Effects of phonological, visual and spatial information processing on a simulated driving task

by

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Abstract

Manufacturers are adding devices to cars, such as route navigation systems, that may compete for the drivers' perceptual and processing resources normally used for driving. The goal of the present thesis was to examine the extent to which manipulations of secondary task perceptual and processing demands impact performance of a simulated driving task. The simulated driving task was a Lane Change Test (LCT) designed for measuring degradation on a primary driving-like task due to concurrent performance of a secondary task. Adults ($n = 112$) performed the lane change test alone and concurrently with secondary tasks that required phonological, visual, or spatial processing. Half the participants perceived the secondary task information visually (i.e., looking away from the road) and half perceived it auditorily. The LCT required participants to repeatedly perform lane changes when prompted by either visual road signs (Experiment 3) or by auditory commands (Experiment 4). Participants' lane change performance was significantly worse when secondary tasks were perceived visually than when perceived auditorily, regardless of whether directional prompts were perceived visually (i.e., visual road signs) or auditorily (i.e., auditory commands). Furthermore, when directional prompts were perceived visually, lane change performance was more disrupted by visual and spatial processing than by phonological processing, independent of whether secondary tasks were perceived visually or auditorily. Conversely, when directional prompts were perceived auditorily, lane change performance was disrupted equally across processing demands, independent of whether secondary tasks were perceived auditorily or visually.

The lane change performance measure was also broken-down into its three components (i.e., lane change initiation, lane maneuver quality and lane position maintenance). Results revealed that when secondary tasks were presented auditorily, participants protected their lane keeping from interference, but did not protect their lane change initiation response. In contrast, when secondary tasks were presented visually, participants' lane change initiation and lane keeping performance were both disrupted.

Results of the present thesis support the view that performance of secondary tasks can interfere with driving performance and provide some much needed detail about how specific perceptual and processing resources are involved in the performance of secondary tasks and driving.

I would like to dedicate this thesis to my parents who's unconditional love has been the source of my strength.

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CHAPTER 1

Driving is a complex activity that requires concurrent mental processing of a wide range of information (Dewar, Olson & Alexander, 2002; Michon, 1985; Wickens, Gordon & Liu, 1998). This information processing may include controlling immediate vehicle inputs (e.g., steering, braking, shifting), guiding the position of the vehicle (e.g., performing lane change maneuvers), and general trip planning (e.g., selecting routes, avoiding traffic; Michon, 1985). Despite the complexity of driving, manufacturers have added a variety of devices to cars such as collision avoidance and route navigation systems. In many cases, these devices are assumed to simplify some aspects of driving. For example, the purpose of collision avoidance systems is to apprise drivers, sufficiently early, of impending collision with obstructions or other vehicles (Owen, Helmers & Sivak, 1993; Hirst & Graham, 1997). Similarly, lane departure warning systems provide timely warning of inadvertent shifting across lanes, due to drowsiness and fatigue. However, each new device may add to the demands of the overall driving situation or, in some cases, introduce a completely new activity (e.g., interacting with an electronic map) that may compete for the processing resources that people normally use for driving (Lansdown, Brook-Carter & Kersloot, 2002). For example, scanning of an electronic map interface may distract driver attention from the road (Dewar 1988; Tufano, 1997). Given that driving involves coordination of various cognitive processes, there is a need to understand how to integrate secondary tasks into the driving activity without overloading the driver's cognitive capabilities (Wickens & Seppelt, 2002). To this end, researchers have explored the benefits of presenting secondary task information auditorily rather than visually (e.g., Burnett & Joyner, 1997; Lee, 1997; Liu, 2001).

Results of research using different modes to present information (reviewed below), however, have been mixed. A plausible explanation for these mixed results is that although information is *presented* in a given modality (e.g., auditorily), people may use a different modality of internal resource (e.g., visual) to *process* the information. For example, when listening (i.e., auditory presentation) to a set of route directions a driver may visualize the route (i.e., visual internal processing) to be followed. The goal of this thesis is to explore the combined effects of secondary task presentation mode (visual or auditory) and processing requirements (phonological vs. visual vs. spatial) on drivers' behaviour. Understanding the effects of performance of mental tasks on driver behaviour will contribute to our ability to predict dual-task interference levels between concurrently performed tasks, and to aid developers in the identification of distracting tasks. In my research, I used a dual-task paradigm to explore whether secondary tasks requiring phonological, visual and spatial processing differentially disrupt driving performance when these tasks and driving instructions are presented in either auditory or visual modes.

In a dual-task paradigm, participants are required to perform two tasks at the same time. Usually, the primary task is presented immediately before, or concurrently with, the secondary task. The dual-task paradigm has helped identify the type of processing resource (e.g., phonological, visual, spatial) that are necessary for carrying out particular cognitive tasks (Logie & Baddeley, 1987). This paradigm is used to explore whether two tasks require the same processing resources. If performance on the primary task is affected by concurrent performance of the secondary task, the two tasks are assumed to use the same processing resources or processing codes. If there is no decrement in task performance when the tasks are combined, the different tasks are assumed to require different processing resources. This dual-task paradigm has been used in a similar way to explore the role of different mental resources in a variety of complex cognitive tasks such as mental arithmetic (Ashcraft & Kirk, 2001; Trbovich & LeFevre, 2003) and word processing (Herdman & Beckett, 1996).

A desktop driving simulation task (which is reviewed in more detail in Chapter 3) was selected to test hypotheses related to the distraction potential of secondary tasks. Specifically, participants used a PC-based driving simulation that uses a standardized test scenario in which drivers perform lane change maneuvers while simultaneously performing secondary tasks (Mattes, 2003). Lane change performance provides an estimate of driver distraction due to concurrent performance of a secondary task. Using a steering wheel, participants are required to drive along a straight three-lane road while attempting to maintain the position of the vehicle in the centre of a given lane, and repeatedly perform lane changes when prompted by road signs. The amount of distraction due to the additional demands of the secondary tasks is evaluated according to drivers' lane change quality relative to a normative model. Secondary tasks were designed to require different processing resources (i.e., phonological, visual, spatial) and were presented both auditorily and visually. Thus, driving performance was measured as a function of secondary task presentation modes and processing requirements.

To explore the potential for secondary task processing to interfere with driving performance, we must understand the actions involved in the driving activity. To this end, Michon's hierarchical model of driving behaviour is described below.

Michon (1985) developed a hierarchical model of driving behaviour that includes three levels: operational, maneuvering, and strategic. The operational level is the lowest level and involves the immediate vehicle control, consisting mainly of automatic action patterns such as steering, braking, and shifting. Decisions at the control level are based on the immediate driving environment and are considered to be executed within milliseconds (e.g., pressing the brake pedal). Given that actions at the operational level are mainly automatic, they are characterized as requiring effortless processing. Researchers have found that automatic processing is not limited to predictable situations (e.g., Fisk & Schneider, 1984; Fisk, Oransky & Skedsvold, 1988). For example, Fisk et al. (1988) have shown that braking and steering patterns may become automatized regardless of variability in the driving scenarios. Thus, actions at the operational level do not impose much cognitive load on the driver. In the present experiments, actions such as steering and speed are examples of immediate vehicle control.

The maneuvering level involves negotiation of common driving situations (e.g., negotiating curves, intersections, gap acceptance in overtaking or entering the traffic stream, performing lane change maneuvers, and obstacle avoidance). It has been well established that driving requires acquisition of visual and spatial information (Cole & Hughes, 1990; Mourant & Rockwell, 1972; Theeuwes, 1989). Therefore, actions at the maneuvering level require perception, processing, and integration of multiple pieces of visual and spatial information in the driving environment. Furthermore, decisions at the maneuvering level are based on the immediate driving environment and take place in seconds (e.g., in the present experiments, performing the maneuver as soon as the sign is viewed). In the present experiments, perception of and reaction to road signs, lane change maneuvers and lane maintenance are examples of tasks at the maneuvering level.

The strategic level involves general trip planning, including setting trip goals (e.g., minimizing time, avoiding traffic), selecting routes, and evaluating the cost and risk associated with alternative trips. There is usually no time limit for decisions made at the strategic level because trip plans can be made in advance and changes to the plan can usually be done while driving as time permits (usually minutes before execution). Furthermore, strategic decision-making is generally memory-driven and does not usually require assimilation of new information. In the present experiments, there are no requirements at the strategic level because drivers are told exactly what route to follow.

In the present research, I am focusing on the maneuvering level of Michon's hierarchy because actions at the maneuvering level of driving behaviour appear to be the ones most susceptible to interference from secondary tasks that also require perception, processing, and integration of information. Thus, the current experiments were designed to assess the interference caused by secondary tasks requiring different types of information processing (i.e., phonological, visual, spatial) on driving activities at the maneuvering level (i.e., perception of and reaction to road signs, lane change maneuvers, and lane position maintenance).

In this thesis, I examine some of the factors that influence the potential for secondary tasks to disrupt driving performance. The general approach was to use a dual-task paradigm to explore whether secondary tasks that require different perceptual and processing resources differentially compete with the mental resources that people use when performing a driving-like task. The results will provide further understanding of how variations in (1) the presentation modes and (2) the resources required to process secondary tasks help predict interference between secondary tasks and driving.

To establish a framework for the present research, I review models of information processing, focusing on multiple resource models, as my research hinges on the hypothesis that separate subsystems are used to process phonological, visual, and spatial information. Second, I review the literature on the effects of secondary task presentation modes and processing requirements on event detection measures of driving performance. Third, I review the literature on the effects of secondary task presentation modes and processing requirements on lane positioning measures of driver performance.

Information Processing Models

Three classes of models of information processing have evolved from their respective theories of human information processing: single channel bottleneck models, general resource model, and multiple resource models (Wickens, 2002).

Single Channel Bottleneck Models

The underlying assumption of a single channel model is that the human information processing system acts as a bottleneck that limits the ability to concurrently process two pieces of information, and thus functions through a series of selections about which piece of information to process at a given time (Broadbent, 1958; Davies, 1965; Deutsch & Deutsch, 1963; Hendy, Liao & Milgram, 1997; Pashler, 1984, 1989; Welford, 1967). Consequently, concurrent performance of two tasks is never as efficient as the individual performance of either task because the bottleneck represents a limited resource that cannot be shared (Craik, 1948; Broadbent, 1958; Welford, 1967). That is, the limited resource cannot be shared because the bottleneck acts as a filter that can only attend to one input channel (e.g., one ear) at a time. According to the single-channel bottleneck model, the bottleneck (or limited resource) is time (Wickens, 2002). Time is defined as the moment at which an event occurs.

Much support for the bottleneck theory comes from the Psychological Refractory Period (PRP) paradigm, which is a form of dual-task interference (Pashler, 1984; 1994; Telford, 1931; Welford, 1952). In the PRP paradigm, two stimuli are presented at different times. That is, presentation of stimuli for two tasks is separated in time by a variable called Stimulus Onset Asynchrony (SOA). The Psychological Refractory Period (PRP) refers to the delay in response to a second stimulus when the period between it and an initial stimulus (i.e., SOA) is very close in time. This obligatory serial processing includes selection of responses. Pashler's (1994) bottleneck theory suggests that the information processing stage of response selection limits dual-task performance by acting as a bottleneck.

Coordinating response selections during dual-task performance (e.g., selecting responses to the driving task and to the secondary task) may be an important consideration to avoid temporal interference between tasks. The goal of the present thesis, however, was to assess the effects of information processing prior to response selection. Therefore, experiments were designed such that coordination of response selection during dual-task performance was consistent across all tasks. Furthermore, in the present experiments, response selection for all secondary tasks was a simple decision rule that was limited to a choice between two alternatives. Therefore, the information processing stage of response-selection was consistent across all secondary tasks.

Although there are many situations in which time is the crucial factor in determining whether two tasks can be concurrently performed (e.g., localizing sound in space), there are many circumstances in which other factors (e.g., task complexity) may be equally, or more important, in determining task performance (e.g., performing an in-vehicle task while driving). Consider, for example, a driver's performance of a secondary task while he negotiates a curve in the road. The driver could perform a low-complexity secondary task (e.g., whistling) during this negotiation, without much interference to the primary driving task. If time was the only factor responsible for task interference, then a low-complexity task such as whistling should interfere with curve negotiation to the same extent as a more complex task such as reading a road map. Research, however, indicates that task complexity (defined in terms of task characteristics and processing demands) is a better predictor of whether or not a task will disrupt driving performance than are timing and duration of the secondary task (Cellier & Eyrolle, 1992; Gillie & Broadbent, 1989; Hess & Detweiler, 1994; Zijlstra, Roe, Leonora & Krediet, 1999). Thus, although the single channel model of information processing is a useful framework for examining dual-task performance in circumstances in which time is the only crucial limited resource, it is limited in terms of generating testable hypotheses in a driving context in which time is only one of many task characteristics that could affect performance.

General Resource Models

A general resource model was developed to be less restrictive than the single channel model (Keele, 1973). Specifically, the general resource model posits that humans possess a limited capacity central processor that can be shared between tasks (Kahneman, 1973; Rolfe, 1973). That is, the general resource model assumes that the mental resources from a limited central processor can be allocated as necessary to meet the demands of a given task. Resources that are left over can then be allocated to a secondary task. Thus, two tasks can be successfully performed at the same time as long as the resources necessary to perform these tasks do not exceed the limited capacity of the central processor. Although proponents (e.g., Cowan, 1997; Engle, 2002) of the general resource model don't always specifically state what they mean by "general resource", they attribute variance in dual-task performance to a quantitative resource demand (e.g., number of items, frequency of items). For example, according to Cowan (1999, 2001), capacity of the general resource is measured by the number of items that can be retained. Thus, the general resource model identifies other quantitative factors, besides time, that could characterize the notion of limited resource demand.

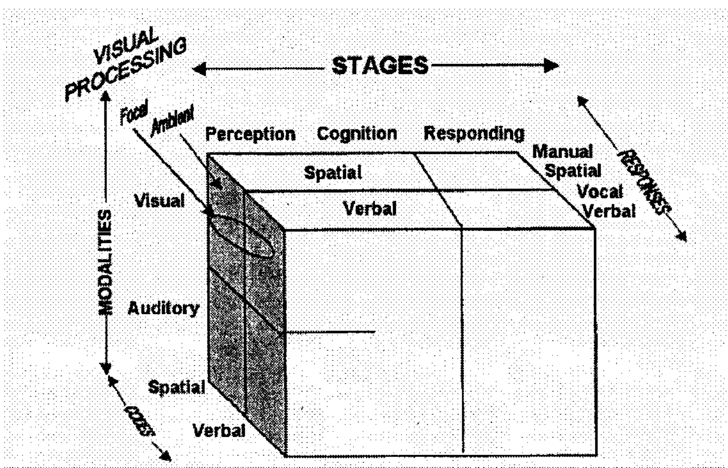
Subsequent to the development of the general resource model of information processing, evidence emerged that variance in individuals' performance in dual-task situations could not be attributed solely to quantitative resource demands of the tasks (e.g., Baddeley & Hitch, 1974; Kantowitz & Knight, 1976; Wickens, 1976). Rather, experimental results suggested that differences in the qualitative demands of the tasks (e.g., visual versus auditory processing) also caused differences in dual-task performance (De Renzi, 1982; Milner, 1971; Paivio, 1971). Such results led researchers (e.g., Baddeley & Hitch, 1974; Wickens, 1976) to posit that the human information processing system (i.e., short-term memory) consisted of separate limited processing resources (hence the term *multiple* resources), and that dual-task performance was worse when two tasks required the same resource than when tasks required separate resources. The finding that short-term memory might consist of separate limited resources provided the basis for multiple resource models of information processing.

Multiple Resource Models

Although there are a variety of mental resource models, Wickens' (1980; Wickens & Hollands, 2000) four-dimensional multiple resource model has proven useful when using a dual-task methodology to predict interference levels between concurrently performed tasks. Wickens' (1980) multiple-resource model comprises four categorical and dichotomous dimensions. As shown in Figure 1, the four dimensions are processing stages, visual channels, perceptual modalities, and processing codes (Wickens, 2002). According to the "processing stage" dimension, resources used for perceptual and cognitive activities are functionally separate from resources used for executing a response. The "visual channels" dimension is assumed to be comprised of focal vision, which is required for recognizing details and patterns, and of ambient vision which is used for sensing orientation. The "perceptual modalities" dimension comprises two independent perceptual subsystems (i.e., auditory and visual) that are used to extract information from the environment. The "processing codes" dimension distinguishes between verbal and spatial resources involved in the temporary storage of verbal and spatial information respectively. Given that the goal of the present thesis is to explore whether secondary tasks that require different *perceptual* and *processing* resources differentially compete with the mental resources that people use for driving, the *perceptual* modality and the *processing* code dimensions will be the focus of the present research.

Figure 1. Three-dimensional representation of the structure of multiple resources.

The fourth dimension (visual processing) is nested within visual resources (Wickens, 2002).



Perceptual Modality Dimension

Wickens divides the perceptual modality dimension into two independent components: the auditory and visual modalities. Because Wickens proposed that these perceptual subsystems are independent, he predicts that there will be more interference between concurrently performed tasks that are presented in the same modality (i.e., between two auditory presentations or between two visual presentations) than between concurrently performed tasks that are presented in different modalities (i.e., between an auditory presentation and a visual presentation).

Many studies on driver distraction (e.g., Hurwitz & Wheatley, 2002; Labiale, 1990; Parkes & Coleman, 1990) have shown that visual presentation of secondary tasks interferes with driving performance more than auditory presentation because the driving task has high visual perceptual demands. Such results have contributed to the false perception that it is safe to drive while performing cognitive tasks that are presented auditorily (Sundeen, 2005), and have led manufacturers to add speech-based devices into cars (ITSA, 2005). These studies, however, are mostly based on driving experiments that have focused on the encoding or the presentation format used to convey information when studying driver distraction, and have not carefully studied the internal structures people use to process the information. Basic cognitive psychology research (reviewed below) suggests that differences in resources required to process secondary task information impact the extent to which a secondary task interferes with primary task performance. Therefore, the present research manipulates both secondary task presentation modes and processing requirements to evaluate the individual contribution of each of these factors in the disruption of driving performance.

In the present research, I predicted that visual presentation of secondary task information would interfere more with primary task performance than auditory presentation, given the high visual perceptual demands of the driving task. My primary interest in the present study, however, is in assessing the codes that are used after information is perceived and enters the information processing system. Specifically, I am interested in assessing whether secondary tasks that require distinct types of information processing differentially affect primary task performance beyond the effects (e.g., visual scanning) attributable to secondary task presentation modes.

Processing Code Dimension

Wickens' "codes of processing" dimension distinguishes between spatial and verbal processing resources. This distinction is derived from Baddeley and Hitch's (1974; Baddeley, 1986; Logie, 1995) multicomponent working memory model (Seppelt & Wickens, 2003). The multi-component model of working memory comprises a limited-capacity central executive, a phonological loop, and a visuospatial sketchpad (VSSP: Baddeley, 1986, 1996; Baddeley & Hitch, 1974; Baddeley & Logie, 1999). The central executive coordinates the activities of the phonological loop and the VSSP and is associated with limitations in the availability of cognitive resources (Baddeley, 1996). The phonological loop is involved in the temporary storage of verbal information (Baddeley, 1986), whereas the VSSP functions as a mental blackboard or workspace for temporary storage of visual and spatial information (Logie, 1995). There is evidence that the visuospatial system can be fractionated into two separate visual and spatial subsystems (Logie, 1995; Logie & Marchetti, 1991; Vecchi & Cornoldi, 1999). Furthermore, Baddeley (2000) proposed a modification of the model of working memory to incorporate links to long-term memory by way of both the subsystems and a new component, the episodic buffer. The episodic buffer is assumed to be capable of combining information from long-term memory with that from the two subsystems.

Baddeley's multicomponent model classifies phonological, visual and spatial processing as separate limited resource components that activate separate brain structures, and that independently rely on the attentional system controlled by the central executive. Given that each component has a limited amount of resources, concurrent performance of tasks that require the same processing resources (e.g., two tasks that require phonological resources) will interfere more than concurrent performance of tasks that rely on separate processing resources (e.g., phonological and visual resources).

Given that there is empirical evidence to support the fractionation of the visuospatial sketchpad (VSSP) into two subsystems for visual and spatial information, I opted to use Baddeley's classification of processing codes (i.e., phonological, visual, spatial) rather than Wickens' dichotomous classification (i.e., verbal and spatial). Thus, in the present paper, three processing codes were explored: phonological, visual, and spatial resources. The next two sections review experiments that attempted to explore the cognitive mechanisms supporting phonological, visual and spatial memory.

Phonological loop. The phonological loop is assumed to consist of a store and a rehearsal mechanism (Baddeley, 1986). To assess the types of representations that are used in short-term memory, researchers (e.g., Baddeley, 1986; Conrad & Hull, 1964) have compared immediate serial recall of items that are similar in sound (e.g., B, C, D, G, T) to that of items that are dissimilar in sound (e.g., Q, R, H, M). Results showed that sequences of dissimilar sounding items were correctly recalled more frequently than sequences of similar sounding items. This latter effect occurred independent of whether items were presented visually or auditorily, suggesting that the phonological confusion presumably occurred during retention in short term memory, not in perceiving the letters. Thus, the phonological store component of the phonological loop appears to be reflected in the qualitative nature of a task (i.e., the similarity in sound).

