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Detailed analysis of distraction induced by in-vehicle verbal interactions on visual search performance

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ABSTRACT

We examined the negative effect of in-vehicle verbal interaction on visual search performance. Twenty participants performed a primary visual search task and a secondary verbal interaction task concurrently. We found that visual search performance deteriorated when the secondary task involving memory retrieval and speech production was performed concurrently. Moreover, a detailed analysis of the reaction time as a function of set size revealed that the increased reaction time was attributed not to the slowing of inspecting each item but to the increased processing time other than the inspection of each visual item, possibly due to task switching between the primary visual search task and the secondary verbal task. These findings have implications for providing information from in-vehicle information devices while reducing the risk of driver distraction.

1. Introduction

Distraction from using a cell phone while driving is a serious safety problem. This issue has been studied extensively, and most studies have indicated that using a cell phone while driving negatively affects driver performance. When a driver engages in a cell phone conversation, negative effects were found on various driver performance measures: reaction time to and detection rate of traffic signals [25,27,28], reaction time to a visual target [1], brake-reaction time [2], performance of a peripheral detection task [3], and situation awareness [7,10]. Distraction from a cell phone conversation was also confirmed by examining brain activities (the event-related brain potential, ERP) elicited by the onset of a pace car's brake lamp in the car-following paradigm [26]. Because the negative effects of cell phone use while driving have been reported, legislation to ban cell phones in some form while driving has already been established in many countries.

Recent studies have shown that a cell phone conversation impairs driver performance even if a hands-free device is used (e.g. [26–28]). In other studies, the level of difficulty of conversation was controlled experimentally. When the conversation became more difficult and more complex, the disruptive effect of conversation on driver performance increased [13,15,17]. Furthermore, a conversation between a driver and a passenger sitting next to the driver may be less obstructive than a cell phone conversation between a driver and someone who is outside the car because a passenger sitting next to the driver can see the driving situation and modulate the pace of conversation based on the traffic situation [7]. While such a suppression of in-car conversation was observed in a previous study [6], Nunes and Recarte [15], in which a live conversation between a driver and a passenger was compared with a cell phone conversation, they found no difference between these two conversation conditions when the same cognitive tasks were performed. This result suggests that a driver distraction by a cell phone conversation mainly depends on the level of cognitive demand imposed by the conversation, and that driver distraction can remain even if the driver and the passenger perform coping behavior such as suppression of conversation when the traffic situation becomes more demanding.

Not only a cell phone conversation but also in-vehicle verbal interaction between a driver and information devices with voice-activated interfaces may impair driver performance. A voice-activated interface, with which a driver can control information devices by voice command, has been used increasingly for in-vehicle information devices. A voice-activated interface may seem to be distraction-free because the demand for manual control is minimal and a driver can continue visual observation. However, Lee et al. [11] reported that brake-reaction time increased when drivers used a speech-based e-mail system while driving, suggesting that speech-based interfaces do not completely remove distraction.

In a study on driver distraction, researchers focused on driver performance impairment (e.g. delay of brake-reaction time) as a behavioral measure of driver distraction, reflecting degraded driver-

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cognitive processes induced by a deficiency in allocated attention resources. When a driver talks with someone or with an in-vehicle device while driving, the driver has to simultaneously allocate attention resources to the driving task and to verbal interaction. Such a dual-task situation may cause a deficit in attention resources allocated to each cognitive process for performing a driving task. We focused on a visual search task, which is one of the most important cognitive sub-tasks for driving. An experienced driver acquires and optimizes this visual search skill through driving experience [33]. The skill of efficiently scanning a traffic scene is obviously required to drive safely in an actual driving situation. To examine the characteristics of visual search under the cognitive load imposed by a concurrent verbal interaction is important for studying driver distraction.

In the studies examining the effect of mental tasks on a driver's visual behavior, the negative effect of concurrent mental tasks has been reported. Richard et al. [22] investigated the effect of auditory tasks on visual search by adopting the change detection paradigm and reported that change detection is delayed when an auditory task is performed concurrently. Recarte and Nunes [20] measured eye movement when participants drove while performing a secondary verbal task or a spatial-imagery task and found that both secondary tasks, particularly the spatial-imagery task, negatively affects visual search performance. Several studies using a peripheral detection task (PDT), which requires drivers to detect the onset of visual stimuli intermittently presented in the peripheral visual field, have reported that a cell phone conversation while driving impairs this visual-detection performance [17,29,30].

