversing on a cell phone? *Proceedings of the 48nd Annual Meeting of the Human Factors and Ergonomics Society,* 2213-2217.

[24] Strayer, D. L., & Drews, F. A. (2007). Cell-phone-induced driver distraction. *Current Directions in Psychological Science*, 16, 128-131.

[25] Szmalec, A., Demanet, J., Vandierendonck, A., and Verbruggen, F. (2009). Investigating the role of conflict resolution in memory updating by means of the one-back choice RT task. *Psychological Research Psychologische Forschung* 73:3, 390-406.

[26] Uno, H., and Nakamura, Y. (2010) Study on surrogate laboratory techniques to assess driver workload induced from voice-input interface. *Proceedings of the JASE annual congress (Fall)*, No.99-10, 1-6. (in Japanese)

[27] Wickens, C.D. (2002): Multiple resources and performance prediction, *Theoretical Issues in Ergonomics Science*, 3:2, 159-177.