The articulatory rehearsal component of the phonological loop, on the other hand, appears to be reflected in the quantitative nature of a task. That is, the articulatory rehearsal component is proposed to account for the word length effect, whereby immediate serial recall of a list of items is directly related to the length of the items being maintained (Baddeley, Thompson & Buchanan, 1975). Specifically, participants are more likely to recall sequences of words that are short (e.g., hit, tap, bed) than sequences of longer words of equal frequency (e.g., capacity, anniversary, television). Researchers (e.g., Baddeley et al., 1975; Garden, Cornoldi & Logie, 2002; Logie, Baddeley, Mane, Donchin & Sheptak, 1989) have observed that this latter effect disappears when rehearsal is prevented by articulatory suppression (i.e., the repetition of an irrelevant sound such as the word "the"). Thus, this word length effect appears to reflect the slower rehearsal of long words compared to short words. In sum, the phonological similarity effect and the word length effect appear to be respectively functions of the phonological store and the articulatory rehearsal components of the phonological loop.

Given that the driving task used in the present research requires visual and spatial resources, it is expected that the secondary task requiring phonological processing will cause less interference with driving than secondary tasks that require visual and spatial processing. Such a result would support the notion of the multiple resource model over the notion of a general resource model of information processing. That is, a multiple resource model would predict that secondary tasks requiring visual and spatial resources would interfere more with driving than secondary tasks requiring phonological resources because the driving task has high visual and spatial demands. Conversely, a general resource model would predict that secondary tasks would interfere with driving performance regardless of whether or not the secondary tasks share common qualitative resources with the driving task.

Visuospatial system. The visuospatial system is assumed to be responsible for the temporary processing and maintenance of visuospatial information, and to play an important role in activities requiring spatial reasoning (Shah & Miyake, 1996), spatial orientation (Garden, Cornoldi & Logie, 2002) and visuospatial problem solving (Robbins, Anderson, Barker, Fearnyhough, Henson, Hudson & Baddeley, 1996). Processing of information in the visuospatial subsystem is believed to be more demanding than processing of information in the phonological loop. Therefore, it is assumed that the visuospatial system taps into the central executive resources more than does the phonological loop (Baddeley, 2002).

Researchers have applied the dual-task approach to investigate the existence of a specialized visuospatial component in short-term memory (Baddeley & Lieberman, 1980; Jones, Farrand, Stuart & Morris, 1995; Logie & Marchetti, 1991). For example, Baddeley and Lieberman (1980) used a tracking task in an attempt to simulate a driving task. Participants were required to perform the tracking task while performing tasks that had already been shown by Brooks (1968) to involve visuospatial and verbal imagery. Results showed that the visuospatial imagery task disrupted tracking performance significantly more than the verbal imagery task, suggesting that the tracking and the visuospatial imagery tasks require common resources, whereas the tracking and the verbal imagery tasks require separate resources. Although Baddeley and Lieberman had initially attributed this result to visual imagery, they subsequently hypothesized that results were equally explicable in terms of a purely spatial/non-visual resource or a combination of visual and spatial resources. This latter hypothesis led to research in the last decade concerned with examining the potential separability of the visual and spatial components of the VSSP (Logie, 1995; Logie & Marchetti, 1991; Logie & Pearson, 1997; Vecchi & Cornoldi, 1999).

Numerous studies have found evidence that primary tasks requiring either visual or spatial processing were differentially impaired by secondary tasks that respectively demanded visual and spatial resources (for reviews see Baddeley & Logie, 1999; Logie 1995; Logie & Marchetti, 1991; Logie, Zucco & Baddeley, 1990). Logie (1995) regarded the visual component of the visuospatial system, which he termed the "visual cache", as a temporary store for visual representations of objects such as shape and colour. The spatial component of the visuospatial system, which Logie (1995) termed the "inner scribe", is considered to be a mechanism for rehearsal of spatial information that involves planning and executing physical movements, as well as representing the path between objects. Support for the proposal that spatial and visual representations are stored in separate working memory subsystems has also emerged from neuropsychological studies (e.g., Carlesimo, Perri, Turriziani, Tomaiuolo & Caltagirone, 2001; De Renzi & Nichelli, 1975; Farah, Hammond, Levine & Calvanio, 1988; Logie, Engelkamp, Dehn & Rudkin, 2001).

It is difficult to ensure that a task is purely visual or purely spatial in nature (Baddeley, 2002). There is evidence, however, that pattern recognition and visual search tasks are associated with visual memory (Cowan, 1997; Della Sala, Gray, Baddeley, Allamano & Wilson, 1999). For example, Della Sala et al. (1999) found that performance of a secondary visual interference task, which consisted of viewing abstract paintings, disrupted performance of a primary visual pattern task more than did a tapping task in which participants tapped a specified pattern. Such findings support the view that visual tasks and spatial tasks are differentially impaired by load tasks that vary in their visual and spatial demands.

Tasks that have been found to interfere with spatial memory include tapping a specified pattern (e.g., corners of a square or a figure 8), or reproducing a sequence of movements by tapping an array of blocks (Logie & Marchetti, 1991; Smyth & Scholey, 1992, 1994). Researchers have found that movement execution also requires spatial resources (Conte, Cornoldi, Pazzaglia & Sanavio, 1995; Pazzaglia & Cornoldi, 1999; Pickering, Gathercole, Hall & Lloyd, 2001; Smyth & Scholey, 1994). For example, Pazzaglia and Cornoldi (1999) found that participants' scores on a spatial memory test (i.e., reproducing the sequence of taps on a set of blocks) predicted performance levels on a route memory recall task that required memory of movement descriptions. Furthermore, performance on the route memory task was disrupted more by a concurrent spatial memory task than by a concurrent verbal memory task, suggesting that spatial resources are involved in movement memory. Garden et al. (2002) found that participants used both phonological and spatial resources when required to follow visually presented navigational instructions. Similarly, Barshi and Healy (2002) found that participants used both phonological and spatial resources when required to follow auditorily presented navigational instructions. These latter two results suggest that although participants encode navigational information in a given mode (e.g., auditorily), they may use a different mode of internal resource (e.g., visual) to process the information.

Encoding and maintenance of visual and spatial information and the planning and execution of movement are particularly important for driving because visual and spatial resources are a critical part of driving requirements. Given that the driving task used in the present research requires visual and spatial resources, it is expected that the secondary tasks requiring visual and spatial processing resources will interfere more with driving than secondary tasks that require phonological processing. Such a result would support the assumptions of the multiple-resource model over those of a general resource model of information processing. That is, a multiple-resource model predicts that secondary tasks requiring visual and spatial resources will interfere more with driving than secondary tasks requiring phonological resources because the driving task has high visual and spatial demands. Conversely, a general resource model predicts that secondary tasks interfere with driving performance regardless of whether or not the secondary tasks share common qualitative resources with the driving task, because the driving task and the secondary tasks compete for the same central processing resource.

In summary, proponents of the original single channel bottleneck model posit that the human information processing system is limited by the fact that only one piece of information can be attended to at a given point in time. Advocates of the general resource model, however, assign various quantitative characteristics to the limited central processor. Finally, proponents of the multiple resource model posit that the human information processing system is comprised of a number of qualitatively different processing resources. A multi-component working memory model was adopted in the present thesis because driving seems to require a range of mental resources and there is evidence for component-specific processing in short-term memory. Specifically, the phonological loop, the visual short-term memory and the spatial short-term memory are the mental systems for internally representing phonological, visual and spatial information respectively, and for maintaining these types of information accessible for further processing. These different memory systems have limited resources. Consequently, concurrent performance of tasks that require the same types of resources are assumed to interfere with each other (Baddeley, 1986, 2002; Wickens, 1984, 2002). Given the well established visual and spatial nature of information processing while driving (Cole & Hughes, 1990; Mourant & Rockwell, 1972; Recarte & Nunes, 2000; Theeuwes, 1989), the present research tests the hypothesis that secondary tasks requiring activation of visual and spatial working memory will disrupt driving performance more than secondary tasks that activate the phonological subsystem.

In the ensuing section, I will establish the context for the present research. Prior research has suggested that event detection and lane maintenance are measures of driving performance that are differentially disrupted by concurrent task demands (Horrey & Wickens, 2004). Given the latter, and the fact that event detection and lane maintenance performance are assessed in the present experiments, I will review studies that used these measures. I will first review studies that have compared the effects of secondary task presentation modes and processing requirements on event detection measures. I will then review studies that have compared the effects of secondary task presentation modes and processing requirements on lane position maintenance measures. Finally, I will review the overall methodology used in the present study to investigate the combined effects of secondary task presentation modes and processing requirements on driving performance.

Event Detection Measures of Driving Performance

Effects of Secondary Task Presentation Modes

It has been well established that actions performed while driving require visual resources (Mourant & Rockwell, 1972; Recarte & Nunes, 2000; Theeuwes, 1989). Thus, visual presentation of secondary task information may interfere more with driving performance than auditory presentation. Researchers have investigated how differences in display presentations (i.e., auditory vs. visual) of secondary task information influence the competition for auditory and visual resources necessary for the main task of safe driving, and for the subordinate performance of in-vehicle tasks such as sending a text message or recording a voice memo (e.g., Hurwitz & Wheatley, 2002; Labiale, 1990; Liu, 2001; Ranney, Harbluk & Noy, 2005). As reviewed below, the existing research on the relative disadvantages of visual versus auditory presentation is complex, however, and the results do not lead to a clear conclusion.

Studies that examined driving performance in terms of drivers' reaction time to route guidance commands or detection times to events and/or to hazards generally show that auditory presentation of secondary task information leads to faster detection times compared to visual presentation. For example, Parkes and Coleman (1990) found that participants completed a navigation task faster when guided by auditory than by visual commands. Similarly, Gish, Staplin, Stewart, and Perel (1999) and Srinivasan and Jovanis (1997) showed that detection of roadway hazards was faster and more accurate when people were interacting with auditory versus visual route guidance commands. Horrey and Wickens (2002) found that the benefit of auditory presentation of secondary task information over visual presentation, in terms of faster hazard detection times, was dependent on the location of the visual display. Specifically, reaction time to hazards was faster when secondary tasks were presented auditorily than when they were presented on a visual heads-down display (i.e., the participants had to move their eyes to perceive the visual information). Conversely, there was no difference between hazard detection times when secondary tasks were presented auditorily or on a visual heads-up display. Finally, Ranney, Harbluk, and Noy (2005) found that drivers detected more targets, and were faster at detecting visual targets on the road scene, when concurrently interacting with an auditory interface than when interacting with a visual-manual interface. Thus, the data provide evidence that auditory presentation of secondary task information is less disruptive to driving performance than visual presentation. This finding is consistent with Wickens' (2002) model which claims that two tasks can be performed more efficiently when separate modes of presentation (i.e., cross-modal) are used than when common modes of presentation (i.e., intra-modal) are used. This assumption was tested in the current research. Specifically, I hypothesized that visual presentation of secondary tasks would interfere more than auditory presentation with the event detection measure of driving performance (i.e., detection and initiation of lane change maneuvers).

Although visual presentation of secondary tasks interferes with event detection measures of driving performance more than auditory presentation, numerous researchers (e.g., Consiglio, Driscoll, Witte & Berg, 2003; Lamble, Kauranen, Laasko & Summala, 1999) have found that auditory presentation of secondary task information also disrupts driving performance relative to driving without performing a secondary task. Such results led researchers to investigate the effects of cognitively demanding tasks on driver performance.

Effects of Secondary Task Processing Modes

Studies examining the effects of cognitive distraction on event detection performance have yielded mixed results. Although some studies have shown that drivers are slower at responding to events in the environment when they are engaged in a cognitively demanding task than when driving without performing a secondary task (e.g., Alm & Nilsson, 1995; Consiglio, Driscoll, Witte & Berg, 2003), others have failed to find such effects (e.g., Rakauskas, Gugerty & Ward, 2004). I hypothesized that the mixed findings in the literature as to whether an auditory presentation of secondary task is more disruptive than driving without performing a secondary task are a consequence of not considering the types of processing resources involved in the performance of these tasks.

In the last decade there have been numerous experiments conducted to test the effects of concurrent secondary tasks on driving (e.g., Goodman, Tijerina, Bents & Wierwille, 1999; McKnight & McKnight, 1993; Parkes, 1993; Strayer & Drews, 2004; Strayer & Johnston, 2001). The evidence as a whole, however, does not provide much information on whether the internal code (i.e., phonological, visual, spatial) used to process the secondary task information interferes with the mental processing required by the driving activity (e.g., maintaining lane position, detecting hazards).

Generally, the extant results support the view that engaging in a cognitive task disrupts driving performance. However, research on driver distraction has not included manipulations of the type of internal processing required in performing secondary tasks. For example, Strayer and Johnston (2001) found that performance of a word-generation task interfered with a pursuit tracking task, and that the interference increased as the difficulty of the driving task increased. Further, when drivers were conversing (i.e., discussing the Clinton presidential impeachment or the Salt Lake City Olympic Committee bribery scandal) on cell phones (both hands-free or handheld), they missed more traffic signals and were slower at responding to the ones they did detect than when they were not conversing. This study showed that performance of a cognitive task interfered with event detection performance, but the researchers did not control or manipulate the type of processing required by the task. For example, the word-generation task may require phonological, visual, spatial, or a combination of processing codes. Furthermore, it is unclear what modes of internal processing drivers used when they were discussing the presidential impeachment or the bribery scandal.

Furthermore, Rakaukas et al. (2004) conducted a study in which they used a driving simulator to determine the effects of cell phone conversations on reaction time to hazardous events. The conversations included questions such as "What is your major", "Do you think that the world will be a better or worse place a 100 years from now?". Results showed that conversations had little effect on participants' reaction time to hazardous events relative to driving without conversing. The researchers claim that special care was taken to avoid including questions that would interfere with visual and spatial tasks, but they do not specify whether testing was undertaken to ensure that questions did not interfere with visual and spatial tasks. These types of studies reduce the construct of cognitive processing to a concept of attention used in everyday language as in "paying attention", and lead researchers to make claims about effects of cognitive mechanisms on driving performance that are based on poorly operationalized definitions of cognitive mechanisms. The lack of knowledge about the modes of internal resource used to process secondary tasks makes it difficult to make predictions about their effects on driving behaviour.

Recarte and Nunes (2000, 2003) performed some of the few driving related studies that operationalize the cognitive mechanisms required by the secondary task. For example, Recarte and Nunes (2000) examined the effects of performing secondary tasks that require different types of internal processing on driver's visual behaviour. Specifically, participants were required to perform a task requiring phonological processing (i.e., generating words starting with a certain letter indicated by the experimenter), and a task requiring spatial processing (i.e., image generation tasks that sometimes required mental rotation) while driving in real traffic. Results showed that participants reduced their visual field of focus, both horizontally and vertically in the dual-task conditions. The effect was greatest with the spatial secondary task. Furthermore, compared to baseline drives (i.e., without secondary tasks), drivers increased their fixation durations and decreased their glance frequencies to mirrors and the speedometer when driving while performing the spatial task.

In a subsequent experiment, Recarte and Nunes (2003) demonstrated that performance of complex mental tasks reduced drivers' detection of in-vehicle and external objects. Although Recarte and Nunes's studies are a good start to evaluating the effects of different modes of internal resources used to process secondary tasks on event detection performance, their studies only focused on driver visual behaviour. Thus, support for the dangers of engaging in cognitive tasks while driving could be further strengthened by empirical evidence that demonstrate the effects of performing specific cognitive tasks on driving performance measures that have a more direct link to safety (e.g., perception of and reaction to events in the environment, lane position maintenance). To this end, the effects of secondary tasks and presentation modes on driving performance will be explored in the present research.

Lane Position Maintenance Measures of Driving Performance

Effects of Secondary Task Presentation Modes

Many researchers have shown that auditory presentation of secondary task information resulted in superior vehicle control (e.g., lane positioning) relative to visual presentation (e.g., Hurwitz & Wheatley, 2002; Labiale, 1990). Likewise, Walker, Alicandri, Sedney, and Roberts (1990) found that participants maintained more precise speed and had better vehicle control when secondary task information was presented auditorily than when it was presented visually. Furthermore, Streeter, Vitello, and Wonsiexicz (1985) provided evidence that auditory displays of navigational aids resulted in more accurate speed control and navigation responses than visual displays. Other researchers (e.g., Burnett & Joyner, 1997; Liu, 2001; Srinivasan & Jovanis, 1997) also found that steering wheel variability and lane position variability diminished when people used an auditory versus a visual route guidance system. Thus, these findings suggest that lane maintenance performance is less affected by auditory presentation of secondary task information than by visual presentation. Given these results, I hypothesized that in the present experiments, visual presentation of secondary task information would disrupt lane maintenance performance more than auditory presentation.

Researchers have shown that auditory presentation of secondary tasks does not disrupt vehicle control relative to baseline driving, that is driving without performing a secondary task (e.g., Alm & Nilsson, 1994; Briem & Hedman, 1995; Brookhuis, de Vries & de Waard, 1991; Lamble, Kauranen, Laakso & Summala, 1999). Thus, these results suggest that cognitive demands associated with secondary task performance might not impact lane maintenance.

In sum, these results suggest that vehicle control measures are sensitive to changes in presentation modes (i.e., visual vs. auditory) but may not be sensitive to secondary task processing demands.

Effects of Secondary Task Processing Modes

Some studies (e.g., Strayer & Johston, 2001) have shown that auditory presentation of secondary task information decreases vehicle control (e.g., tracking performance) relative to driving without a secondary task. The majority of studies (e.g., Alm & Nilsson, 1995; Briem & Hedman, 1995; Brookhuis, de Vries & de Waard, 1991), however, show that auditory presentation of secondary tasks does not disrupt vehicle control relative to driving without a secondary task. A meta-analysis conducted by Horrey and Wickens (2006) provides the most recent support for this latter finding.

Horrey and Wickens (2006) conducted a meta-analysis of studies that examined the degradation in driving performance when using a cell phone (i.e., cognitive distraction) compared with performance on a single-task (i.e., driving only) control condition. Results from the meta-analysis revealed that cognitive distraction impaired response time to critical road hazards or stimuli but did not significantly disrupt lane keeping or tracking performance relative to driving without a secondary task. Based on these results, Horrey and Wickens (2006) posited that lane maintenance performance is largely an automatic task, whereas event detection requires mental processing (and thus cognitive resources). The studies examined in the meta-analysis, however, did not operationalize the processing resources required by the secondary tasks. That is, the studies examined in the meta-analysis did not manipulate the mode of internal processing required by the secondary tasks, resulting in a lack of knowledge of the processing resources required by these tasks. Therefore, it is difficult to ascertain whether the lack of disruption of secondary tasks on driving performance occurred because (a) no processing resources are required for lane maintenance performance (as proposed by Horrey & Wickens, 2006) or (b) lane maintenance does require processing resources (e.g., visual) which may at times be different from those required by the secondary tasks (e.g., phonological).

Results from the present experiments will help determine which of these two hypotheses is supported. Specifically, the present experiments will manipulate the types of processing resources required by the secondary tasks and evaluate their impact on lane position maintenance. If the results of the present experiments demonstrate that processing requirements do not impact lane maintenance performance relative to the baseline drives, this result would support Horrey and Wickens' (2006) hypothesis. Conversely, if results of the present experiment demonstrate that secondary tasks processing requirements differentially affect lane maintenance performance, this would suggest that (1) lane position maintenance requires processing resources, and (2) studies that failed to find an impact of secondary task processing on lane maintenance performance may have used secondary tasks that required different processing resources (e.g., phonological) than those required by the primary lane maintenance task (e.g., visual).

In sum, studies have shown that visual perceptual resources are required for event detection and lane maintenance performance. Consequently, driving while concurrently performing secondary tasks that require visual perceptual resources decreases event detection and lane maintenance performance. Although cognitive processing appears to be required for event detection, it is unclear whether such processing is required for lane maintenance. I have proposed that there are two potential hypotheses concerning the processing requirements for lane maintenance. Either lane maintenance requires minimal cognitive processing, or processing requirements need to be operationalized to examine whether different types of processing resources affect lane maintenance. To determine which of these two hypotheses is supported, the present experiments explore the effects of different processing requirements (i.e., phonological, visual, spatial) on lane maintenance.

Summary

The goal of the present thesis is to explore the effects of secondary task presentation modes and processing requirements on driving performance. In the present research, I chose a driving-like task that mainly requires actions at the maneuvering level of Michon's (1985) hierarchical model of driving behaviour to test the effects of secondary tasks on driving performance because these actions require coordination of various processes. Therefore, it seems plausible that performance of secondary tasks, which also involve a variety of mental activities, might interfere with driving activities at the maneuvering level.

Research has been conducted to examine the interference caused by performance of secondary tasks on driving. Many studies were framed around predictions such as Wickens' (2002) claim that tasks presented in the same modality would interfere more with each other than tasks presented in separate modalities. Given that information in the driving environment is presented visually, Wickens (2002) predicted that visual presentation of secondary task information would interfere more with driving performance than auditory presentation of secondary tasks. Many studies on driver distraction have supported this latter prediction by showing the relative disadvantages of visual versus auditory presentation of secondary tasks on driving performance (e.g., Gish, Staplin, Stewart & Perel, 1999; Horrey & Wickens, 2002; Parkes & Coleman, 1990; Srinivasan & Jovanis, 1997).