In a basic visual search study, two visual search modes have been distinguished; efficient parallel search and effortful serial search. This distinction is based on the feature of the visual items such as the color of the target [32]. When the target is defined by one feature, visual search is executed in the parallel search mode; all items are processed in parallel so that the search time is independent of the number of items (i.e. set size). When the target is defined by a conjunction of several features, visual search is executed in the effortful serial mode; each item is verified serially so that the search time depends on the number of items. The reaction time obtained in a visual search experiment is typically a linear function of the number of items. The slope of the reaction time function was steeper in the serial mode than in the parallel mode, while the intercept of the function was the same in both modes.

In an actual driving situation, a driver should perform both types of visual search. For example, when a driver drives at night, a prominent signal light located at an intersection without road illumination can be detected instantaneously using efficient parallel search. However, when a driver drives in a downtown area, there are many kinds of hazardous objects (e.g. pedestrians, cyclists, or vehicles stopping in the road) to detect. During the day, there are many such objects with many perceptual features, making it difficult for a driver to differentiate them by using efficient parallel search. Visual search in such a driving situation should be serial and effortful, and search time depends on the number of objects in the situation.

The purpose of this study was to examine the negative effect of in-vehicle verbal interaction on effortful visual search performance by adopting the dual-task paradigm and analyzing the search time function in detail. Previous studies on cell phone conversations while driving have indicated that verbal interaction impairs driver's performance. Furthermore, in basic experimental studies of visual search, it has been proposed that visual working memory has an important role in visual search, and visual search efficiency is impaired by concurrent working memory tasks [8,36]. These findings imply that verbal interaction negatively affects visual search performance when a heavy working memory load is imposed by verbal interaction, even though it is desirable that visual search can be done when a driver performs additional tasks. Even though previous studies have examined the effect of mental tasks on visual search while driving and reported that additional load clearly impaired visual search performance [15,21,22], sufficient detailed analysis of a distraction's effects on visual search processes has never been conducted.

For specifying this susceptible processing stage to concurrent verbal processing, it is not sufficient to compare task performance during driving plus an additional task (dual-task) in a driving only (control) condition. It is necessary to do a compositional analysis of search time, which has been considered a reliable method for studying cognitive processes and has been applied in the field of cognitive psychology. This makes it possible to estimate the processing time required to complete each stage of a cognitive process. It is possible to specify a susceptible processing stage to concurrent verbal processing, of which participants are not subjectively aware. This finding will be useful in making a guideline for designing a user interface of in-vehicle devises that is resistant to distraction. It will also be helpful in making a guideline of driver's behavior during verbal interaction while driving.

2. Method

2.1. Participants

Twenty people (6 females and 14 males) were recruited to take part in this study. Participants had a mean age of 30.8 years and more than two years of driving experience.

2.2. Apparatus

Stimuli for the visual search task were presented on a plasma display (Pioneer PDP-506HD) placed in front of the participant. A Windows PC (DELL Precision 380) was used to generate the stimuli and record participants' responses for the visual search task. The visual search task was programmed using Microsoft Visual Basic 6.0. A gaming steering wheel (Logicool GT Force LPRC-10000) was put on the desk in front of the participant's seat. Small keys located on the center of the steering wheel were used for participants' responses.

The car navigation system (Pioneer AVIC-HRZ09) was placed in front of the driver to the left. From the participants' point of view, they could not directly see the LCD display of the car navigation system. An auditory message from the car navigation system was presented from a sound speaker, which was in the same place as the system. To present an auditory stimulus for the secondary task, an MD audio player was used.

2.3. Tasks

The primary task was a simple visual search task that required participants to search for a target in a visual stimulus array (Fig. 1), subtended approximately 6.52° x 8.64° at a viewing distance of 1.5 m. It contained 16 possible positions for the stimulus to appear. Each visual item was subtended at 1.63° × 2.16°. Two types of circles were used as a visual item for the visual stimulus array: a circle with a tiny part of the circumference missing (distracter) and a complete circle (target). Participants were asked to search the visual stimulus array to detect the target as quickly as possible and to decide which target was in the stimulus array by pressing a key on the steering wheel. Treisman [31] conducted an experiment using circles with and without part of the circumference missing as a target and a distracter and found that the search time increased with set size when the target was a complete circle and the distracter was a circle with a gap. Thus, the visual search process in our primary task is thought to be serial and effortful.