A shortcoming of these studies, however, has been a lack of consideration of the internal structures used to process the secondary task information. That is, conclusions contained in studies about the effects of cognitive processing on driver distraction have been based on poorly operationalized definitions of cognitive processing requirements. The lack of knowledge about the internal structures used to process the secondary tasks used in studies on driver distraction make it difficult to interpret the results unambiguously. To understand the processing requirements involved in cognitive tasks, I used Baddeley and Hitch's (1974) multi-component model of information processing to frame my research.

According to Baddeley and Hitch's (1974) multi-component model, tasks that require separate resource structures (e.g., phonological and visuospatial structures), facilitate more efficient parallel processing than tasks that require common resource structures. The multi-component model was used in the present thesis because I hypothesize that secondary tasks requiring different processing resources will differentially impact driving performance.

In summary, in the present thesis, I am interested in assessing whether secondary tasks that require different types of information processing differentially affect driving performance (e.g., event detection and lane maintenance performance), beyond the effects attributable to differences in secondary task presentation modes. Internal structures used to process visual and spatial secondary tasks are hypothesized to interfere with the visual and spatial processing requirements of the driving task, independent of the modes used to present the secondary task information. The general approach was to manipulate secondary tasks that are known to require phonological, visual and spatial processing resources and explore the effects of these tasks on the primary driving task. Interference between the secondary tasks and the driving measures should be observed when driving measures, such as event detection and lane maintenance, require the same processing resources as the secondary tasks. I have proposed that event detection requires visual and spatial processing, and will therefore be more disrupted by secondary tasks that require visual and spatial resources than by tasks requiring phonological resources. Furthermore, I hypothesize that lane maintenance either requires minimal processing, and therefore will not be affected by processing demands of secondary task, or requires visual and spatial resources and will therefore be more affected by visual and spatial than by phonological secondary tasks.

Overview of Experiments

In this thesis I present a series of four experiments. The first and second experiments (Chapter 2) were conducted to explore whether the three secondary tasks (i.e., phonological, visual and spatial) necessitated the phonological, visual and spatial processing resources they were designed to require. This approach ensures proper operationalization of the cognitive mechanisms required by these secondary tasks, and justifies the use of these tasks to explore the effects of information presentation and processing on driving performance, which were the objectives of Experiments 3 and 4. Specifically, the goal of the third experiment was to explore the effects of secondary task information presentation and processing on a lane maneuver task that required perception of and response to arrows on road signs. The goal of the fourth experiment was to explore the effects of secondary task information presentation and processing on a lane maneuver task that required perception of and response to auditory directional commands. Thus, the only difference between the two driving scenarios is that Experiment 3 required detection of and reaction to visual road signs, whereas Experiment 4 required detection of and reaction to auditory directional cues.

The specific target of my research is to assess how changes in the *presentation* and *processing* of secondary task information influence the driving task. To measure the interference resulting from a redirection of attentional resources from the driving task to the secondary task, the present research required participants to drive while performing secondary tasks that required different processing resources (i.e., phonological, visual, spatial) that were presented auditorily and visually. The driving simulation (which is described in detail in Chapter 3) required that participants perform lane change maneuvers while maintaining a constant, predetermined speed. While driving forward, participants encountered visual traffic signs (Experiment 3) or auditory directional cues (Experiment 4) that prompted them to change lanes. Between these lane change maneuvers, participants strove to maintain their position in the centre of the lane. Performance of the secondary tasks while driving permitted assessment of secondary task demands upon event detection and lane position maintenance. A control condition was included under which there was no secondary task requirement.

Experiments 1 and 2

Three secondary tasks were constructed. They were designed to respectively require phonological, visual, and spatial processing resources. The three tasks were constructed so that they would require approximately the same amount of time to perform and so that they could be presented both auditorily and visually. In the two first experiments, the secondary tasks were combined with other tasks that are known to require phonological, visual, and spatial processes. Some pilot testing was done to refine the secondary tasks. Versions of the tasks were discarded that were too difficult or too easy. For example, a phonological task requiring that participants compare three words and judge whether at least two of the three words contain a common sound was discarded because it was too hard: Participants made many errors even when the secondary task was not combined with an interference task. Final versions of the secondary tasks were as follows:

- *Phonological secondary task.* Participants judged whether two words contained a common sound.
- *Visual secondary task.* Participants visualized the spelling of two words (in capital letters) and judged whether at least two of the three words contain a closed letter (i.e., letter which contains a closed area such as B, D, P).

- *Spatial secondary task.* Participants were given two clock times and were instructed to imagine the corresponding analog clock faces. They judged at which of the two times the clock hands formed the greater angle.

The following is a brief description of the Experiments 1 and 2 which I conducted to assess the validity of the secondary tasks that I subsequently used in my driving simulation studies. Experiment 1 was conducted to explore whether the secondary tasks (referred to as "secondary tasks" because they will be "secondary" to the primary driving simulation task in subsequent experiments) required the processing resources they were designed to require. An interference paradigm was used to explore the involvement of the phonological loop, and the visual and spatial components of the VSSP in the performance of the secondary tasks. The secondary tasks were presented auditorily. Participants performed the secondary tasks while performing either a phonological interference task (i.e., repetition of the sequence "a,b,c,d,e,f,g"; Baddeley, 1986; Levy, 1971; Murray, 1967), a visual interference task (i.e., a visual search task; Rayner & Fisher, 1987) or a spatial interference task (i.e., a tapping task; Farmer, Berman & Fletcher, 1986; Smyth & Pendleton, 1989). Observation of mutual interference between the secondary task and the interference task was assumed to indicate that the two tasks use the same processing resources. I hypothesized that each of the secondary tasks would interfere more with their respective interference tasks (e.g., phonological secondary task- phonological interference task) than with the other interference tasks (e.g., phonological secondary task- visual interference task).

Experiment 2 was identical to Experiment 1 except that the secondary tasks were presented visually. This experiment was conducted to ensure that when presented visually, the secondary tasks required the processing resources they were designed to require. As in Experiment 1, I hypothesized that each of the secondary tasks would interfere more with their respective interference tasks than with the other interference tasks. Table 1 shows a summary of the different combinations of secondary tasks and interference tasks that were tested in Experiments 1 and 2. The results of these experiments are reported in Chapter 2.

Table 1. Experiments 1 and 2: Summary of the different combinations of secondary tasks and interference tasks

	Processing Required by Secondary Tasks											
	Phonological				*Visual*				*Spatial*			
	Processing Required by Interference Tasks											
Secondary Task Presentation Mode	*Control*	*Phonological*	*Visual*	*Spatial*	*Control*	*Phonological*	*Visual*	*Spatial*	*Control*	*Phonological*	*Visual*	*Spatial*
Auditory				Experiment 1								
Visual				Experiment 2								

Experiments 3 and 4

In Experiments 3 and 4, participants performed the three secondary tasks (tested in Experiments 1 and 2) while performing the simulated driving task. Specifically, the secondary tasks were presented auditorily or visually to drivers while they performed the lane change task. The purpose of this experiment was to explore the effects of different processing resources (i.e., phonological, visual, spatial) on lane change performance, as a function of the presentation mode (i.e., auditory vs. visual). Thus, participants detected and responded to either visual road signs (Experiment 3), or auditory directional prompts (Experiment 4), and tried to maintain lateral positioning while performing the phonological, visual and spatial processing tasks. Table 2 provides an outline of design of Experiments 3 and 4.

Table 2. Experiments 3 and 4: Experimental Design

		Secondary Task Processing Mode			
Lane Change Prompt	Secondary Task Presentation Mode	*Control*	*Phonological*	*Visual*	*Spatial*
Visual	Auditory				
	Visual		Experiment 3		
Auditory	Auditory				
	Visual		Experiment 4		

Based on the assumption that drivers rely on visual and spatial resources to detect and respond to visual road signs and to maintain lateral positioning, I hypothesized that in Experiment 3, the visual and spatial secondary tasks would interfere more with drivers' lane change performance than the phonological secondary task, regardless of whether the tasks were presented auditorily or visually. The results of this experiment are described in Chapter 4.

In Experiment 4, given that the driving scenario had an auditory load (i.e., drivers were required to listen to lane change commands), I hypothesized that the secondary task that were presented auditorily would create an equal amount, or more, interference with the lane change task as the secondary tasks that were presented visually. The results of this experiment are described in Chapter 5.

CHAPTER 2

Experiments 1 and 2 were conducted to explore whether the three secondary tasks (i.e., phonological, visual and spatial) necessitated the phonological, visual and spatial processing resources they were designed to require. An interference paradigm was used to explore the involvement of the phonological loop and the visual and spatial components of the Visual Spatial Sketchpad (VSSP) in the performance of the secondary tasks. Specifically, the secondary tasks were combined with interference tasks that are known to require either phonological, visual, or spatial processing. Observation of mutual interference between the secondary task and the interference task is assumed to indicate that the two tasks use the same processing resources (Logie & Baddeley, 1987). The phonological interference task consisted of having participants repeat the sequence "a,b,c,d,e,f,g". The visual interference task required participants to perform a visual search task. The spatial interference task involved tapping a prescribed sequence. These type of tasks have been widely used in research investigating whether cognitive tasks respectively require phonological (Baddeley, 1986; Levy, 1971; Murray, 1967), visual (Rayner & Fisher, 1987) or spatial resources (Farmer, Berman & Fletcher, 1986; Smyth & Pendleton, 1989). I hypothesized that each of the secondary tasks would interfere more with their respective interference tasks (e.g., phonological secondary task- phonological interference task) than with the other interference tasks (e.g. phonological secondary task- visual interference task). To verify that the processing resources used to perform the secondary tasks did not vary as a function of presentation mode (i.e., auditory vs. visual presentation), secondary task information was presented auditorily in Experiment 1 and visually in Experiment 2.

Method - Experiment 1

Participants

Eighteen participants (11 males and 7 females) received $10 for their participation. All participants had English as their first language. The participants ranged in age from 19 to 37 years, with a median of 32.

Design

The participants performed the three secondary tasks (i.e., phonological, visual and spatial) in each of four interference conditions (i.e., no interference, phonological, visual and spatial). Thus, the design was a 3 (secondary task: phonological, visual or spatial) x 4 (type of interference: control, phonological, visual or spatial) repeated measures design.

Materials

Secondary Tasks

The secondary tasks described in this section were used in all four experiments. The items used in the secondary tasks are presented in Appendices A1 through A3. Secondary task stimuli were presented auditorily. Participants listened to the message given by the experimenter and vocalized their answer. Three secondary tasks were presented (i.e., phonological, visual and spatial). Each participant solved 12 trials of each secondary task in each of the four interference conditions (i.e., control, phonological, visual, spatial). Combinations of secondary and interference tasks were counterbalanced across participants.

Phonological secondary task. The phonological items were pairs of words (e.g., pewter and compute) that either contained a common phonetic sound (e.g., the sound "pewt" in pewter is phonetically the same as the "pute" in compute) or did not contain a common sound (e.g., fitness and sweater do not contain a common sound). A sound was defined as any part of a word that contained at least two letters (e.g., "fa" is considered a sound but "a" is not). The pairs of words containing a common sound were constructed so that the sound was phonetically the same but was spelled differently. For example, the words boating and remote contain the same phonetic sound "ō" but are spelled differently (i.e., "oat" for boat and "ote" for remote). To minimize differences in word duration, the lists of words were constructed so that the pairs of words contained the same total number of syllables. Five lists of 12 different pairs of words were constructed. Each list contained 6 pairs of words that contained a common sound and 6 pairs of words that did not contain a common sound. Each word pair was used only once during the experiment. The order in which the pairs of words appeared in each list was counterbalanced across participants.

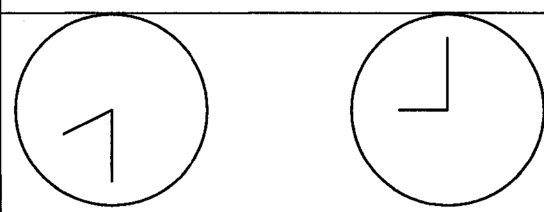
The participants listened to the experimenter vocalize two words. They were instructed to subvocally repeat the two words slowly and judge whether a common sound was contained in the two words. Participants verbalized their answer to the phonological secondary task by saying "yes" if the two words contained a common sound or "no" if not.

Visual secondary task. The visual secondary items were sets of three words (e.g., STICKY, WILD, RICE). The words were chosen so that when they were written in capital letters, they either contained a closed letter or they did not. Closed letters are defined as those that contain a closed area such as D, O and P, whereas open letters are those that do not contain a closed area such as C,L and S. Five lists, containing 12 combinations of 3 words, were constructed. Each list contained 6 combinations of 3 words in which at least two of the three words contained a closed letter, and 6 combinations of 3 words in which two of the three words did not contain a closed letter. The combinations of words in which at least two of the three words contained a closed letter were constructed so that the same number of words containing a closed letter came from the first, second and third word. Each set of 3 words was used only once during the experiment. The order in which the sets of 3 words appeared in a list was counterbalanced across participants. Thus, each participant saw the sets of 3 words in different orders. To avoid differences in word length, 3 word combinations were constructed so that they contained an equal number of total letters (e.g., combination #1: LUCKY, FURRY, DICE and combination #2: THREE, BLIND, MICE contain a total of 14 letters each. Combinations of words were constructed so that they were commonly associated words to reduce the need for participants to use verbal rehearsal when remembering the words.

The participants listened to the experimenter vocalize three words. They were instructed to visualize, one by one, the letters (in capitals) that spell out the three words and to judge whether at least two of the three words contained a closed letter. Participants verbalized their answer to the experimenter by saying "yes" if at least two of the three words contained a closed letter and "no" if not.

Spatial secondary task. The spatial items were pairs of times (e.g., eight-thirty and nine o'clock) in which the hour and minute hands formed different angles (e.g., eight-thirty forms a 30 degree angle and nine forms a 90 degree angle, see Figure 2). Times were selected so that they involved only half-hours (e.g., eight-thirty) or hours (e.g., nine). Five lists of 12 pairs of times were constructed. In each list, half of the pairs contained times for which the greater angle corresponded to the greater time (e.g., three vs. one o'clock) and half for which the greater angle corresponded to the numerically smaller time (e.g., eight-thirty vs. eleven). The pairs of times were also balanced so that the hour and minute hands, for both times, were equally as often on the right side of the clock (e.g., two o'clock and three o'clock), the left side of the clock (e.g., nine o'clock and ten o'clock) or on both sides of the clock (e.g., two o'clock and nine o'clock). Each pair of times was used only once during the experiment. The order in which the pairs of times appeared in a list was counterbalanced across participants. Thus, each participant saw the pairs of times in different orders.

Figure 2. Example of the spatial secondary task

Presentation	Hypothesized Internal Processing
Auditory: "eight-thirty and nine" Visual: 8:30 and 9:00	

The participants listened to the experimenter vocalize two times (e.g., "eight-thirty and nine"). They were instructed to imagine two analogue clock faces based on the times they heard and to judge at which of the two times the clock hands formed the greater angle. Participants were instructed to visualize the acute angle (i.e., angle measuring between 0 and 90 degrees) rather than the obtuse angle (i.e., angle measuring between 90 and 180 degrees), and were given practice to familiarize themselves with the task. Furthermore, participants were advised that times were selected such that the two angles would never be the same size. Participants verbalized their answer by saying the time that formed to the greater angle.

Interference Tasks

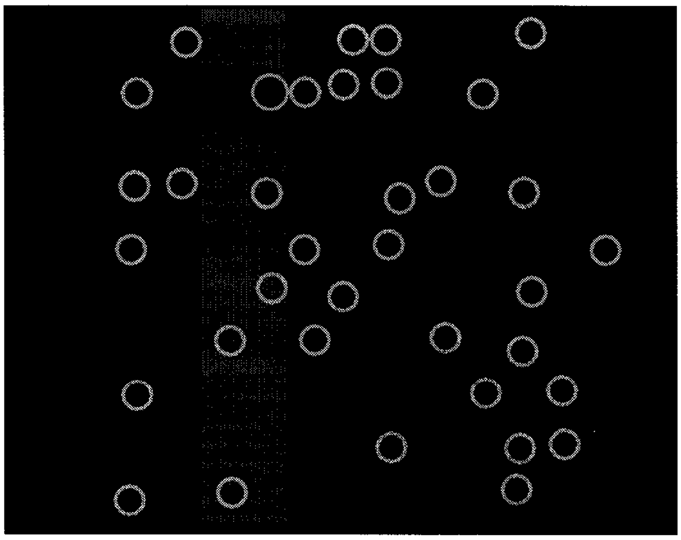
The interference tasks described in this section were used in both Experiments 1 and 2.

Phonological interference task. Participants continuously verbalized "a,b,c,d,e,f,g" while performing the secondary tasks (phonological, visual, spatial described above). Participants continuously vocalized "a,b,c,d,e,f,g" (approximate rate of one "a,b,c,d,e,f,g" per 2.5 seconds), except for when they stopped for a brief moment to verbalize their answer to the secondary task. As soon as they verbalized their answer to the secondary task, they immediately began vocalizing "a,b,c,d,e,f,g" again, commencing with the letter "a".

Visual interference. A Toshiba Satellite laptop computer was used to present the visual interference stimuli and to record responses. The participants were seated approximately 50 cm in front of the computer. The visual interference task consisted of a visual search task requiring participants to search for a larger circle amongst a number of 35 smaller circles.

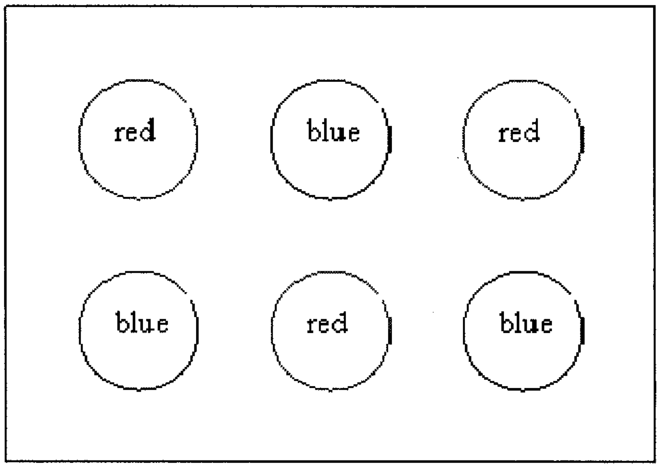
At the start of the visual search task, the computer screen was blank (i.e., black). Participants began the visual search task by pressing the space bar on the keyboard, at which point the 36 white circles (i.e., 35 small circles and one larger circle) appeared on the screen. Participants used the left and right arrows on the keyboard to begin their search task. That is, as soon as the participant pressed on the right or left arrow key, a narrow grey rectangle appeared on the screen, highlighting a group of circles (see Figure 3). If the larger circle was amongst the highlighted circles, participants pressed the up arrow to indicate their answer. If the larger circle was not amongst the group of highlighted circles, participants used the right and left arrow keys to move the grey rectangle to the right and left respectively, until the larger circle was highlighted. Once the larger circle was highlighted, participants pressed the up arrow to indicate their answer. Following indication of their answer, the next set of circles appeared on the screen initiating the next search task. Participants performed this search task while performing the secondary tasks. Given that participants verbalized their answers to the secondary tasks, there was no need for participants to stop the search task while performing the secondary task.

Figure 3. Example of the visual interference task



Spatial interference task. The spatial interference task was a tapping board made up of 6 quarters taped to the front of a cardboard covered book which measured 19 x 12 cm. The six quarters were taped to the book in two rows containing three quarters each. The quarters were perfectly centered on the book with 3 cm separating each quarter from the other and 3 cm separating the quarters from the edge of the book. To help participants memorize the tapping pattern, the quarters were outlined with a red or blue marker. Specifically, the top row of quarters was outlined with red, blue and red marker respectively, while the second row was outlined with blue, red and blue marker respectively (see Figure.4).

Figure 4. Sketch of tapping board



The participants repeatedly tapped (using their index finger) a given pattern on the tapping board. The pattern they were asked to repeatedly tap was to first tap the red circles and then tap the blue circles, commencing at the top left red circle. Participants could look at the circles during practice trials but were required to not look at the board while they tapped during the test trials. Given that participants verbalized their answers to the secondary tasks, there was no need for participants to stop the tapping task while performing the secondary task.

Procedure

Participants performed each of the 3 secondary tasks at each of the 4 levels of interference. Every participant first completed 12 practice trials of each type of secondary task. Participants were given as much time as they needed to familiarize themselves with the visual and spatial interference tasks (there was no need to familiarize themselves with the phonological interference task as they just had to repeat “a,b,c,d,e,f,g”). Trial-by-trial feedback on both the secondary tasks and the interference tasks was given in the practice block. Each trial began with the participant initiating the interference task. As soon as the participant started the interference task, the experimenter vocalized the secondary task stimuli (phonological, visual or spatial). As soon as the experimenter finished vocalizing the secondary task stimuli, she began timing the participant's response using a stopwatch. Participants continued performing the interference task while verbally responding to the secondary task. As soon as the participant responded, the experimenter stopped the timing, and recorded the response. While the participant continued performing the interference task, the experimenter vocalized the next stimulus and started timing again. The participants were asked to respond to the secondary task as quickly and as accurately as possible while attempting to maintain steady performance on the interference task. They were instructed to place the same emphasis on both the secondary task and the interference task.

Results - Experiment 1

Dual-Task Performance

Participants completed a total of 2592 trials. Two indices of performance were calculated and analyzed: latencies to secondary tasks and errors on secondary tasks. The error score was the number of trials (out of 12 trials in each condition) on which the participants made an error on the secondary task. No error performance was calculated for the interference tasks. The assumption is that because the experimenter was present to ensure participants were continuously performing the interference task, breakdown in performance on the secondary tasks indexed working memory demands. Unless otherwise indicated, the alpha level for the analyses was .05. Greenhouse-Geisser procedures were used for correcting degrees of freedom and mean square error terms under violation of sphericity. Post hoc pairwise comparisons between means were made using Bonferroni correction. To assist in the interpretation of figures, 95% confidence intervals (CIs) are presented on figures (calculated using the formula recommended by Masson & Loftus, 2003).

Secondary Task Latencies

Secondary task latency differences were calculated by subtracting participants' latencies to correctly answered secondary tasks in the control condition (i.e., no interference) from their latencies to correctly answered secondary tasks in each of the dual task conditions (i.e., phonological, visual, spatial interference). Analyses on difference scores were appropriate for the present experiment, as I was interested in evaluating changes in performance from baseline to dual- task conditions. Difference scores, however, do not permit testing related to performance at each level of secondary task and interference. Therefore, for referencing purposes, Table 1 in Appendix B presents the mean latencies, standard deviations, and error scores at each level of secondary task and interference. Secondary task latency differences (i.e., performance decrements) were analyzed in a 3 (secondary task: phonological, visual, spatial) x 3 (interference task: phonological, visual, spatial) repeated measures ANOVA. ANOVA results are presented in Table 3.

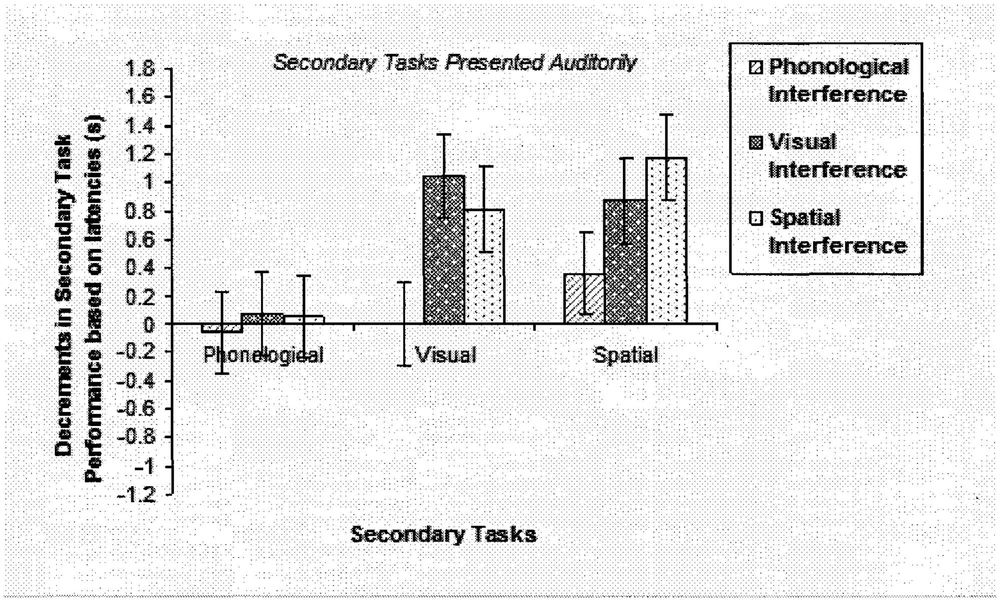
Table 3. Experiment 1: ANOVA for mean secondary task performance decrements (based on latencies)

	df	*MS*	*F*
Secondary Task	2		8.37**
Error (Secondary Task)	34	1.07	
Interference	2		16.23**
Error (Interference)	34	0.36	
Secondary Task x Interference	4		3.30*
Error (Secondary Task x Interference)	68	0.40	

Note. * $p < .05$, ** $p < .01$

Decrements in performance were significantly larger when participants performed the visual (0.62 s) and spatial (0.81s) secondary tasks than when they performed the phonological (0.03 s) secondary task. There was no difference in performance decrements between the visual and spatial secondary tasks. Furthermore, visual (0.66 s) and spatial (0.68 s) interference caused significantly larger decrements in secondary task performance than did phonological interference (0.10 s). There was no difference in performance decrements between the visual and spatial interference. Most relevant is the finding that the type of secondary task interacted with the type of interference. As is shown in Figure 5, when the secondary tasks were visual and spatial, decrements in performance were significantly larger with visual and spatial interference than with phonological interference. When the secondary task was phonological, however, decrements in performance did not vary with the type of interference. Thus, results suggest that the tasks designed to necessitate visual and spatial resources do indeed require visual and spatial resources. However, the present results do not provide strong evidence with respect to showing that the task designed to necessitate phonological resources does indeed require phonological resources. That is, I had expected that decrements in performance on the phonological secondary task would be greater with phonological interference than with visual or spatial interference. Results, however, did not reveal any differences on phonological secondary task performance across interference conditions.

Figure 5. Experiment 1: Mean decrements in secondary task performance as a function of interference and secondary task. Error bars represent 95% confidence intervals, based on the MS_e from the two-way interaction.



Secondary Task Errors

Difference scores were calculated by subtracting participants' percent errors on secondary tasks in the control condition (i.e., no interference) from their percent errors on secondary tasks in each of the dual-task conditions (i.e., phonological, visual, spatial interference). These difference scores were analyzed in a 3 (secondary task: phonological, visual, spatial) x 3 (interference task: phonological, visual, spatial) repeated measures ANOVA. ANOVA results are presented in Table 4.

Table 4. Experiment 1: ANOVA for mean secondary task performance decrements (based on % error scores)

	df	*MS*	*F*
Secondary Task	2		3.83*
Error (Secondary Task)	34	70.02	
Interference	2		0.40
Error (Interference)	34	103.77	
Secondary Task x Interference	4		0.97
Error (Secondary Task x Interference)	68	112.09	

Note. * $p < .05$

Decrements in performance were significantly larger when participants performed the phonological secondary task (8.2%) than when they performed the visual (4.3%) and the spatial (4.3%) secondary tasks. Decrements in performance on the visual and spatial secondary tasks did not differ significantly. There were no effects of interference type (i.e., phonological vs. visual. vs. spatial interference) and no interaction between secondary tasks and type of interference.

Discussion – Experiment 1

Results for the visual and spatial secondary tasks were as predicted. Specifically, performance decrements (in terms of latencies) on the visual secondary task were largest with visual interference and performance decrements (in terms of latencies) on the spatial secondary task were largest with spatial interference. Furthermore, performance on the visual secondary task decreased with spatial interference and performance on the spatial secondary task decreased with visual interference. This pattern of results suggests that the visual and spatial secondary tasks are not purely visual or spatial tasks but rather a combination of visual-spatial tasks. Although these effects could be attributable to the competition for the limited visual and spatial resources, it could also be argued that the visual and spatial interference merely acted as general distractors. This interpretation, however, is not adequate to explain the result that when participants were required to perform the phonological secondary task (i.e., judge whether two words contain a common sound), they showed no evidence of a performance decrement when visual or spatial interferences were present. Thus, results suggest that performance of the visual and spatial secondary tasks depend on visual and spatial resources.

Results for the phonological secondary tasks did not turn out as predicted. It was hypothesized that the phonological secondary task and the phonological interference task shared a common resource. Therefore, it was expected that the phonological interference would cause a greater decrement on phonological secondary task performance than would visual and spatial interference. This hypothesis, however, was not supported.

Results (see Figure 5) show that none of the interference conditions had an effect on phonological secondary task latencies. One interpretation of this result is that the phonological secondary task was not sufficiently difficult, compared to the visual and spatial secondary tasks, to be influenced by an interference task. Accordingly, we would expect that performance decrements (in terms of percent errors) would also be smaller for the phonological secondary task than for the visual and spatial secondary tasks. Results, however, revealed that performance decrements on percent errors were significantly larger for the phonological than for the visual and spatial secondary tasks. Thus, although participants showed a smaller performance decrement (in terms of secondary task latencies), they showed a larger performance decrement (in terms of percent errors) when performing the phonological task than when performing the visual and spatial tasks. In sum, it appears that although participants were responding quickly to the phonological secondary task, they were not always responding correctly. This tradeoff is perhaps an indication that participants were not subvocalizing the words prior to answering. Although participants were asked to subvocally rehearse the words prior to providing their answer, they might have answered directly after hearing the experimenter vocalize the two words. This more direct processing of the phonological task would afford greater speed, but would not afford opportunity to minimize errors. Thus, results suggest that the phonological secondary task is just as difficult, if not more difficult, as the visual and spatial secondary tasks.

If participants were not subvocalizing the words before answering, this could potentially explain why latencies on the phonological secondary task did not increase with phonological interference. Baddeley's (1986) phonological loop model suggests that the phonological loop is comprised of an articulatory rehearsal system and a phonological store. As reflected in the names of these two components, the articulatory rehearsal system is used to "rehearse" phonological information before it is "stored" in the phonological store. When information is presented auditorily, it has direct access to the phonological store, unless the information needs to be refresehed, in which case it is first rehearsed in the articualtory rehearsal system prior to being stored.

A suppression task (e.g., repetition of the word "the") has been found to prevent operation of the articulatory rehearsal system (e.g., Baddeley, 1986; Levy, 1971; Murray, 1967). In the present experiment, I attempted to disrupt the articulatory rehearsal system by having participants continuously repeat "a,b,c,d,e,f,g". When performing the phonological secondary task [i.e., stating whether two words (e.g., compute and pewter) contain a common sound], participants were asked to subvocalize the two words before providing their answer. I hypothesized that performance of the phonological interference task (i.e., continuous rehearsal of "a,b,c,d,e,f,g") would interfere with the subvocalization of the two words (e.g. compute, pewter), and consequently increase participant's response latencies. If participants were not subvocalizing the words, however, the words would have direct access to the phonological store without passing through the process of articulatory rehearsal. Consequently, performance of the phonological interference task would not interfere with participants secondary task latencies. The material in the present experiment was presented auditorily. Therefore, it is possible that the phonological interference task did not affect phonological secondary task performance, because the latter task had direct access to the phonological store.

One way to ensure that participants rehearse the phonological information is to present the information visually rather than auditorily. When information is presented visually, participants must read, and therefore are forced to subvocally articulate the information (Estes 1973; Levy, 1971; Murray, 1968; Peterson and Johnson, 1971). In Experiment 2, I performed the same experiment but with the stimuli presented visually rather than auditorily.

In Experiment 2, I hypothesized that each of the secondary tasks would interfere more with their respective interference tasks than with the other interference tasks. In particular, I expected that visual presentation of the phonological secondary task would force participants to articulate the words, and therefore the phonological interference tasks (i.e., repeating "a,b,c,d,e,f,g") should interfere with judging whether two visually presented words contain a similar sound.

Method - Experiment 2

The methodology for experiment 2 was the same as the method for experiment 1 with the following modifications:

Participants

Eighteen participants (8 males and 10 females) received $10 for their participation. All participants had English as their first language. The participants ranged in age from 18 to 32 years, with a median of 20.

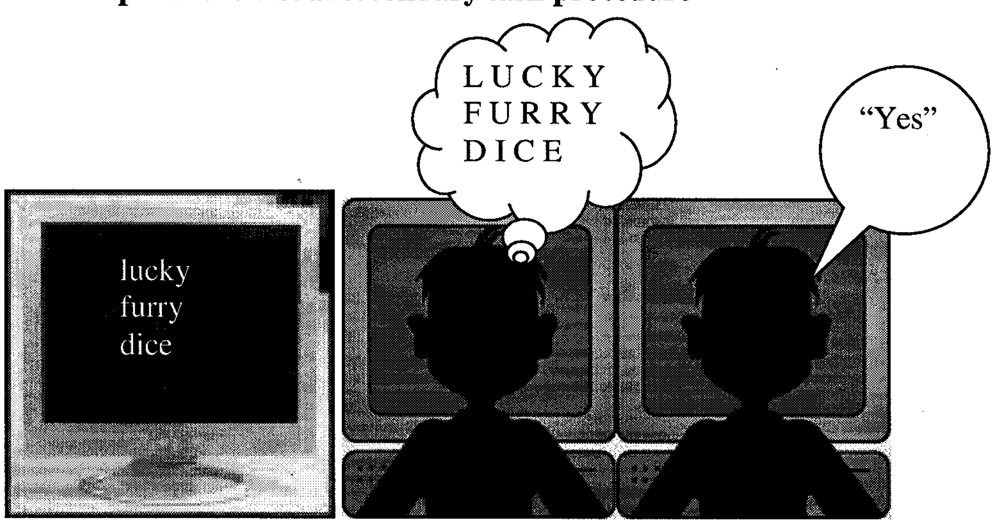
Materials

Secondary Tasks

Secondary task stimuli were presented visually on a Toshiba Satellite laptop. An auditory "clicking" sound was emitted prior to the visual presentation of secondary task material, to inform participants of its onset. Participants read the message on the computer screen and vocalized their answer. It was desirable that the message remain on the screen for the same amount of time as it took the experimenter to vocalize the message in Experiment 1. Therefore, the message was presented for a fixed amount of time (i.e., 2 seconds) and was only presented once. Experimental trials were performed to evaluate the exact message duration. As soon as the participant completed a given trial, the experimenter pressed the spacebar on the keyboard so that the next secondary task stimulus appeared.

Visual secondary task. The visual secondary items were the same sets of three words (e.g., STICKY, WILD, RICE) used in Experiment 1. The words were chosen so that when they were written in capital letters, they either contained a closed letter or they did not. As depicted in Figure 6, participants viewed three words that were presented (for 2 seconds) on a computer screen. They were instructed to subvocally read the three words. Participants were then required to visualize, one by one, the letters (in capitals) that spell out the three words, and to judge whether at least two of the three words contain a closed letter. Participants verbalized their answer to the experimenter by saying "yes" if at least two of the three words contained a closed letter and "no" if not. Given that the words were presented visually, participants could have simply looked at the computer screen to identify whether or not two of the three words contained a closed letter, without visualizing the words in their heads. To prevent such a strategy, words were presented in lower case letters on the computer screen (e.g., lucky, furry, dice). Therefore, to correctly answer the question, participants had to visualize the words in upper case letters because some letters (e.g., r) are "open" when written in lower case letters but "closed" when written in upper case letters (e.g. R). Therefore, in both Experiments 1 and 2, participants were required to subvocally rehearse the letters prior to responding.

Figure 6. Example of the visual secondary task procedure



1. Three words (in lower case letters) are presented on the screen

2. Participants visualize the letters (in upper case)

3. Participants verbalize their answer by saying "yes" if at least two of the three words contain a closed letter, and "no" if not

Interference Tasks

Visual interference task. Given that both the secondary tasks and the visual interference task required that participants read information on a computer screen, two different computers were used to present the secondary and interference task information. Specifically, a desktop computer was used to present the visual interference stimuli on a video monitor and the Toshiba Satellite laptop was used to present the secondary task stimuli. The video monitor used to present the interference task was positioned directly to the left of the laptop; both screens were fully visible. As in Experiment 1, participants used a keyboard to respond to the visual interference task while verbalizing their answers to the secondary tasks.

Procedure

As in Experiment 1, each trial began with the participant initiating the interference task. As soon as the participant started the interference task, the experimenter pressed the spacebar on the keyboard to initiate presentation of secondary task stimuli. A "clicking" sound was emitted to inform participants of the onset of the secondary task stimulus. As soon as the secondary task stimulus appeared on the screen, the experimenter began timing the participant's response using a stopwatch. Participants continued performing the interference task while verbally responding to the secondary task. The experimenter stopped timing as soon as the participant had responded. While the participant continued to perform the interference task, the experimenter pressed the spacebar to initiate presentation of the next stimuli and started timing again.

Results – Experiment 2

Dual-Task Performance

I hypothesized that each of the secondary tasks would interfere more with their respective interference tasks than with the other interference tasks. Furthermore, I hypothesized that because the phonological secondary task was presented visually, participants would have to articulate the words, and therefore phonological interference would impact performance on the phonological secondary task. Thus, unlike results found in experiment 1, I expected that performance on the phonological secondary task would vary as a function of type of interference.

The participants completed a total of 2592 trials. Two indices of performance were calculated and analyzed: latencies to secondary tasks and errors on secondary tasks. The error score was the number of trials (out of 12 trials in each condition) on which the participants made an error on the secondary task. No error performance was calculated for the interference tasks. The assumption is that because the experimenter was present to ensure participants were continuously performing the interference task, breakdown in performance on the secondary tasks indexed working memory demands. Unless otherwise indicated, the alpha level for the analyses was .05. Greenhouse-Geisser procedures were used for correcting degrees of freedom and mean square error terms under violation of sphericity. Post hoc pairwise comparisons between means were made using Boneferroni correction. To assist in the interpretation of figures, 95% confidence intervals (CIs) are presented on figures.

Secondary Task Latencies

Difference scores were calculated by subtracting participants' latencies to correctly answered secondary tasks in the control condition (i.e., no interference) from their latencies to correctly answered secondary tasks in each of the dual-task conditions (i.e., phonological, visual, spatial interference). These secondary task latency differences (i.e., performance decrements) were analyzed in a 3 (secondary task: phonological, visual, spatial) x 3 (interference task: phonological, visual, spatial) repeated measures ANOVA. ANOVA results are presented in Table 5. For referencing purposes, Table 2 in

Appendix B presents the mean latencies, standard deviations, and error scores at each level of secondary task and interference.

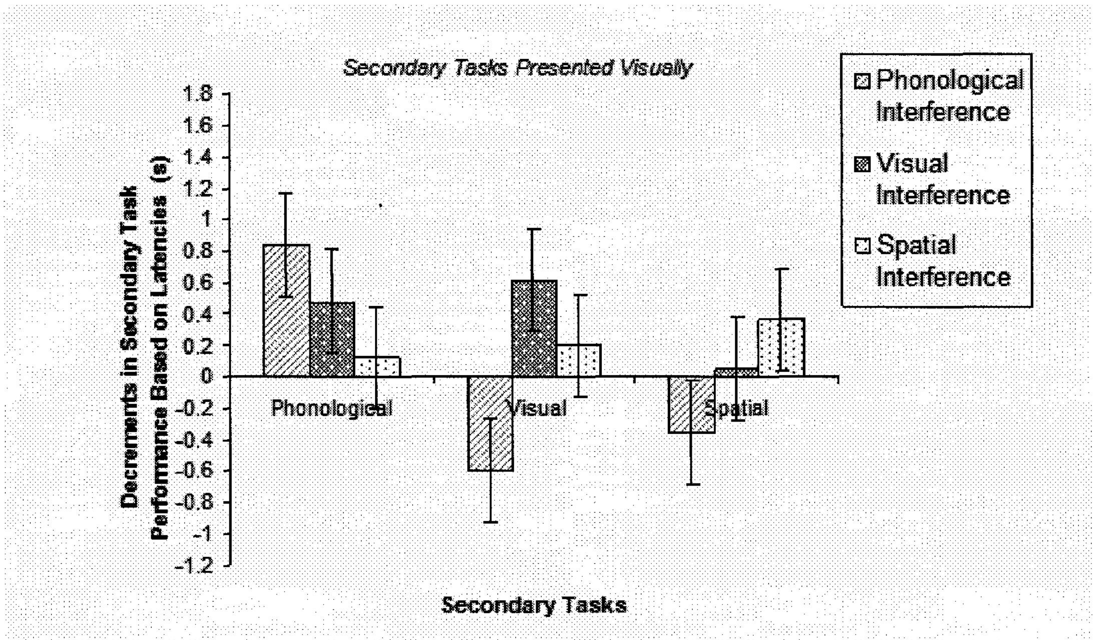
Table 5. Experiment 2: ANOVA for mean decrements in secondary task performance (based on latencies)

	df	*MS*	*F*
Secondary Task	2		1.33
Error (Secondary Task)	34	2.62	
Interference	2		3.37*
Error (Interference)	34	0.72	
Secondary Task x Interference	4		4.07*
Error (Secondary Task x Interference)	68	1.12	

Note. * $p < .05$

Decrements in performance were significantly larger with visual and spatial interference than with phonological interference. No difference in performance decrement was obtained between visual and spatial interference. Furthermore, type of secondary task interacted with type of interference. As is shown in Figure 7, when the secondary task was phonological, decrements in performance were significantly larger with phonological than with spatial interference. Visual interference on phonological secondary task performance did not differ significantly from phonological or spatial interference. Thus, as predicted, phonological secondary task performance was predominantly lowered by phonological interference. This latter result supports the hypothesis that when phonological material is presented visually, participants must subvocally articulate the material and therefore presence of an articulatory suppression task (i.e., phonological interference task) decreases performance on the phonological task. When participants performed the visual secondary task, decrements in performance were significantly larger with visual interference than with phonological interference. Decrements in visual secondary task performance due to spatial interference did not differ significantly from decrements due to phonological or visual interference. Thus, as predicted, visual secondary task performance was predominantly lowered by visual interference. When the secondary task was spatial, decrements in task performance did not vary significantly across interference conditions but decrements were largest with spatial interference. In sum, the interference tasks produced the expected patterns. Specifically, each of the secondary tasks interfered more with their respective interference tasks than with the other interference tasks.

Figure 7. Experiment 2: Mean decrements in secondary task performance (based on latencies) as a function of interference and secondary task. Error bars represent 95% confidence intervals, based on the MS_e from the two-way interaction.