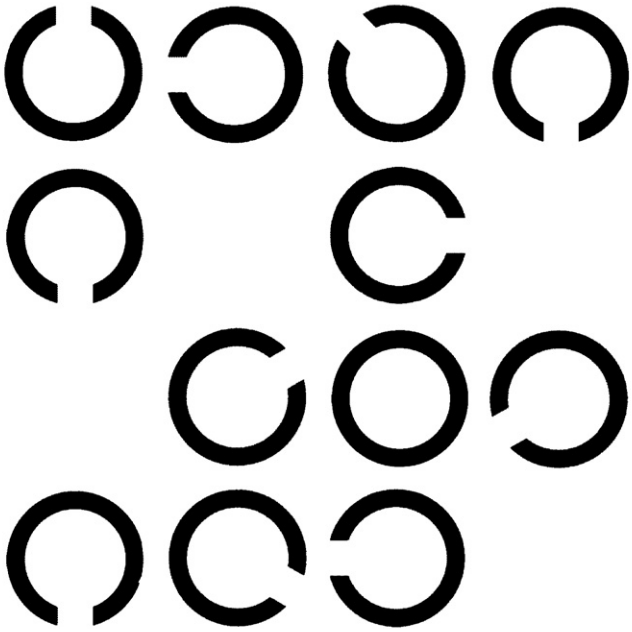

Fig. 1. Stimuli used in visual search task.

The primary task is so simple that it is not directly related to visual search when drivers perform while driving. In an actual driving situation, drivers' visual search patterns are strongly regulated by their mental models on driving, which have been acquired through their driving experiences. Drivers evaluate a situation based on this mental model and scan an important part of the situation preferentially. However, in the visual search task of this study, the possibility of a target appearing was the same in 16 possible stimulus positions so that participants were not able to use expectations based on their mental model. The performance of the primary task was simply related to the visual search efficiency of the participant. Although the visual search task of this experiment is essentially different from the visual search in driving situation, it is helpful to examine the characteristic of visual search when a driver is engaging driving while doing some distracting tasks because the visual search efficiency can be clearly assessed by adopting such a simple visual search task.

Additionally, the visual search task of this experiment seems to be relevant when the characteristic of visual search of a novice driver whose mental model has not been sufficiently developed. It may also be comparable to a visual search when drivers encounter an unfamiliar situation. Because a mental model for driving is not available for such an unfamiliar situation, a driver has to give up an automatic driving style and to intentionally search the situation in a sequential manner, looking for hazardous objects.

The secondary tasks, which corresponded to in-vehicle verbal interaction, were “explaining”, “listening”, and “recalling”. In the explaining task, participants were asked to verbally explain to a passenger how to control the car navigation system to complete several operation tasks (e.g. setting the destination location). At the beginning of the experiment, all participants were unfamiliar with the car navigation system used in the experiment. Participants were trained how to operate the car navigation system before starting the dual-task session. During the dual-task session, participants were prohibited to refer to the user manual. Thus, participants relied on their knowledge acquired in the training to explain the system.

Participants were prohibited from looking at the LCD monitor and were told to operate the car navigation system manually. A researcher acting as a passenger operated the car navigation system as the participants instructed. The car navigation system worked so that participants could hear the auditory feedback from the car navigation system. Additionally, the researcher reported back the result of the instructed operation to the participants. Thus, participants had to perceive the current status of the car navigation system by the auditory feedback and the researcher's verbal report.