Secondary Task Errors

Difference scores were calculated by subtracting participants' percent errors on secondary tasks in the control condition (i.e., no interference) from their percent errors on secondary tasks in each of the dual-task conditions (i.e., phonological, visual, spatial interference). These difference scores were analyzed in a 3 (secondary task: phonological, visual, spatial) x 3 (interference task: phonological, visual, spatial) repeated measures ANOVA. ANOVA results are presented in Table 6.

Table 6.* Experiment 2: *ANOVA for mean decrements in secondary task performance (based on % error scores)

	df	*MS*	*F*
Secondary Task	2		1.23
Error (Secondary Task)	34	427.45	
Interference	2		0.26
Error (Interference)	34	112.25	
Secondary Task x Interference	4		0.45
Error (Secondary Task x Interference)	68	132.90	

Note. * $p < .05$

There were no effects of task type, interference type and no interaction between task type and interference type.

In sum, the results from Experiment 1 and 2 suggest that the secondary tasks did indeed require the processing resources they were designed to require. Thus, I was justified in using these secondary tasks to explore the effects of information presentation and processing on driving performance, which were the objectives of Experiments 3 (Chapter 4) and of Experiment 4 (Chapter 5).

CHAPTER 3

Lane Change Test (LCT)

Overview

The driving simulator is a simple PC-based standardized test scenario entitled "Lane Change Test (LCT)" (Mattes, 2003) that requires drivers to perform lane changes. The LCT requires drivers to repeatedly perform lane changes when prompted by road signs. The amount of distraction due to the additional demands of a secondary task is evaluated according to drivers' lane change quality relative to a normative model. The difference between the driver's actual lane change path and the ideal lane change path is influenced by the driver's ability to detect and respond to the road signs and maintain lateral positioning. Thus, an increase in deviation of lane change path would reflect the following aspects of the driver's performance: (1) perception of the road sign (e.g., late perception of the sign or missing the sign), (2) quality of lane change maneuver (e.g., slow lane change results in larger deviation) and (3) quality of lane position maintenance (e.g., swerving results in poorer lane maintenance quality). The top frame of Figure 8 shows the driver's view of the simulated three-lane road scene with signs instructing the driver to change into the left lane. The middle frame illustrates the difference in area (red) between the normative path (green) and actual path (blue) for a quick response (adapted from Mattes, 2003). The bottom frame illustrates performance during slower lane-change response. More area (i.e., red) indicates poorer performance. Thus, in my thesis, I am using a very restrained definition of driving performance. That is, I am defining driving as the driver's ability to detect and react to road signs, and maintain lateral positioning.

This definition of driving is contained in the operational and maneuvering levels of Michon's (1985) three-level hierarchical model of driving.

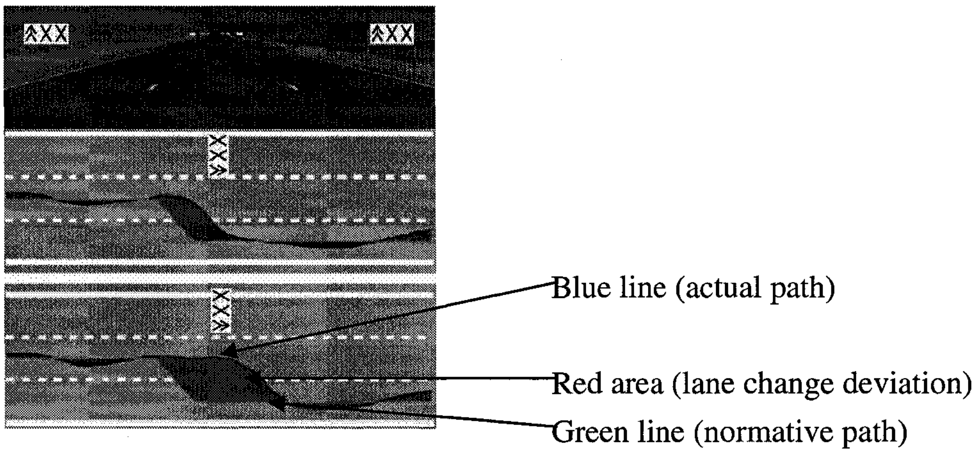
General Operation

The LCT simulation is a driving simulation that requires participants to perform lane-change maneuvers while maintaining a constant speed of 60km/hour. The test-track is 3 km straight 3 lane road with 18 signs. The mean distance between road signs is 150m with a mean duration of 9 seconds between two lane changes. While driving forward, participants encounter traffic signs which prompt them to change lanes. Once they have performed the lane change, participants try to maintain their position in the center of a given lane. There is no surrounding traffic in the scenario.

When initiating operation of the LCT, participants are required to navigate through a U-shaped curve to reach the start of the lane. At the end of the curve participants must be in the middle lane and be driving at the maximum speed which is limited to 60 km/hour. The participants are instructed to not reduce their speed while driving the track. Rather, they should keep the accelerator pedal pressed to the floor during the entire run. Participants are instructed to change lanes as soon as the information on the sign appears. Thus, the lane change should be performed before they actually reach sign. Furthermore, lane change maneuvers must be performed in a deliberate manner. That is, participants should not drift or gradually change lanes; but do so as quickly and as efficiently as possible.

In conditions with secondary tasks, the experimenter presents the first stimuli when the participant reaches the yellow "Start" sign. The experimenter begins timing the participant's response by pressing the key "M" which corresponds to the "start" marker. Once participants have completed the secondary task, the experimenter stops the timing by pressing the "N" key which corresponds to the "finish" key. Participants repeatedly perform a given task type on a single track. The end of the track is reached after 3 minutes.

Figure 8. Image of LCT and illustrations of performance



Breakdown of Overall LCT Measure

The overall measure of driving performance can be broken down into three components; lane change initiation, lane maneuver quality, and lane maintenance performance. Specifically, the overall mean deviation in lane change path measure encompasses three tasks; (1) a lane change initiation task: responding to road signs or auditory commands, (2) a maneuvering task: maneuvering quickly and efficiently into a given lane, and (3) a lane maintenance task: maintaining lane position between two consecutive signs. These component measures are of interest because the predictions about how secondary tasks will influence driving may vary according to the particular driving component. For example, Horrey and Wickens (2002, 2006) reported that although concurrent performance of a secondary task while driving disrupted road hazard detection, it did not disrupt vehicle control.

Lane Change Initiation (LCI)

The difference between the distance (in meters) at which the lane change direction appeared on the sign (i.e., distance at which the driver would ideally initiate a lane change) and the distance at which drivers actually initiated their lane change was used as an index of lane change initiation (see #1 in Figure 9). In the present experiments, lane change initiation represents an event detection measure.

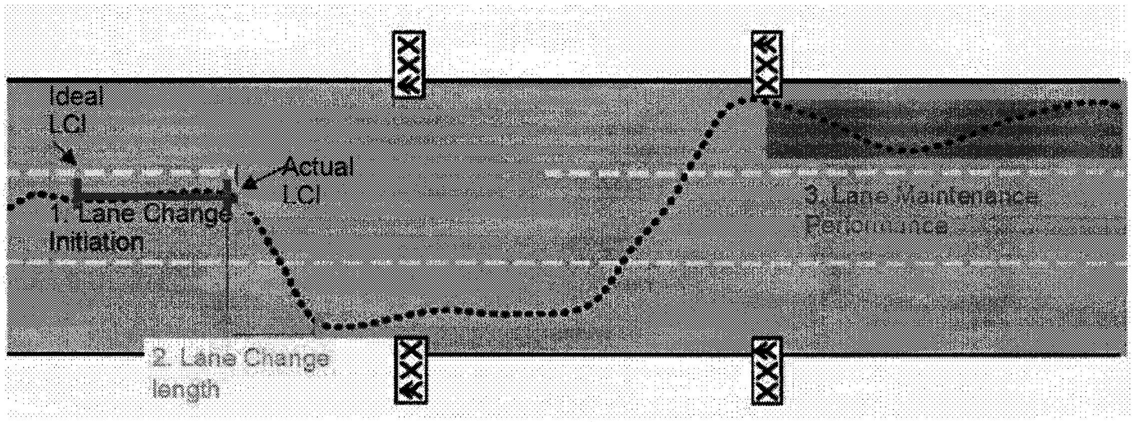
Lane Maneuver Quality

The second aspect of driving performance that is reflected in the overall lane change deviation measure is the quality of the lane change maneuver. In the present experiments, good quality of lane change maneuver is defined as a rapid lane change. In terms of distance, a good lane change maneuver corresponds to a small difference between the distance at which the driver completed the lane change and the distance at which he/she initiated the lane change (see #2 in Figure 9).

Lane Maintenance Performance

The third aspect of driving performance that is reflected in the overall lane change deviation measure is the lane keeping quality. Drivers' ability to maintain their lane position between lane changes was used as an index of mean lane maintenance performance (see #3 in Figure 9).

Figure 9. Three breakdown components of the overall LCT driving measure



CHAPTER 4

The first goal of the present research was to investigate the effects of secondary task presentation mode, auditory versus visual, on driving performance. In particular, the perceptual modality dimension of Wickens' (1980) multiple resource model predicts that cross-modal time-sharing (e.g., auditory-visual) is better than intra-modal time-sharing (e.g., visual-visual or auditory-auditory) because it is easier for people to divide attention between a visual display and an auditory command than between two visual displays or two auditory commands. The present experiment tests the hypothesis that visual presentation of secondary tasks will cause more interference with driving performance than will auditory presentation because driving has heavy visual demands. The second goal of the present research was to explore the effects of mental resources used to process secondary task information on driving performance. In particular, multiple resource models of information processing (e.g., Baddeley & Hitch, 1974; Wickens, 1980) predict that two tasks can be time-shared more efficiently when they employ different processing resources than when they employ common processing resources. In the present experiment the driving task requires visual and spatial processing. Therefore, it is expected that secondary tasks that require visual and spatial processing will interfere more with driving than tasks that require phonological processing, regardless of the mode (i.e., auditory or visual) used to present task information.

Method – Experiment 3

Participants

Fifty-six participants (21 males and 35 females) received course credit or $10 for their participation. All participants had English as their first language. They ranged in age from 17 to 55 years, with a median of 22.

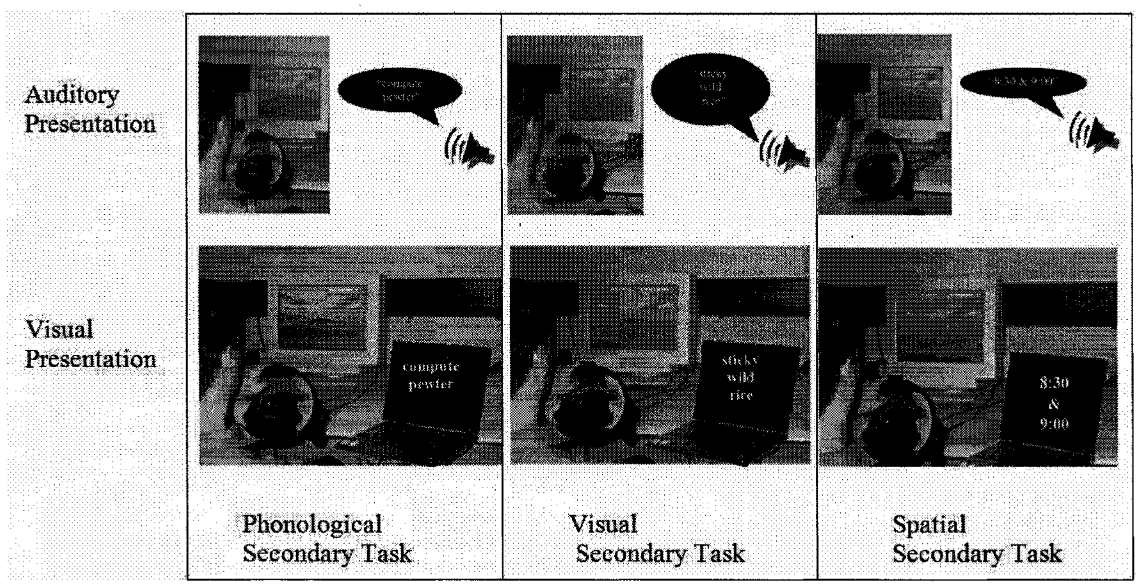
Design

Participants drove nine full runs on the simulated test track. Three of these nine runs were baseline runs (i.e., without secondary tasks). The remaining six runs were driven while participants performed phonological, visual and spatial secondary tasks. Specifically, of the total nine runs, participants performed three without a secondary task (i.e., baseline conditions), two with a phonological secondary task, two with a visual secondary task, and two with a spatial secondary task. Thus, the design was a 2 (secondary task presentation mode: auditory or visual) x 4 (secondary task processing mode: no processing (i.e., baseline), phonological, visual, and spatial) mixed factors design with repeated measures on the last factor.

Apparatus

A Toshiba Satellite laptop and external video monitor were used to present the Lane Change Test (LCT) driving simulation. A Logitech MOMO Racing Force-Feedback Wheel with foot pedals was used to control the simulated vehicle. When the secondary task was presented visually, participants read information relevant to both tasks on computer monitors. The driving simulation was shown on an external video monitor whereas the secondary tasks were presented on a Sony Vaio laptop. The Sony laptop was positioned to the right of the external monitor used to present the driving task so that both screens were fully visible (see bottom panel of Fig 10).

Figure 10. Examples of secondary task presentation and processing modes



Materials

Driving Simulation

The LCT driving simulation described in Chapter 3 was used in this experiment.

Secondary Tasks

The phonological, visual and spatial secondary tasks were the same as those used in Experiments 1 and 2.

Other Measures

Participants answered a driving questionnaire concerning their driving background and experiences (Appendix C). This measure includes questions regarding demographic information, driving experience, and medical information (e.g., visual acuity).

Sessions were videotaped for data collection and presentation purposes. Specifically, a Sony video camera was used to capture the computer screens, the back of participants' head, and their voice. All tapes were kept strictly confidential through the assignment of a coded identification number.

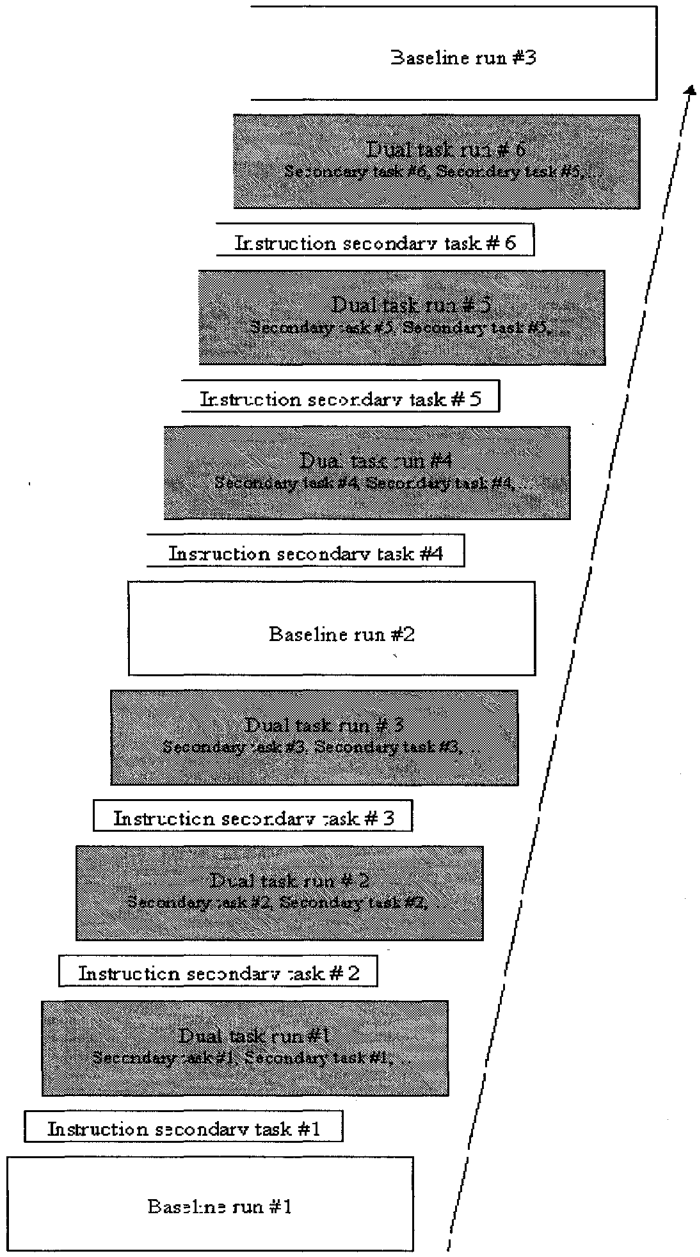
Procedure

Participants were randomly assigned to one of the two secondary task presentation conditions. Specifically, half of the participants (n = 28) were assigned to the auditory secondary task presentation mode (see top panel of Figure 10) and half (n = 28) were assigned to the visual secondary task presentation mode (see bottom panel of Figure 10). Every participant first completed practice trials on the LCT (without performing secondary tasks) until they felt comfortable with the task. Each participant completed at least one full run on the test track during practice. Participants then performed 12 practice trials of each type of secondary tasks (without performing the LCT task). Trial by trial feedback on secondary task performance was given during the practice block.

Experimental Conditions

A trial consisted of nine runs. On each trial, participants performed three baseline runs in which they drove the track without performing a secondary task, and six dual-task runs, two in combination with each secondary task. Each participant performed a baseline run on the first, fifth, and ninth runs. The first three dual task runs were performed between the first and second baseline runs, and the final three dual-task runs (i.e., runs with the second occurrence of each secondary task) were performed between the second and last baseline runs (see Figure 11). For both the first and second occurrences of secondary tasks, the order of the secondary task runs was counterbalanced. Participants were reminded that their primary task was to drive as safely as possible, as they would in the real world, and were asked to perform secondary tasks as quickly and as accurately as possible.

Figure 11. Example of experimental design



Each run began with the experimenter announcing which secondary task was going to be performed in a given run (or that the run involved only driving). The participant then started driving the simulation. At the beginning of each run, participants were required to navigate through a U-shaped curve to reach the start of the lane. At this point, participants had to be driving in the middle lane at maximum speed, which was fixed at 60 km/hour when the accelerator pedal was fully depressed. Participants were required to maintain this maximum speed for the entire run. Participants were instructed to change lanes as soon as the information on the sign appeared. Thus, the lane change should be performed before they actually reached the sign. Furthermore, lane change maneuvers had to be performed in a deliberate manner. That is, participants should not drift or gradually change lanes; but do so as quickly and as efficiently as possible.

Auditory presentation mode. In conditions with auditory presentation of secondary tasks, the experimenter verbally stated the first set of stimuli (e.g., "eight-thirty" and "nine") when the participant reached the yellow Start sign in the scenario. As soon as the experimenter finished vocalizing the secondary task stimuli, she began timing the participant's response by pressing the key "M" which corresponds to the "start" marker. Participants continued performing the lane change maneuvers while verbally responding to the secondary task. As soon as the participant responded, the experimenter stopped the timing by pressing the "N" key which corresponds to the "finish" key, and pressed the "9" key if the participant made an error when answering the secondary task. While the participant continued performing the lane change task, the experimenter vocalized the next set of stimuli and pressed the "M" key to start timing again. Participants responded to the secondary task as soon as possible and the experimenter immediately gave the next set of stimuli. Participants repeatedly performed a given task type (e.g., spatial task) on a single track. The end of the track was reached after three minutes. After each run, participants were asked to rate their workload on a scale from 1 to 10 reflecting the difficulty of driving while performing the secondary task they had just completed. A rating of "1" corresponded to a minimal workload and a rating of "10" corresponded to a very high workload during the tasks. The driving simulation was then restarted for the next run.

Visual presentation mode. In conditions with visual presentation of secondary tasks, the experimenter pressed the spacebar on the Sony laptop computer to initiate the first set of stimuli (e.g., 8:30 and 10:00 appeared on the computer screen) when the participant reached the yellow Start sign in the driving scenario. The secondary task stimuli were presented for two seconds. To warn participants that they must look at the Sony laptop to view the stimuli, presentation of the stimuli was accompanied by a beep. As soon as the stimuli appeared on the screen, the experimenter began timing the participant's response by pressing the key "M" (on the Toshiba laptop keyboard) which represents to the "start" marker. Participants performed the lane change maneuvers while verbally responding to the secondary task. Participants were instructed to respond to the secondary task as soon as possible. As soon as the participant responded, the experimenter stopped timing by pressing the "N" key which corresponds to the "finish" key. She pressed the "9" key if the participant made a mistake when responding to the secondary task. While the participant continued to perform the lane change task, the experimenter pressed the Sony laptop spacebar to initiate the next set of stimuli and pressed the "M" key (on the Toshiba laptop keyboard) to start timing again. Thus, there was minimal delay between the secondary task trials. After each run, participants were asked to rate their workload on a scale from 1 to 10 reflecting the difficulty of driving while performing the secondary task they had just completed. The driving simulation was then restarted for the next run.

Other measures. After finishing all other tasks, the participants spent approximately two minutes completing the questionnaire.

Testing was completed within a single session of approximately 90 minutes. The experimenter concluded the session by verbally describing the purpose of the study and providing a written debriefing.

Results –Experiment 3

Questionnaire

All participants reported having a valid driver's license. The number of years for which participants had a driver's license ranged from one to 39 years, with a median of 3.5 years (mean of 8.1 years). On average, participants reported driving 16,160 km/year (median of 15,000 km/year). Ninety-six percent of participants reported that they usually wear their seatbelt while driving. Seventy-one percent of participants usually drove automatic, 18% drove standard, and 11% drove both.

The average number of accidents that participants reported being involved in as a driver was 0.75 (median of 0). Of these accidents, participants reported that 48 % were considered their own fault, 28 % were considered the other driver's fault and 24 % were shared fault. Participants reported receiving on average one moving violation (median of 0) since they began driving. The types of moving violations that were reported were mostly speeding tickets and stopping violations. All participants reported normal or corrected-to-normal vision. No participants had previous experience with the desktop driving simulator.

Dual-Task Performance

The following indices of performance were calculated and analyzed:

- Mean deviation in lane change path: mean deviation between the position of the normative model and the actual driven course.
- Percentage of missed signs: number of times drivers did not change lanes or performed the wrong lane change maneuver, divided by 18 (total number of signs per route) and multiplied by 100.
- Mean performance on secondary task: mean latency and percent error differences between performance on secondary tasks while driving (dual task) versus without driving (single task).
- Subjective workload: participants' subjective workload when driving and performing secondary tasks

Unless otherwise indicated, the alpha level for the analyses was 0.05. Greenhouse-Geisser procedures were used for correcting degrees of freedom and mean square error terms under violation of sphericity. Post hoc pairwise comparisons between means were made using Boneferroni corrections. To assist in the interpretation of figures, 95% confidence intervals (CIs) are presented on figures (Masson & Loftus, 2003). Baseline performance on the LCT task was calculated by averaging performance across each participant's three baseline runs. Similarly, LCT performance while performing each type of secondary task (i.e., phonological, visual, spatial) was calculated by averaging performance across the two occurrences of each secondary task run.

Overall Driving Measure (i.e., Mean Deviation in Lane Change Path)

I hypothesized that visual presentation of secondary tasks would interfere with lane change performance more than auditory presentation because lane change performance requires visual perception of road signs. I also hypothesized that secondary tasks requiring visual and spatial processing would degrade lane change performance more than would the task requiring phonological processing, independent of whether tasks were presented in a visual or auditory mode, because of the visual-spatial demands of driving. Thus, I expected to find a main effect of presentation mode, with visual presentation affecting performance more than auditory presentation, a main effect of secondary task processing mode such that visual and spatial interfered more than phonological but I did not expect to find an interaction between secondary task presentation and processing modes.

Difference scores were calculated by subtracting participants' mean deviation in lane change path in the control condition (i.e., without performance of a secondary task) from their mean deviation in lane change path in each of the dual-task conditions (i.e., while performing secondary tasks requiring phonological, visual or spatial processing). Analyses of difference scores were appropriate for the present experiment as I was interested in contrasting decrements in performance across different types of secondary task conditions. Although many studies have demonstrated that performance of secondary tasks while driving results in performance decrements in driving relative to baseline driving, few studies have examined the impact that different *types* of cognitive processing have on driving performance. Thus, difference scores are entirely appropriate for contrasting decrements in performance as a function of secondary task processing modes.

Difference scores, however, do not show the absolute levels of performance for each condition. Absolute levels of performance may be relevant for assessing, in general, how driving in the LCT task was affected by the variables in the present experiment. Therefore, Table 1 in Appendix D presents the absolute mean deviation in lane change path and standard deviations for all the secondary task presentation and processing mode conditions.

Difference scores (i.e., performance decrements) were analyzed in a 3 (secondary task processing mode: phonological, visual, spatial) x 2 (presentation mode: auditory vs. visual) ANOVA with repeated measures on the first factor. ANOVA results are presented in Table 7.

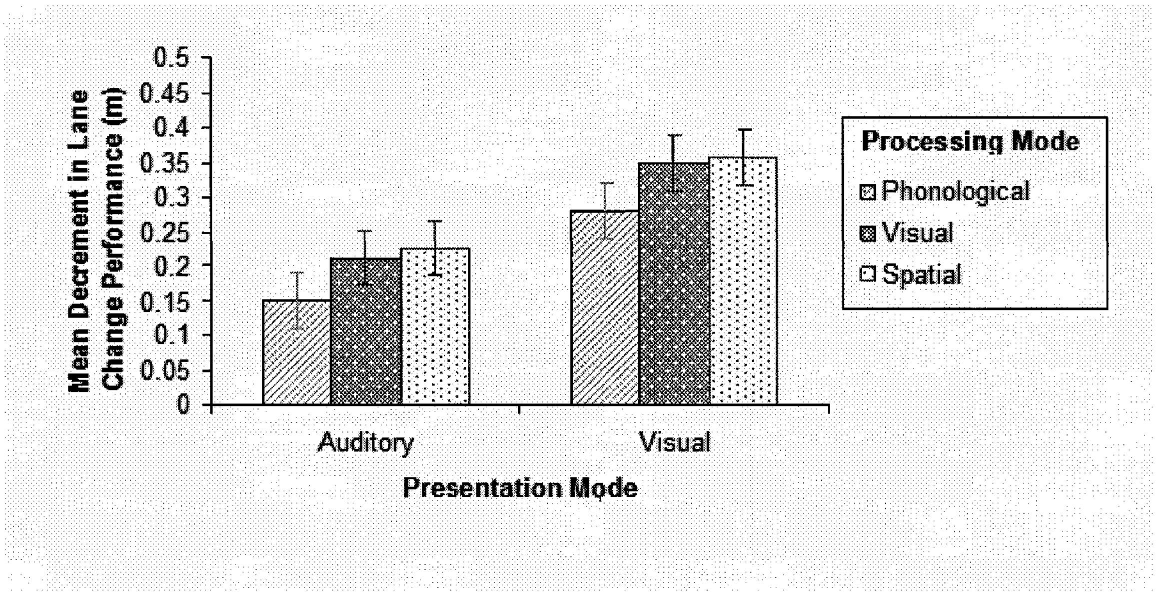
Table 7. Experiment 3: ANOVA for decrements in mean lane change performance

	df	*MS*	*F*
Between participants			
Presentation mode	1		7.13*
Error (Presentation mode)	54	0.11	
Within participants			
Processing mode	2		3.91*
Processing x Presentation mode	2		0.01
Error (Processing mode)	108	0.02	

Note. * $p < .05$

Differences between the baseline condition and each of the dual-task conditions (i.e., performance decrements) are shown in Figure 12 for mean deviation in lane change path. Clearly, visual presentation of the secondary tasks was more detrimental to mean deviation in lane change performance than was auditory presentation. This result supports the prediction of the multiple resource model that secondary tasks are better presented auditorily than visually while participants are concurrently driving because driving has high visual demands. Specifically, the multiple resource model attributes this pattern to the fact that cross-modal time-sharing (i.e., auditory-visual) is better than intra-modal time-sharing (i.e., visual-visual). Furthermore, as predicted, for both auditory and visual presentation, participants showed a significantly greater mean deviation in lane change performance (see Figure 12) when performing the secondary tasks requiring visual and spatial processing than when performing the phonological processing task. This result supports the hypothesis that the phonological processing task shares fewer mental resources with the driving task than do the visual or spatial processing tasks. There was no interaction between secondary task processing and presentation modes.

Figure 12. Experiment 3: Mean decrements in lane change performance as a function of secondary task presentation and processing modes. Error bars represent 95% confidence intervals, based on the MS_e from the two-way interaction.



These results suggest that although visual presentation of secondary tasks interferes more with driving than does auditory presentation, both can be problematic for driving. Furthermore, driving is disrupted more by concurrent performance of visual and spatial processing tasks than by a phonological processing task, independent of the presentation mode. Thus, the mixed findings in the literature as to whether auditory presentation of secondary task information is less disruptive to driving performance than visual presentation are perhaps a consequence of not considering the processing resources involved in the performance of these tasks.

Missed Signs

Overall, participants responded very accurately, missing only 2.5% of signs across all conditions. Nevertheless, for completeness, differences in mean percentage of missed signs between the baseline condition and each of the secondary task conditions was analyzed in a 3 (secondary task processing mode: phonological, visual, spatial) x 2 (presentation mode: auditory vs. visual) ANOVA with repeated measures on the first factor. The difference in mean percentage of missed signs did not differ significantly across secondary task presentation modes $F(1,54) = 0.07$, $MS_e = 1.89$ (auditory: 3.6%; visual: 3.2%) or processing modes $F(2,108) = 2.87$, $MS_e = 0.64$ (phonological: 2.5%; visual: 3.2%; spatial: 4.4%) and the interaction between presentation and processing modes was not significant ($F < 1$). Thus, regardless of the secondary task presentation or processing mode, participants saw and responded appropriately to most of the signs.

Secondary Task Performance

Secondary task latencies. Given that these experiments required that participants perform two tasks, decrements in task performance could be reflected in the primary (i.e., driving), the secondary (i.e., phonological, visual, spatial) tasks, or in both the primary and secondary tasks. To explore the patterns of performance on the secondary task, mean differences between participants' latencies when performing the task while NOT driving (i.e., single task performance) and while driving (i.e., dual task performance) were analyzed in a 3 (secondary task processing mode: phonological, visual, spatial) x 2 (presentation mode: auditory vs. visual) ANOVA with repeated measures on the first factor. ANOVA results are presented in Table 8. Latencies on the secondary task without driving were calculated by averaging participants' latencies on the 12 secondary task trials. Latencies on the secondary tasks while driving were calculated by averaging participants' latencies on the number of tasks they completed during the 3-minute driving run. The difference between single and dual task latencies provides an indication of a person's ability to maintain performance on a secondary task while driving (i.e., extent to which the driving task interferes with the secondary task). Table 2 in Appendix D presents the absolute mean latencies, standard deviations, and percent errors for all the secondary task presentation and processing mode conditions.

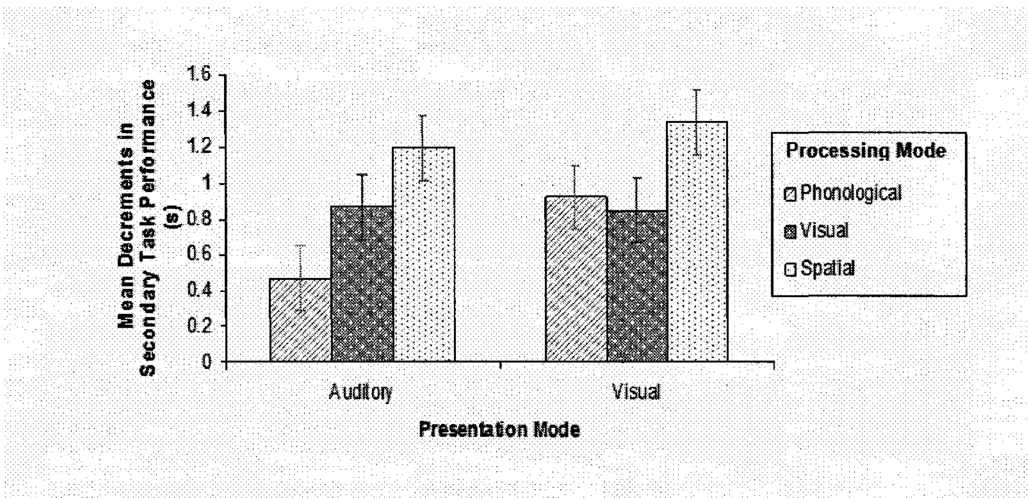
Table 8. Experiment 3: ANOVA for mean differences in secondary task latencies

	df	*MS*	*F*
Between participants			
Presentation mode	1		1.62
Error (Presentation mode)	54	0.93	
Within participants			
Processing mode	2		11.06**
Processing x Presentation mode	2		1.86
Error (Processing mode)	108	0.44	

Note. ** $p < .01$

Performance decrements were significantly greater in the spatial processing condition (1.27 s) than in the phonological (0.70 s) and visual (0.86 s) secondary task processing conditions, which did not differ, suggesting that the spatial processing task was influenced when combined with driving. These results suggest that driving interferes more with the processing resources required to perform the spatial secondary task than with processing resources required to perform the phonological and visual secondary tasks. Although the secondary task presentation by processing interaction was not significant, differences between latencies in the single task condition and each of the dual task conditions (i.e., performance decrements) are shown in Figure 13.

Figure 13. Experiment 3: Mean decrements on secondary tasks (based on latencies) as a function of secondary task presentation and processing modes. Error bars represent 95% confidence intervals, based on the MS_e from the two-way interaction.



Percent errors on secondary tasks. Differences between participants' percent errors on the secondary task without driving (i.e., single task performance) and while driving (i.e., dual task performance) were analyzed in a 3 (secondary task processing mode: phonological, visual, spatial) x 2 (presentation mode: auditory vs. visual) ANOVA with repeated measures on the first factor. The difference in percent errors on secondary tasks did not differ significantly across secondary task presentation modes (auditory: 1.6% visual: 2.2%) $F(1,54) = 0.11$, $MS_e = 160.77$, or processing modes (phonological: 1.8%, visual: 0.6%, spatial: 3.3%) $F(2,108) = 0.94$, $MS_e = 109.83$, and the interaction between presentation and processing mode was not significant ($F < 1$). These error results suggest that participants made few, and approximately the same percentage of errors, across all secondary task conditions.

Subjective Workload

Differences between participants' subjective workload in the baseline condition (i.e., driving without performance of a secondary task) and in the dual-task conditions (i.e., driving while performing secondary tasks requiring phonological, visual or spatial processing) were analyzed in a 3 (secondary task processing mode: phonological, visual, spatial) x 2 (presentation mode: auditory vs. visual) ANOVA with repeated measures on the first factor. A rating of "1" corresponded to a minimal workload and a rating of "10" corresponded to a very high workload during the tasks. The difference in subjective workload differed significantly across secondary task processing modes $F(2, 108) = 14.53$, $MS_e = 0.90$. Pairwise comparisons revealed that differences between participants' subjective workload in the baseline condition and the dual-task conditions were significantly higher when they were performing the visual (3.6) and the spatial (4.0) secondary processing tasks than when they were performing the phonological processing task (3.1). Furthermore, pairwise comparisons revealed that participants' subjective workload was significantly higher when driving while performing the spatial versus the visual secondary processing task. There was no significant main effect of presentation mode and no secondary task presentation by processing mode interaction. Thus, participants' perception of the relative difficulty was consistent with their secondary task and driving performance.

Breakdown of Overall Driving Measure

To better understand which aspects of the driving task are disrupted by the different secondary tasks, further analyses were performed. Specifically, separate analyses were performed on the three components that make up the mean lane change deviation measure (i.e., lane change initiation, lane maneuver quality, lane position maintenance).

In the present experiment, I hypothesized that visual presentation of secondary task information would disrupt lane change initiation more than would auditory presentation, because initiation of a lane change was dependent on driver's visual perception of the road sign. Furthermore, I expected that, independent of the mode used to present secondary tasks, tasks requiring visual and spatial processing would interfere more with lane change initiation than would the task requiring phonological processing. Central to this assumption is Recarte and Nunes's (2003) finding that mental tasks requiring visual and spatial processing affect driver's capacity to process visual stimuli such as the road signs in the present experiment. With respect to lane maneuver quality, I hypothesized that spatial processing would impair lane maneuvers more than would phonological and visual processing, independent of the mode used to present secondary task information. This latter hypothesis was based on findings that deficits in information processing, particularly spatial processing, affect drivers ability to perform lane change maneuvers (e.g., Knoblauch, Nitzburg, & Seifert,1997; Staplin, Gish, Decina, Lococo, & McKnight,1998). Finally, I hypothesized that visual presentation of secondary tasks would disrupt lane position maintenance more than would auditory presentation. This hypothesis was based on Hurwitz and Wheatley's (2002) finding that tasks that are presented visually disrupt lane position maintenance more than tasks that are presented auditorily.

Whereas the overall lane change deviation measure was developed to cover many features of driving behaviour (i.e., late response, slow maneuver, poor lane keeping, and missed signs), the breakdown measures reflect single indices of driving performance. Therefore, although the overall lane change deviation analysis included runs for which responses to the road sign were incorrect (i.e., missed sign or turned into wrong lane), the breakdown measure analyses excluded those runs. Thus, breakdown measure analyses excluded 2.5% of runs across all conditions.

Differences between the baseline condition and each of the secondary task conditions (i.e., performance decrements) were calculated for the three measures of driving. Separate 3 (secondary task processing mode: phonological, visual, spatial) x 2 (presentation mode: auditory vs. visual) ANOVAs with repeated measures on the first factor were performed for the three driving measures. ANOVA results for lane change initiation, lane maneuver quality, and lane maintenance performance are presented in Table 9. As shown, both main effects and the interaction were significant for all three driving measures. Tables 3, 4, and 5 in Appendix D respectively present the absolute means and standard deviations for the three driving measures.

Table 9. Experiment 3: F values (MSe in parentheses) for ANOVAs for each of the Driving Task Measures

		Driving Task Measure		
	df	*Initiation*	*Maneuver*	*Maintenance*
Between participants				
Presentation mode	1	23.13**	7.95**	22.89**
Error (Presentation mode)	54	(8.64)	(51.87)	(.74)
Within participants				
Processing mode	2	10.90**	5.80**	3.56*
Processing x Presentation mode	2	4.66*	4.74*	3.07*
Error (Processing mode)	108	(2.92)	(10.13)	(.01)

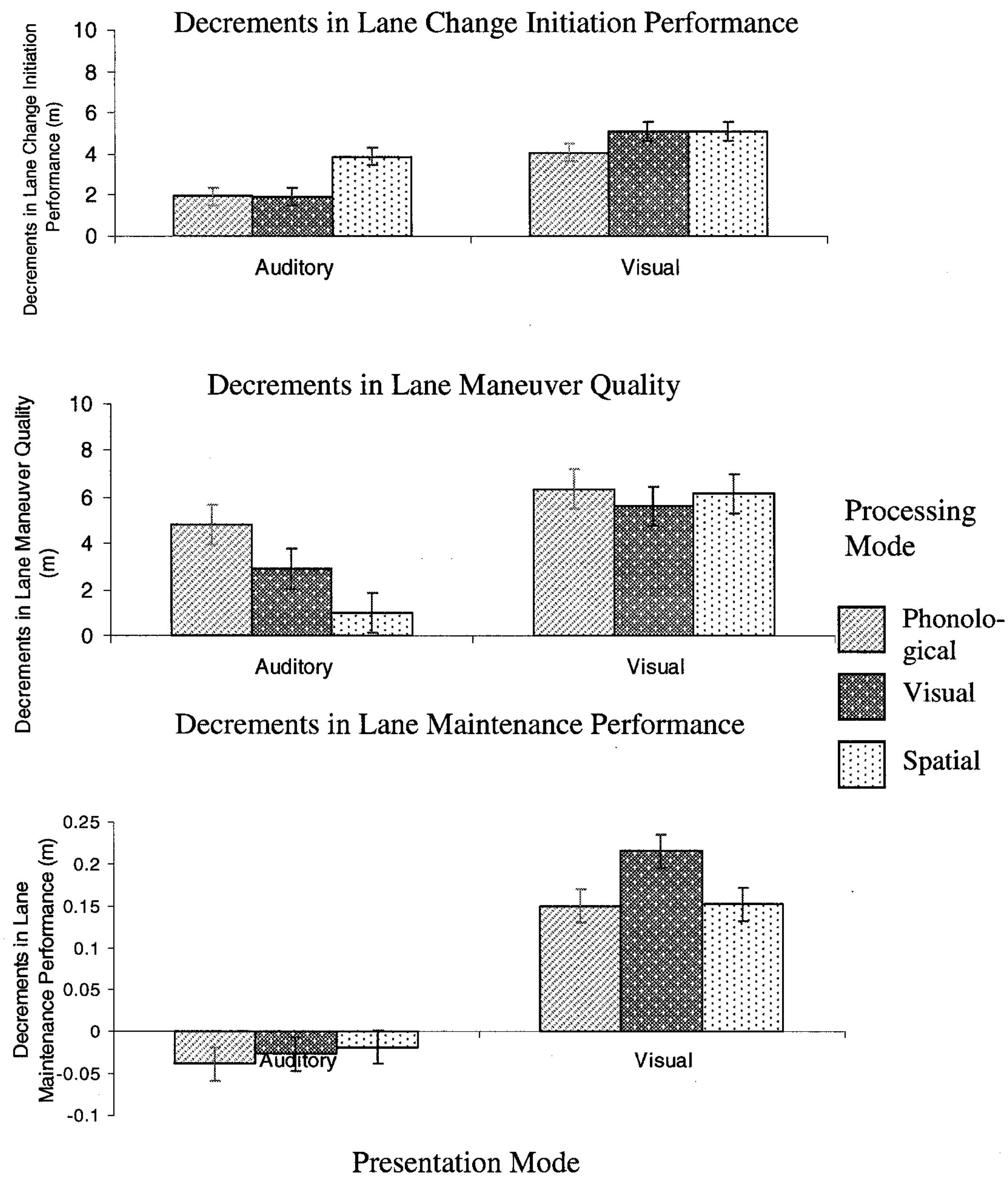
Note: * $p < .05$, ** $p < .01$

Differences between the baseline condition and each of the dual-task conditions (i.e., performance decrements) are shown in Figure 14 for the three measures of driving: lane change initiation, lane maneuver quality, and lane maintenance performance. Visual presentation of the secondary tasks was significantly more detrimental to performance of all three driving components than auditory presentation. Importantly, however, auditory presentation interfered with performance of lane change initiations and lane change maneuvers.