The explaining task was designed to simulate the above situation, including functions for both driver and passenger. For example, if the passenger operates the car navigation system to search for information around the current position while the driver is driving, it is assumed that the passenger would ask the driver to explain how to operate the car navigation system. Following a question from the passenger, the driver has to verbally instruct the passenger on how to operate the car navigation system. Because the driver is not allowed to execute a complex operation sequence by himself while driving, he has to explain how to do it verbally unless he stops the car. This type of task seems to be unusual for a driver. However this task is essentially equivalent to an in-vehicle conversation on difficult and complex topics because both the explaining task and a difficult conversation impose a heavy cognitive load on a driver. Moreover, if a personal information and entertainment system (e.g. personal display monitors which are connected to a car navigation system or a media player controllable by each passenger) is introduced, a driver, who is perhaps the most familiar with this car, will be frequently requested to explain how to use it. For drivers driving such a car, this explaining task will be normal.

In the listening task, participants listened to audio clips that included traffic information, radio news, a talk show, and weather forecast. Twenty-one audio clips were used in the experiment. The average length of the audio clips was 89 s. Participants were required to remember the information included in each audio clip.

In the recall task, participants were required to recall the content of speech information presented in the respective listening task. They did not have to recall the content strictly word for word, but they were encouraged to recall as much content as possible.

2.4. Procedure and design

Participants were given approximately 1.5-h training sessions to become familiar with the car navigation system and learn how to operate it. This was the first time for all participants to operate the navigation system used in this experiment. During the training session, participants were permitted to operate the navigation system freely and to refer to the user's manual. They were asked to learn how to operate the car navigation system to complete instructed tasks. There were 33 tasks (e.g. change default values of the car navigation system, retrieve traffic or area information) to be learned. At the end of the training session, the participants' knowledge of the car navigation system was checked. We also confirmed that participants were clearly able to explain how to operate the car navigation system without referring to the user manual and without visually checking the status of the car navigation system.

After the training session, participants performed a visual search task training session which included 96 trials in which they performed only the visual search task. Following these training sessions, participants experienced the dual-task session in which they performed the visual search task concurrently with each of the secondary tasks. There were three experimental conditions in the dual-task session. The control, in which participants performed the visual search task without the secondary task, included 320 trials. The control took about 29 min on average. In the explaining task, participants were required to answer 20 questions posed by the researcher about the operation of the car navigation system while performing the visual search task. The time required to complete this condition was dependent on the efficiency of the explaining task, i.e., the number of trials for the visual search task varied among participants. The average time required to complete the explaining task was 58 min, and the average number of visual search trials in the explaining task was 568. The listening and the recall tasks were performed in the same block: recalling the content of the audio clip immediately after listening to the audio clip. In the listening and recall tasks, 21 audio clips were presented. The time required to complete this task was affected by the time participants took to answer the question[s?] about the contents of audio clips. Thus, the number of trials of the visual search task varied among participants as in the explaining task. The average time required to complete the listening and recall tasks was 58 min, and the average number of visual search trials in the listening and recall tasks was 604. The order in which the participants experienced each secondary task and the control was counterbalanced.

The independent variables of this experiment were the set size, the secondary task, and the target presence. All variables were within-participant. The dependent variables were the reaction times and the detection rate of the visual search task.

3. Results

The median reaction times and the detection rates were calculated as representative values for each participant, target presence, set size, and secondary task. SPSS version 14 was used for the statistical analysis.

3.1. Reaction time measures

Fig. 2 shows the mean reaction times for each combination of tasks in the target-present condition when the target appeared in the stimulus array. The mean reaction times were subjected to a repeated analysis of variance (ANOVA) in each condition with factors of set size (4, 8, 12 and 16) and secondary task (explaining, listening, recall, and control). Because the Mauchly sphericity test indicated the violation of the sphericity assumption, the Greenhouse–Geisser Epsilon was used for the analysis. From the ANOVA, the main effects of set size (F (1.57,28.26) = 152.79, MSe = 126,730, $p < .001$, partial $\eta^2 = .895$) and secondary task (F(1.60,28.73) = 24.45, MSe = 229,483, $p < .001$, partial $\eta^2 = .576$) were confirmed. Reaction times increased monotonously as the set size increased. For the secondary task, the Bonferroni post-hoc test showed that the mean reaction times when the explaining task or the recall task were performed were significantly longer than those when the listening task was performed or no secondary task was performed ($p < .05$). There was no significant interaction between set size and secondary task (F(3.78,67.83) = 1.50, ns).