As predicted, when the secondary task required spatial processing, lane change initiations were substantially affected even when the presentation of the secondary task was auditory (top panel Figure 14). This result suggests that the initiation of a lane change involves substantial spatial processing, consistent with Recarte and Nunes (2003). In contrast, lane change *maneuvers* (middle panel) were affected by the combination of the phonological secondary task and auditory presentation, suggesting that lane change maneuvers involved phonological processes. Furthermore, when the presentation was auditory, lane change maneuvers were affected significantly more by the secondary task requiring visual processing than by the secondary task requiring spatial processing, suggesting that lane change maneuvers also involved visual processes. These latter results do not support the hypothesis that spatial processing disrupts lane change maneuvers more than phonological and visual processing, and will be considered further in the Discussion.

Lane maintenance performance after the change was accomplished (bottom panel of Figure 14) was not affected by any of the secondary tasks processing modes when the presentation was auditory. Consistent with results found by Hurwitz and Wheatley (2002) and Horrey and Wickens (2006), this latter result suggests that when secondary tasks are presented in an auditory mode, they do not impair the quality of drivers' lane keeping, regardless of the secondary task processing requirements. Together, results from lane change initiation and lane position maintenance support Horrey and Wickens' (2002, 2006) finding that drivers show reduced event detection but maintain lane maintenance when performing secondary processing tasks while driving. In sum, these results indicate that auditory presentation can be problematic for driving depending upon the mental processes required by the secondary tasks, and the driving measures being assessed.

Figure 14. Experiment 3: Mean decrements in lane change performance for the three driving measures (i.e., lane change initiation, lane maneuver quality, lane maintenance performance) as a function of secondary task presentation and processing modes. Error bars represent 95 % confidence intervals, based on the MS_e from the two-way interactions.



When input was visual, as shown in each panel on the right side of Figure 14, there were significant decrements in performance with all three secondary processing tasks. The secondary tasks requiring spatial and visual processing affected lane change initiations significantly more than did the secondary task requiring phonological processing. This result suggests that the initiation of a lane change involves spatial and visual processing, consistent with Recarte and Nunes (2003). For lane change maneuvers, the three types of secondary tasks processing modes had equally large effects on performance. For lane maintenance performance, however, the combination of secondary task requiring visual *processing* and visual *presentation* influenced performance significantly more than the phonological or spatial processing tasks. This result suggests that maintaining lane position depends on visual processes. Thus, these results indicate that although visual presentation of secondary tasks interferes with all three measures of driving, the degree of interference varies as a function of the mental processes required by the tasks.

In sum, the breakdown of the overall deviation measure into its three components (i.e., lane change initiation, lane maneuver quality and lane maintenance performance) revealed that the various combinations of secondary task presentation and processing modes differentially impact the three driving measures. Specifically, performance of the secondary task requiring spatial processing while driving slowed drivers' lane change initiation regardless of whether it was presented in an auditory or visual mode. Similarly, driving while performing the secondary task requiring phonological processing impaired quality of lane change maneuver regardless of whether the secondary task was presented in an auditory or visual mode. Performance of the secondary task requiring visual processing impaired drivers' lane position maintenance when it was presented visually.

Discussion – Experiment 3

The results are consistent with those from researchers (e.g., Gish et al., 1999; Burnett & Joyner, 1997; Liu, 2001) who have suggested that visual presentation of secondary task information disrupts driving performance more than auditory presentation. The results of the present research, however, provide detailed information about the conditions that influence whether auditory presentation of secondary tasks is less disruptive than visual presentation.

The present results support the hypothesis that differences in how the information is processed (i.e., phonological vs. visual vs. spatial) account for differential effects that secondary task performance have on driving, independent of the mode used to present the secondary task information. First, tasks requiring phonological processing interfered less with the lane change performance than tasks requiring visual or spatial processing. This finding is consistent with the view that driving shares fewer mental processes with the phonological secondary task than with the visual or spatial secondary tasks. The smaller decrements in secondary task performance for the phonological and the visual tasks, compared to the spatial task, suggest that the spatial task shares more mental processes with the driving task than do the phonological and visual tasks. Taken together, the results from the lane change performance and the secondary task performance suggest that driving involves primarily spatial processing, and requires more visual than phonological processing. Participants' subjective workload results also support this view.

During drives where lane change directions were presented visually (by arrows on signs), visual presentation of secondary tasks was overall more disruptive to driving than auditory presentation. This result is consistent with the view that similarities in perceptual demands between driving and the secondary tasks influenced performance. However, auditory presentation also disrupted lane change initiation and lane change maneuvers, such that spatial processing was particularly disruptive for lane change initiation and phonological processing for lane change maneuvers.

Although it is easy to understand that performance of a secondary task that requires taking one's eyes off the road (i.e., visual presentation) disrupts driving performance, the impact of auditory secondary task presentation on driving performance is not so apparent. The results for lane change initiation help facilitate comprehension of the impact of auditory task presentation on driving performance. Specifically, patterns of decrements in lane change initiation when drivers were performing the spatial processing task suggest that resources required to process the spatial task interfered with resources required to respond to signage on the road. The result that initiation of a lane change involves substantial spatial processing is consistent with Recarte and Nunes (2003).

The finding that phonological processing disrupted lane change maneuvers is in contrast with findings that deficits in information processing, particularly spatial processing, affect drivers ability to perform lane change maneuvers (e.g., Knoblauch, Nitzburg & Seifert, 1997; Staplin, Gish, Decina, Lococo & McKnight,1998). This discrepancy may be due to the nature of the lane change maneuver in the present experiment. Specifically, a good lane maneuver was defined as a rapid lane change.

Given that participants were slower at initiating their lane change when performing the spatial task than when performing the phonological task, they may have compensated for this delay by effecting a more rapid lane change maneuver when performing the spatial than when performing the phonological task. This explanation, however, is speculative.

In sum, similarities in perceptual and/or processing demands between driving and secondary tasks influenced driving performance. Specifically, the driving task had high visual-spatial perceptual and processing demands. Therefore, secondary tasks that were presented visually, and that required visual-spatial processing interfered with driving performance. Extrapolating from these results, I predicted that adding an auditory component to the driving task (i.e., presenting lane change directions auditorily) would cause secondary tasks that are presented auditorily and/or that require phonological processing to interfere with driving performance. To test this hypothesis, Experiment 4 used auditory lane change cues rather than the visual lane change cues used in Experiment 3. Thus, Experiment 4 was identical to Experiment 3 except that the lane change cues were presented auditorily rather than visually.

CHAPTER 5

Experiment 3 showed that similarities in perceptual and/or processing demands between driving and secondary tasks influenced performance. Specifically, in Experiment 3, the driving task had high visual and spatial demands. Therefore, when secondary tasks were presented visually and/or required visual and spatial processing, they disrupted driving performance more than secondary tasks that were presented in an auditory mode and/or required phonological processing. Based on this pattern of findings, I predict that secondary tasks that are presented in an auditory mode, and/or that require phonological processing, should interfere with driving when lane change directions are communicated using auditory cues (i.e., auditory turn by turn directions).

Auditory lane change cues were used in Experiment 4 to test this hypothesis. Specifically, the road signs were blank and drivers listened to auditory cues that prompted them to perform the lane change maneuvers. As in Experiment 3, auditory and visual modes were used to present secondary task information. The purpose of this experiment was to assess whether auditory directional cues add a sufficient level of auditory perceptual demand to the driving task to cause auditory presentation of secondary tasks to disrupt driving performance more than visual presentation. Similarly, I also wanted to examine whether the addition of auditory perceptual demands to the driving task cause phonological secondary tasks (i.e., tasks that require phonological processing) to disrupt driving performance to the same extent, or more than, secondary tasks requiring visual and spatial.

Method - Experiment 4

The methodology for Experiment 4 was the same as the methodology used in Experiment 3, except for the following modifications:

Participants

Fifty-six participants (20 males and 36 females) received course credit or $10 for their participation. All participants had English as their first language. The participants ranged in age from 17 to 40 years, with a median of 19.

Materials

Lane Change Test (LCT)

The same desktop driving simulator that was used in Experiment 3 was used in Experiment 4. Whereas Experiment 3 required drivers to repeatedly perform lane changes when prompted by visual road signs, Experiment 4 required that participants repeatedly perform lane changes when prompted by auditory commands. In Experiment 3, the lane change signs were always visible and remained blank until the lane instructions appeared instantaneously on the sign when the driver reached a distance of 40m in front of the sign. In the present experiment, the lane change signs were always visible (to give the same pre-emptive cue as in Experiment 3 that a lane direction change was imminent) but remained blank at all times. Drivers listened to auditory cues that prompted them to perform lane change maneuvers (see Figure 15). The auditory commands used in Experiment 4 were presented at the same times as the road signs appeared in Experiment 3 (i.e., at a distance of 40 meters before the sign). A female voice was used to present the auditory commands. Participants were instructed to change lanes as soon as they heard the command.

The auditory commands consisted of the spoken word "left" when participants were required to turn into the left lane, "middle" when required to turn into the middle lane, and "right" when required to turn into the right lane. If participants were in the left lane when they heard the "right" command, they were required to cross two lanes (see Figure 16). Thus, the only difference between the driving scenarios in Experiments 3 and 4 was the mode (i.e., visual vs. auditory) used to present the lane change directions.

Figure 15. Example of auditory lane change command

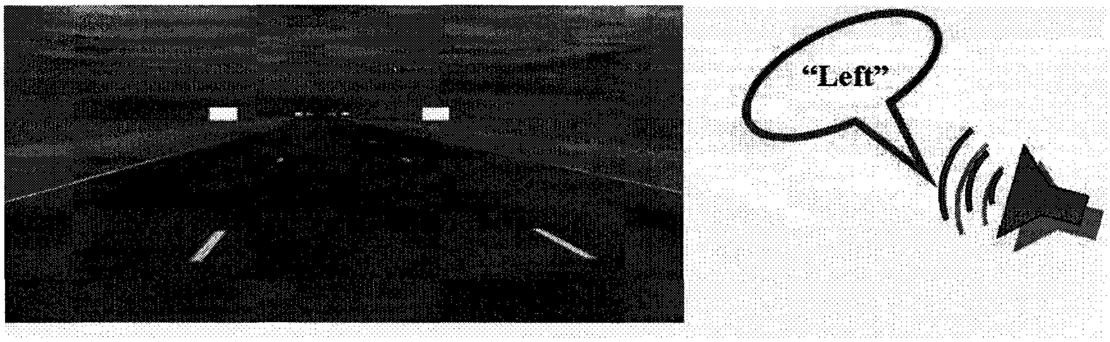
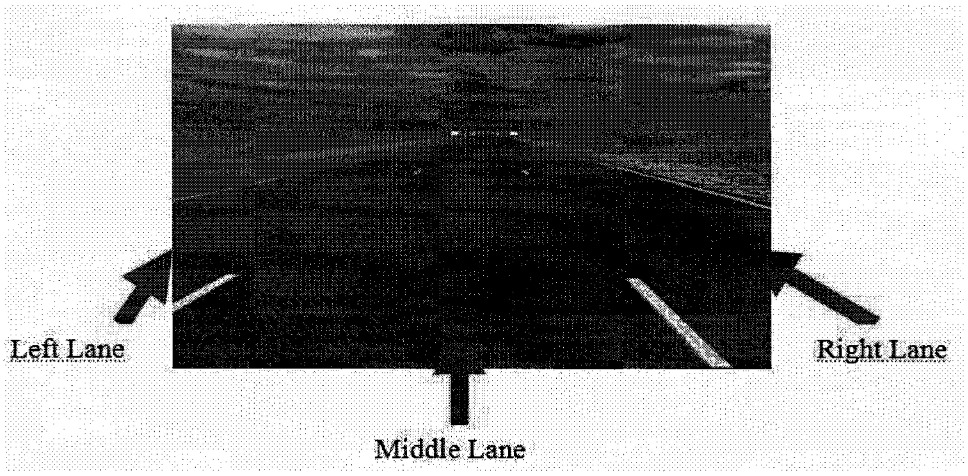


Figure 16. Lane Configuration



Results- Experiment 4

Questionnaire

All participants reported having a valid driver's license. The number of years for which participants had a driver's license ranged from one to 24 years, with a median of 2.5 years (mean of 3.4 years). On average, participants reported driving 21,482 km/year (median of 15,000 km/year). Ninety-six percent of participants reported that they usually wear their seatbelt while driving. On average, 80% of participants usually drove automatic, and 20% drove standard.

The average number of accidents participants reported being involved in as a driver was 0.64 (median of 0). Of these accidents, participants reported that 40 % were considered their own fault, 35 % were considered the other driver's fault and 25 % were shared fault. Participants reported having received on average 0.75 moving violations (median of 0) since they began driving. The types of moving violations that were reported were mostly speeding tickets. All participants reported normal or corrected-to-normal vision. None of the participants had previous experience with the desktop driving simulator.

Dual-Task Performance

Unless otherwise indicated, the alpha level for the analyses was .05. Greenhouse-Geisser procedures were used for correcting degrees of freedom and mean square error terms under violation of sphericity. Post hoc pairwise comparisons between means were made using Boneferroni corrections. To assist in the interpretation of figures, 95% confidence intervals (CIs) were presented on figures (Masson & Loftus, 2003). Baseline performance on the LCT task was calculated by averaging each participant's three baseline runs. Similarly, LCT performance while performing in each dual-task condition (i.e., phonological, visual, spatial processing) was calculated by averaging the two occurrences of each secondary task run (e.g., average of two LCT runs while performing secondary task requiring spatial processing).

Overall Driving Measure (i.e., Mean Deviation in Lane Change Path)

I hypothesized that auditory presentation of secondary tasks would degrade lane change performance more than, or to the same extent as, visual presentation because lane change performance required auditory perception of road signs and visual perception of the road scene. I also hypothesized that the secondary task requiring phonological processing would degrade lane change performance to the same extent as secondary tasks requiring visual and spatial processing, independent of whether tasks were presented using a visual or auditory mode. The underlying rationale for the latter hypothesis is that processing of the directional command is assumed to require a combination of phonological and visual-spatial processing. Thus, I expected to find a main effect of presentation mode, with auditory presentation affecting performance more than visual presentation, but I did not expect a main effect of secondary task processing mode, nor did I expect an interaction between secondary task presentation and processing modes.

Difference scores were calculated by subtracting participants' mean deviation in lane change path in the control condition (i.e., driving without performance of a secondary task) from their mean deviation in lane change path in each of the secondary task conditions (i.e., driving while performing secondary tasks requiring phonological, visual or spatial processing). Analyses of difference scores were appropriate for the present experiment as I was interested in contrasting decrements in performance across secondary task conditions. Although many studies have demonstrated that performance of secondary tasks while driving results in performance decrements in driving relative to baseline driving, few studies have examined the impact that different *types* of cognitive processing have on driving performance. Thus, difference scores are entirely appropriate for contrasting decrements in performance as a function of the different secondary task processing modes.

Difference scores, however, do not show the absolute levels of performance for the different secondary task presentation and processing mode conditions. Absolute levels of performance may be relevant for assessing, in general, how driving in the LCT task was affected by the variables in the present experiment. Therefore, Table 1 in Appendix E presents the absolute mean deviation in lane change path, and standard deviations for all the secondary task presentation and processing mode conditions. Difference scores (i.e., performance decrements) were analyzed in a 3 (secondary task processing mode: phonological, visual, spatial) x 2 (presentation mode: auditory vs. visual) ANOVA with repeated measures on the first factor. ANOVA results are presented in Table 10.

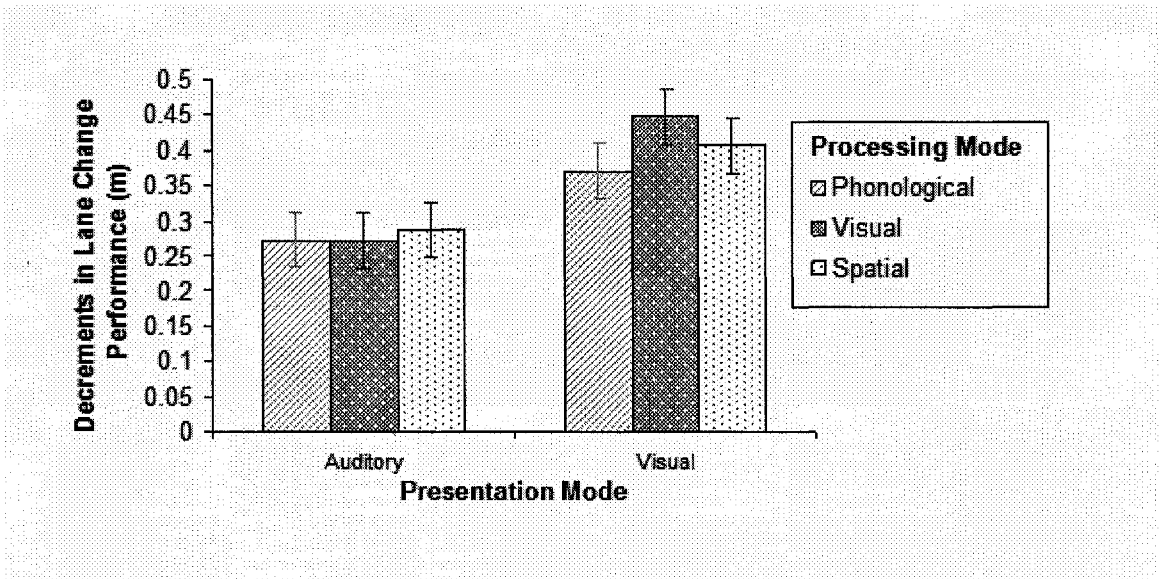
Table 10. Experiment 4: ANOVA for decrements in mean lane change performance

	df	*MS*	*F*
Between participants			
Presentation mode	1		7.80**
Error (Presentation mode)	54	0.09	
Within participants			
Processing mode	2		0.82
Processing x Presentation mode	2		0.88
Error (Processing mode)	108	0.03	

Note. $^{*}p < .05$, $^{**}p < .01$.

As shown in Figure 17, visual presentation of secondary tasks was significantly more detrimental to driving performance than auditory presentation. Therefore, secondary tasks that drew participants' visual attention away from the road (i.e., visual presentation mode) disrupted driving performance more than secondary tasks that were presented in an auditory mode. Thus, the hypothesis that auditory presentation of secondary task information would interfere more with performance of lane changes while attending to auditory cues, than would visual presentation of secondary task information was not supported. Further, there was no significant effect of secondary task processing mode and no interaction between secondary task presentation and processing modes. Lane change performance was equally disrupted by secondary tasks requiring all three modes of processing (i.e., task requiring phonological, visual, and spatial processing). This latter result differs from results found in Experiment 3. In Experiment 3, although driving performance was disrupted by secondary tasks requiring all three types of processing (relative to baseline performance), tasks requiring visual and spatial processing were significantly more disruptive than the phonological processing task. That is, results from Experiment 3 suggested that the secondary task requiring phonological processing interfered less with driving performance than did tasks requiring visual and spatial processing, because the driving task did not require phonological processing. The results from Experiment 4, on the other hand, suggest that the addition of a phonological component to the driving task (i.e., attending to auditory directional cues) lessened the advantage that the secondary task requiring phonological processing had over the tasks requiring visual and spatial processing, because all three processing tasks now shared mental processes with the driving task. Taken together, results from Experiments 3 and 4 suggest that cognitive processing of directional information that has been perceived visually (i.e., visual prompts used in Experiment 3) requires visual and spatial resources, whereas processing of auditory directional information (i.e. auditory prompts used in Experiment 4) requires a combination of phonological, visual and spatial resources.

Figure 17. Experiment 4: Mean decrements in lane change performance as a function of secondary task presentation and processing modes. Error bars represent 95% confidence intervals, based on the MS_e from the two-way interaction.



Missed Signs

Overall, participants responded very accurately, missing only 0.6% of signs across all conditions. Nevertheless, for completeness, differences in mean percentage of missed signs between the baseline condition and each of the dual-task conditions was analyzed in a 3 (secondary task processing mode: phonological, visual, spatial) x 2 (presentation mode: auditory vs. visual) ANOVA with repeated measures on the first factor. The difference in mean percentage of missed signs did not differ significantly across secondary task presentation modes $F(1,54) = 0.31$, $MS_e = 0.21$ (auditory: 0.7% visual: 0.8%) or processing modes $F(2,108) = 1.64$, $MS_e = 0.12$ (phonological: 0.3%, visual: 0.9%, spatial: 0.9%) and the interaction between presentation and processing modes was not significant ($F < 1$). Thus, regardless of the secondary task presentation or processing modes, participants saw and responded appropriately to most of the signs.

Secondary Task Performance

Secondary task latencies. Mean differences between participants' latencies when performing secondary tasks while NOT driving (i.e., single task performance) and while driving (i.e., dual task performance) were analyzed in a 3 (secondary task processing mode: phonological, visual, spatial) x 2 (presentation mode: auditory vs. visual) ANOVA with repeated measures on the first factor. ANOVA results are presented in Table 11. Latencies on the secondary task without driving were calculated by averaging participants' latencies on the 12 secondary task trials. Latencies on the secondary tasks while driving were calculated by averaging participants' latencies on the number of tasks they completed during the 3-minute driving run. The difference between single and dual task latencies provides an indication of a person's ability to maintain performance of a secondary task while driving (i.e., extent to which the driving task interferes with the secondary task). Table 2 in Appendix E presents the absolute mean latencies, standard deviations, and percent errors for all secondary task presentation and processing mode conditions.