Fig. 3 shows the mean reaction times for each combination of tasks in the target-absent condition when the target did not appear in the stimulus array. For the data in the target-present condition, a 4×4 repeated measures ANOVA was conducted. Because the Mauchly sphericity test indicated the violation of the sphericity assumption, the Greenhouse–Geisser Epsilon was used. The main effect of the secondary task was significant (F(1.33, 23.96) = 20.57, MSe = 657,416, $p < .001$, partial $\eta^2 = .533$). The Bonferroni post-hoc test showed that the mean reaction time with the control was not significantly different from the mean reaction time with the listening task. The main effect of the set size was also significant (F(1.56, 28.15) = 216.19, MSe = 193,767, $p < .001$, partial $\eta^2 = .923$), and the post-hoc test indicated that reaction times increased monotonously as the set size increased. No significant interaction between set size and secondary task was found (F(2.85,51.31) = 2.30, ns).

Linear regressions for reaction time as a function of set size were computed separately for each secondary task for target-present and target-absent trials. The slopes and intercepts for each secondary task are listed in Table 1. The slopes were from 58.12 to 81.40 in the target-present condition while the slopes were from 123.46 to 157.55 in the target-absent condition, indicating that the visual search in this task was confirmed to be serial and self-terminating as expected. Each item was inspected serially and the search process was terminated at the moment when the target was found [14]. While the slopes were monotonous among secondary tasks in each target-present condition, there were clear differences in the intercepts. Thus, the differences in the reaction times among secondary tasks were based on processing other than the serial inspection of each item, and not on the slowing of inspection of each item.

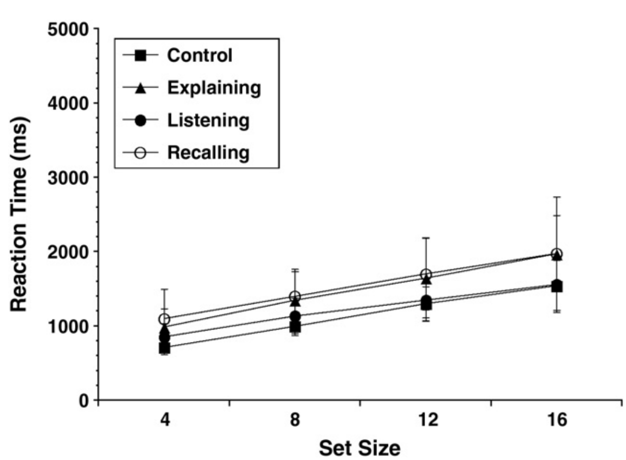

Fig. 2. Mean of reaction times for visual search task in trials where target was present in stimulus array. Data are shown as function of set size and of secondary tasks. Error bars mean standard deviations.

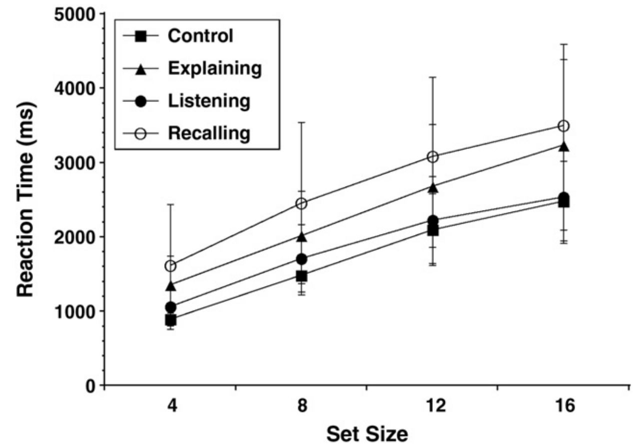

Fig. 3. Mean of reaction times for visual search task in trials where target was absent in stimulus array. Data are shown as function of set size and of secondary tasks. Error bars mean standard deviations.

3.2. Detection rate measures

The mean detection rates are shown in Fig. 4. Inverse sine transformation was applied to the detection rates, and a repeated

Table 1
Linear regression for reaction time as function of set size.

Target	Secondary task	Slope	Intercept	R^2
Present	Control	69.98	442.72	.682
	Explaining	81.40	678.61	.342
	Listening	58.12	647.92	.475
	Recalling	73.19	817.79	.365
Absent	Control	134.13	389.37	.708
	Explaining	157.55	739.72	.456
	Listening	123.46	641.65	.557
	Recalling	156.74	1088.43	.330

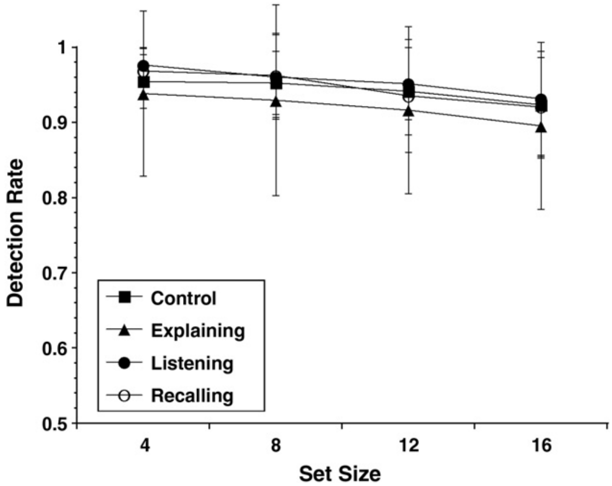

Fig. 4. Mean detection rates for visual search task as function of set size and of secondary task. Error bars mean standard deviations.

ANOVA with set size and secondary tasks was performed on these transformed values.

An ANOVA, which also used the Greenhouse–Geisser Epsilon because of the violation of the sphericity assumption, indicated that the main effect of set size was significant ($F(1.86, 24.27) = 11.47$, $MSe = 42.14$, $p < .001$, partial $\eta^2 = .469$). The post-hoc test indicated that there were significant differences when the set size was 16 and less than 12 ($p < .05$). The main effect of the secondary task was not significant ($F(1.41, 18.32) = 1.47$, ns), and there was also no significant interaction ($F(4.88, 63.49) = .919$, ns). These results suggest that the possibility of missing the target increases when participants are asked to process many items to be inspected, irrespective of which secondary task is combined with the visual search task.

4. Discussion

The purpose of this study was to examine the effect of in-vehicle verbal interaction on the visual search performance of a driver. Participants performed the visual search task while performing one of the secondary verbal tasks. Results revealed that the reaction time increased when some verbal tasks were performed concurrently with the visual search task, confirming that the concurrent verbal interaction had a negative impact on visual search performance.

This study resulted in two important findings; one is that a speech production including verbal interaction affects visual search performance, and the other is that verbal interaction does not slow the inspection speed of each visual item. In our research, three types of verbal interaction tasks were investigated. Results indicated that reaction times in the visual search task increased when either the explaining task, which involved asking participants to explain how to operate the car navigation system, or the recall task, which involved asking participants to recall the content of a radio broadcast they listened to, was used as the secondary task. On the contrary, the listening task, which involved asking participants to listen to a radio broadcast in silence, had no effect on the visual search task.

Both the explaining and recall tasks, which were obstructive to the visual search task, required participants to recall the memorized contents and to report them verbally. However, the listening task, which was not obstructive to the visual search task, involved neither memory retrieval nor speech production. Thus, the critical feature of verbal interaction, which has a negative impact on visual search, seems to be memory retrieval and speech production processes. Previous studies on cell phone conversations while driving have shown that a verbal task involving a memory retrieval process induced driver distraction [9,17,19]. Moreover, some studies have reported that listening to a radio while driving does not induce distraction [5,12,28], suggesting that memorizing an auditory message provided from a radio does not affect a driver's attention. Passive information processing such as memorizing incoming auditory information may not be detrimental to a driver's attention. Active information processing, which is required to output information processed in the internal cognitive system to someone in the external world, may be critical for attention. A verbal explanation, including memory retrieval and speech production, leads directly to distraction.

As shown in Figs. 2 and 3, the reaction times increased as the set size increased in all secondary tasks. Slopes of the reaction time function, which reflected the inspection rate of each item, were approximately the same, and the differences in reaction time between the secondary tasks depended on the difference in the intercepts, which reflected cognitive processes other than searching. This result suggests that verbal interaction does not slow inspecting each item but negatively affects processes other than that of inspecting each item.

Possible processes affected by verbal interaction are the following: (1) task switching from a verbal secondary task to a visual search task, (2) the pre-attentive process to recognize the spatial configuration of stimuli to be searched for and to decide how to search for it before starting to inspect each stimulus, and (3) response selection and execution after completing inspection of each stimuli. Although it is impossible to identify which process is the most susceptible to the concurrent verbal interaction from the data obtained in this study, task switching seems to be the most susceptible. The stimulus for the visual search task was presented immediately after participants responded to the previous stimulus presentation in this study. By contrast, no visual stimuli for the explaining and the recall tasks were presented, and the performance of these tasks was self-paced because participants could modulate their timing of utterance. Thus, the dual-task performance of our experiment was characterized by task switching between an inserted cognitive process for verbal interaction tasks (i.e. memory search, speech production, etc.) and a continuous process for the visual search task. Participants performed the continuous visual search task and sometimes switched the priority of processing from the visual search task to the secondary verbal task. The central executive of the working memory system is responsible for task switching [4], and several previous studies focusing on task switching (e.g. [23]) have reported the “switching cost,” which was a degraded task performance immediately after executing task switching. Thus, an increased intercept of the reaction time function in the explaining and the recall tasks may be reflecting the cost to execute task switching from the verbal interaction task to the visual search task. The similar slopes for each secondary task condition may mean that once a task switching from the secondary verbal interaction task to the visual search task is completed, an inspection of each stimulus can be executed efficiently without affecting the secondary verbal interaction task.

If a driver encounters an attention-demanding situation in which efficient task switching between the visual search and the verbal tasks is not allowed, slowing of inspection may be observed. In studies examining a dual-task situation including visual search and working memory tasks [8,16], the experiments were designed to require participants to perform a dual-task, with the result that the search slope was steeper in the dual-task than in the single task. This result means that performing a working memory task deteriorates visual search efficiency.

Two important considerations mentioned above have implications for reducing driver distraction induced by in-vehicle vehicle information devices and for establishing safety tips for drivers and passengers. The finding that a verbal interaction task, including memory search and speech production interferes with a driver's visual attention, suggests that it is important to reduce the demand on memory search and speech production when an in-vehicle information device with a verbal interface is installed. Moreover, driver distraction due to verbal interaction was caused not only by the interaction between a driver and in-vehicle devices with verbal interfaces, but also by a conversation between driver and passenger. Particularly, the risk of driver distraction may increase when a driver has to allocate much attention resources to a verbal task involving heavy demands on memory search and speech production. On the other hand, it seems that interaction without such demands has little adverse impact on a driver's attention. Thus, providing information requiring verbal interaction including memory search and speech production should be avoided, particularly when the traffic situation is so difficult and complex that a driver has to concentrate on driving. In such a situation, the passenger should stop conversation with a driver if the conversation relates to demand on memory search and speech production. If a driver and a passenger know which kinds of cognitive processes are harmful to driver attention, they can regulate the conversation to more efficiently reduce distraction.

The finding that a verbal task does not affect inspection speed and affects processes other than inspection, most likely the task switching process, suggests that it is important for the in-vehicle information device's interface design using verbal interaction to minimize the task switching cost or to avoid task switching when a driver has to concentrate on driving in an attention-demanding situation. To accomplish such timing control, it is necessary to develop a technological solution to provide real-time estimations of the driver's cognitive load (e.g. [18]).

Further research is needed to focus on the driver distraction problem that derives from the demand of task switching between a driving task and a secondary task. One of the important issues of this problem is the characteristics of the secondary task. In our study, all the secondary tasks were essentially based on verbal processing. If the secondary task depends on spatial cognitive processing, such as mental imagery, is the effect of such a visual secondary task equivalent to that of a verbal secondary task? According to the multiple resources concept of attention [34,35], there are separate processing resources corresponding to spatial and verbal codes, suggesting that an effect of secondary task on the primary visual search performance is different based on the processing involved in the secondary task. A previous study [24] examined the effect of verbal or spatial processing included in secondary working memory tasks on peripheral visual-detection performance, and showed that a secondary task required spatial processing, impaired the peripheral visual-detection performance more than a secondary task requiring verbal rehearsal. Visual-imagery processing while driving may be deteriorate visual search performance, the same as for peripheral visual-detection performance. The effect of secondary visual-imagery processing on visual search performance should be studied for future work.

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