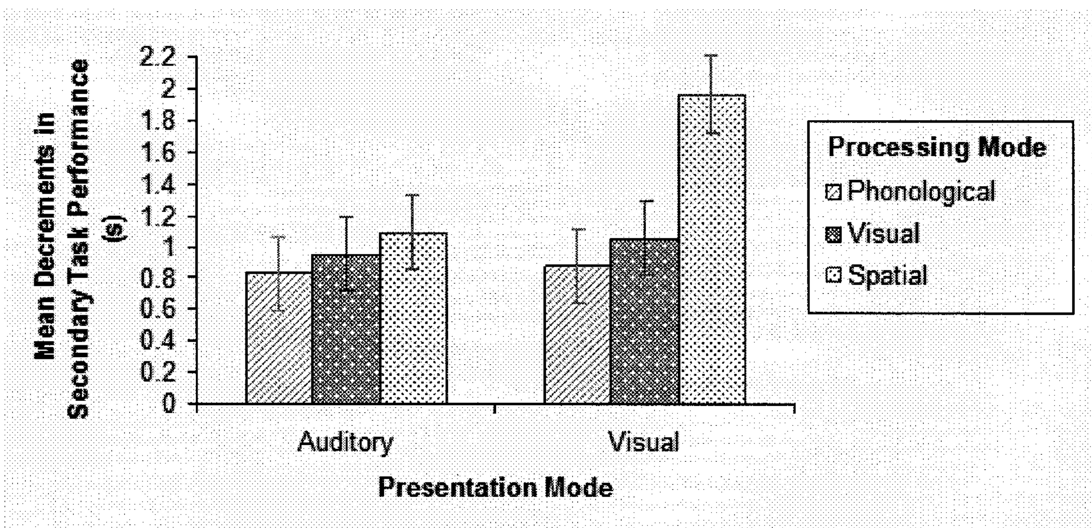
Table 11. Experiment 4: ANOVA for mean differences in secondary task latencies

	df	*MS*	*F*
Between participants			
Presentation mode	1		4.97*
Error (Presentation mode)	54	0.98	
Within participants			
Processing mode	2		8.68**
Processing x Presentation mode	2		3.58*
Error (Processing mode)	108	0.82	

Note. $^{*}p < .05$, $^{**}\ p < .01$

Differences between latencies in the single task condition and each of the dual task conditions (i.e., performance decrements) are shown in Figure 18. Performance decrements were significantly higher when secondary tasks were presented visually than when presented in an auditory mode, suggesting that driving interfered more with visual presentation of secondary tasks than with auditory presentation. Furthermore, performance decrements were significantly higher when tasks required spatial processing than when they required phonological and visual processing. This latter result, however, was mediated by the modes (i.e., auditory vs. visual) used to present the secondary tasks. Specifically, when tasks were presented in an auditory mode, secondary task performance decrements were not significantly different across processing modes. Conversely, when tasks were presented visually, secondary task performance decrements were significantly higher when tasks required spatial processing than when they required phonological and visual processing. Overall, these results suggest that driving interfered more with the resources required to perform the spatial secondary task than with resources required to perform the phonological and visual secondary tasks, especially when tasks were presented visually.

Figure 18. Experiment 4: Mean decrements in secondary task performance (based on secondary task latencies) as a function of secondary task presentation and processing modes. Error bars represent 95% confidence intervals, based on the MS_e from the two-way interaction.



Percent errors on secondary tasks. Differences between participants' percent errors on the secondary task while NOT driving (i.e., single task performance) and while driving (i.e., dual task performance) were analyzed in a 3 (secondary task processing mode: phonological, visual, spatial) x 2 (presentation mode: auditory vs. visual) ANOVA with repeated measures on the first factor.

Although participants made more errors when tasks were presented visually (5.4%) than when presented in an auditory mode (1.3%), this difference was not significant, $F(1,54) = 3.48$, $MS_e = 195.39$, $p = 0.07$. Furthermore, the difference in percent errors on secondary tasks did not differ significantly across secondary task processing modes $F(2,108) = 1.88$, $MS_e = 142.22$ (phonological: 0.9%, visual: 3.8%, spatial: 5.2%) and the interaction between presentation and processing mode was not significant, $F(2, 108) = 1.23$, $MS_e = 142.22$. These error results suggest that participants made few, and approximately the same percentage of errors, across all secondary task conditions.

Subjective Workload

Differences between participants' subjective workload in the baseline condition (i.e., driving without performance of a secondary task) and in the dual-task conditions (i.e., driving while performing secondary tasks requiring phonological, visual or spatial processing) were analyzed in a 3 (secondary task processing mode: phonological, visual, spatial) x 2 (presentation mode: auditory vs. visual) ANOVA with repeated measures on the first factor. A rating of "1" corresponded to a minimal workload and a rating of "10" corresponded to a very high workload during the tasks. Pairwise comparisons revealed that differences between participants' subjective workload in the baseline condition and each of the secondary task conditions were significantly higher when they were performing the visual (4.1) and the spatial (4.5) secondary tasks than when they were performing the phonological task (3.6). Pairwise comparisons also revealed that participants' subjective workload did not differ when driving while performing the spatial versus the visual secondary task. There was no significant main effect of presentation mode and no presentation by processing mode interaction. Thus, participants' perception of the relative difficulty was consistent with their secondary task performance.

To better understand which aspects of the driving task were affected by secondary tasks requiring different types of processing, further analyses were performed. Specifically, separate analyses were performed on the three components that make up the mean lane change deviation measure (i.e., lane change initiation, lane maneuver quality, lane maintenance performance).

Breakdown of Overall Driving Measure

In the present experiment, I hypothesized that auditory presentation of secondary task information would disrupt lane change initiation more than would visual presentation because lane change initiation was dependent on driver's auditory perception of the directional command. Furthermore, I expected that independent of the mode used to present secondary tasks, tasks requiring phonological processing would interfere equally with lane change initiation compared to tasks requiring visual and spatial processing. This hypothesis is based on the assumption that processing of the auditory directional command requires a combination of phonological and visual-spatial processing. Therefore, the three types of secondary processing demands are expected to interfere equally with lane change initiations. With respect to lane maneuver quality, I hypothesized that spatial processing would impair lane maneuvers more than would phonological and visual processing, independent of the mode used to present secondary task information. This latter hypothesis was based on findings that deficits in information processing, particularly spatial processing, affect drivers' ability to perform lane change maneuvers (e.g., Knoblauch, Nitzburg, & Seifert,1997; Staplin, Gish, Decina, Lococo, & McKnight,1998). In the Discussion of Experiment 3, I hypothesized that the reason this pattern was not found in Experiment 3, was that participants were slower at initiating their lane changes when performing the spatial secondary task than when performing the phonological secondary task. Therefore, participants may have compensated for this delay by effecting more rapid lane change maneuvers when performing the spatial secondary task than when performing the phonological secondary task. In the present experiment, however, I expect that the task requiring phonological processing will interfere equally with lane change initiation as the task requiring spatial processing. Therefore, there should be no need to compensate for delays in lane change initiation when performing lane change maneuvers, and spatial processing should impair lane maneuvers more than should phonological and visual processing. Finally, I hypothesized that visual presentation of secondary tasks would disrupt lane position maintenance more than would auditory presentation. This hypothesis was based on the findings from Hurwitz and Wheatley (2002) and from Experiment 3 that visual presentation of secondary tasks disrupts lane position maintenance more than auditory presentation.

Differences between the baseline condition and each of the dual-task conditions (i.e., performance decrements) were calculated for the three driving measures. Runs for which response to the sign were incorrect (i.e., missed a sign or turned in the wrong direction) were excluded from the analyses. Thus, breakdown measure analyses excluded 0.6% of runs across all conditions. Tables 3, 4, and 5 in Appendix E present the absolute means and standard deviations for the three driving measures. Separate 3 (secondary task processing mode: phonological, visual, spatial) x 2 (presentation mode: auditory vs. visual) ANOVAs with repeated measures on the first factor were performed for the three measures of driving. ANOVA results for lane change initiation, lane maneuver quality and lane maintenance performance are presented in Table 12.

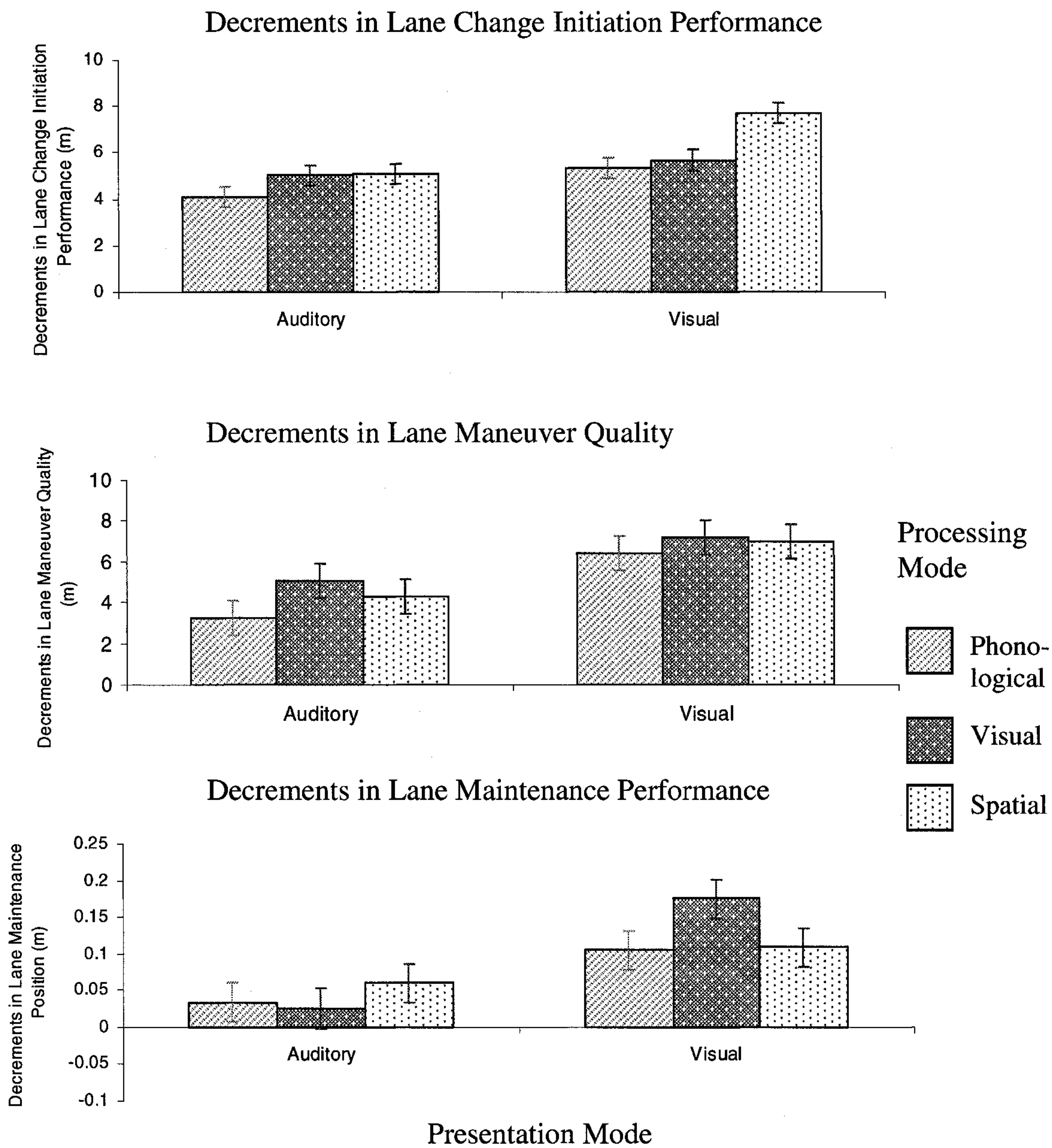
Table 12. Experiment 4: F values (MSe in parentheses) for ANOVAs for each of the Driving Task Measures

		Driving Task Measure		
	df	*Initiation*	*Maneuver*	*Maintenance*
Between participants				
Presentation mode	1	3.90	2.94	10.32**
Error (Presentation mode)	54	(24.52)	(102.43)	(.03)
Within participants				
Processing mode	2	14.68**	2.43	1.23
Processing x Presentation mode	2	5.17**	0.40	3.60*
Error (Processing mode)	108	(2.69)	(10.05)	(.01)

Note: * $p < .05$, ** $p < .01$

Differences between baseline conditions and each of the secondary task conditions (i.e., performance decrements) are shown in Figure 19 for the three driving measures: lane change initiation, lane maneuver quality, and lane maintenance performance. Visual presentation of the secondary tasks was significantly more detrimental to performance of two driving measures (i.e., lane maneuver quality and lane maintenance performance) than auditory presentation. Importantly, however, auditory and visual presentation modes had similar (i.e., non significantly different) negative impacts on performance of lane change initiations. During drives where secondary tasks were presented auditorily, lane change initiations were affected similarly by the three types of processing tasks (i.e., phonological, visual, spatial; see top left panel of Figure 19). This result suggests that the initiation of a lane change involves all three types of processing during drives where both secondary task information and lane change cues are presented auditorily. Similarly, when the presentation of the secondary task was auditory, lane change maneuvers (left middle panel of Figure 19) were equally affected by the three types of processing tasks, suggesting that lane change maneuvers involved phonological, visual and spatial processing. Thus, the hypothesis that lane change maneuvers require more spatial processing than phonological or visual processing was not supported. Lane maintenance performance after the change was accomplished (bottom left panel of Figure 19), however, was not affected by any of the secondary tasks when the presentation was auditory. As predicted, this result suggests that when secondary tasks are presented auditorily, they do not impair the quality of driver's lane keeping. Considered together, the results for lane change initiation and lane position maintenance are consistent with results obtained in Experiment 3 and by other researchers (e.g., Horrey & Wickens, 2002, 2006), that have shown that drivers show reduced event detection but maintain lane positioning when secondary tasks are presented auditorily. In sum, these results indicate that when secondary tasks are presented auditorily, all three types of processing tasks (i.e., phonological, visual, spatial) can be problematic for initiating and performing lane change maneuvers that are prompted by auditory commands.

Figure 19. Experiment 4: Mean decrements in lane change performance for the three driving measures as a function of secondary task presentation and processing modes. Error bars represent 95 % confidence intervals, based on the MS_e from the two-way interactions.



When secondary tasks were presented visually, as shown in each panel on the right side of Figure 19, there were significant decrements in performance with all three tasks. The combination of visual presentation and spatial processing of a secondary task affected lane change initiations significantly more than did phonological and visual processing. This result suggests that during drives where directional cues are presented auditorily and secondary tasks are presented visually, lane change initiations involve more spatial processing than phonological or visual processing. For lane change maneuvers, the three secondary tasks had equally large effects on performance, suggesting that all three types of processes are involved in lane maneuvers. For lane maintenance performance, however, the combination of visual presentation and visual processing influenced performance significantly more than phonological and spatial processing. As predicted, this result suggests that maintaining lane positioning depends on visual processes. Thus, these results demonstrate that although visual presentation of secondary tasks interfered with all three measures of driving, the degree of interference varied as a function of the mental processes required by the tasks.

In sum, the breakdown of the overall deviation measure into its three components (i.e., lane change initiation, lane maneuver quality, lane maintenance performance) revealed that the various combinations of secondary task presentation and processing modes differentially impacted the three driving measures. Although performance of the spatial secondary task was especially detrimental to lane change initiations when perceived visually, all three secondary processing tasks were detrimental to initiations of lane changes, independent of presentation mode. This latter result is interesting when compared to results found in Experiment 3. Specifically, in Experiment 3, in which lane changes directions were presented visually, performance of the phonological processing task interfered less with lane change initiations than did the spatial processing task, regardless of whether tasks were presented auditorily or visually. In the present experiment, in which lane changes were presented auditorily, performance of phonological and spatial secondary tasks caused similar amounts of interference with lane change initiations when tasks were presented auditorily. It appears that the auditory directional cues, used in Experiment 4, added a substantial level of auditory demand to the driving task. Specifically, the resources required to perceive **auditory** directional cues seem to have competed with the resources required to perform the secondary task that was presented **auditorily** and required **phonological** processing. Thus, it appears that the combination of auditory presentation and phonological processing of a secondary task interfered more with lane change initiations when lane changes were presented auditorily (Experiment 4) than when presented visually (Experiment 3).

Performance of all three secondary tasks impaired quality of lane change maneuvers, independent of presentation mode. The latter result is interesting when compared to results found in Experiment 3. Specifically, results from Experiment 3 showed that visual presentation of secondary tasks affected lane maneuver quality significantly more than auditory presentation. Thus, it appears that addition of an auditory perceptual demand to the driving task, in Experiment 4, caused auditory presentation of secondary tasks to impact lane maneuver quality to the same extent as visual presentation.

Performance of the visual task was more detrimental to lane position maintenance than the phonological and spatial tasks when tasks were presented visually. This latter finding is consistent with results obtained in Experiment 3. Specifically, in both Experiments 3 and 4, when secondary tasks were presented in an auditory mode, they did not impair drivers' lane keeping quality. When secondary tasks were presented visually, however, performance of a visual secondary task impaired drivers' lane keeping quality to a greater extent than did performance of a phonological or spatial secondary task.

Discussion- Experiment 4

The data provided evidence that when an auditory component is added to the driving task (i.e., auditory directional cues), auditory presentation of secondary task information can be as disruptive to driving performance as visual presentation, depending on the driving measures being assessed. In the present experiment, participants performed a simulated driving task while performing secondary tasks that were presented in either an auditory or visual mode. The simulated driving task required both visual perception (i.e., looking at the road) and auditory perception (i.e., attending to auditory turn by turn commands). When secondary tasks were presented auditorily, they required auditory perception and when secondary tasks were presented visually, they required visual perception.

Wickens' (1980) model holds that two tasks that require the same mode of perceptual resource (e.g., concurrent performance of two tasks that require visual perception) will interfere more with each other than two tasks that require different perceptual resources (e.g., concurrent performance of a task that requires visual perception and a task that requires spatial perception). Thus, I hypothesized that auditory presentation of secondary tasks would disrupt driving performance to the same extent as visual presentation of secondary task, because they both shared common perceptual demands with the driving task. Based on the present findings, support for this hypothesis was dependent upon the driving measure being assessed.

Although the driving task required that participants attend to auditory directional cues, auditory presentation of secondary tasks was less disruptive of overall lane change performance than was visual presentation of secondary tasks. Thus, results from the overall lane change performance measure suggested that secondary tasks that distract driver's visual attention away from the road substantially disrupt driving performance.

Although results from the overall lane change performance measure showed that visual presentation of secondary tasks was worse than auditory presentation, results from the lane change initiation and lane maneuver quality measures revealed that auditory and visual presentation of secondary tasks were equally disruptive to performance on these components of the driving task. From a safety perspective, lane change initiations may be the most important driving measure in the present study, because this measure is directly related to drivers' ability to detect and react to relevant stimuli in the environment. According to Wickens (2002), competition for limited auditory perceptual resources within the brain may provide an explanation for auditory secondary task presentation being as disruptive to lane change initiation as visual presentation. That is, the lane change initiation task, which was prompted by auditory cues, may have competed for the same limited auditory perceptual resources as required for auditory perception of the secondary task. Thus, although auditory directional commands are intended to reduce the distraction arising from visually demanding navigation systems, their potential for distraction must be considered and properly assessed.

CHAPTER 6

General Discussion

A number of societal trends are contributing to increasing levels of driver distraction. For example, as a result of increasing populations in urban centers, the associated urban sprawl has led to longer commutes from residential locales to the business core. In addition to increased travel time, there is mounting pressure on the working public to become more productive. Increasingly people are turning to in-vehicle devices to conduct telephone discussions, send and receive emails, and access work related data. Automotive manufacturers are attempting to cater to the demands for in-vehicle devices that help to address commuters' time management concerns. This trend is contributing to significant levels of driver distraction both at a perceptual and cognitive level. In an attempt to alleviate the physical and visual demands associated with the use of in-vehicle devices, automotive manufacturers are integrating auditory hands-free interfaces into these devices. However, auditory interaction with in-vehicle devices is cognitively demanding and can therefore also impair driving performance (Lee et al., 2001; Ranney et al., 2005; Strayer et al., 2003).

The goal of this research was to use theories of cognitive processing to investigate the question of whether auditory presentation of information is inherently less disruptive to driving than visual presentation. It seems uncontroversial that presenting visual information, for example in the form of a map, to people while they are driving is likely to interfere with some aspects of their driving performance. The use of vision is required by both tasks (i.e., reading a map and driving). Consequently, some designers have assumed that information presented in an auditory format will have little or no impact on driving performance (compared to a visual format), presumably because driving doesn't involve overt auditory perception. Wickens' (1980) theory and data support the view that in some circumstances, drivers can more easily perceive information presented cross-modally than intra-modally. Furthermore, the additional assumption in this thesis was that secondary task processing requirements (i.e., phonological, visual, spatial) disrupt driving performance, independently of whether information is presented visually or auditorily. Specifically, I hypothesized that regardless of whether drivers look at an interface to perceive the secondary task information, or hear the information via a speech-based interface, performance of secondary tasks will disrupt driving performance when the resources required for the internal processing of secondary task information are also required for processing driving information. Thus, both the perception and processing requirements for the secondary tasks were expected to disrupt driving performance in the present experiments.

To test this hypothesis, factors that are known to affect driving performance such as task completion time, task complexity, display location and message relevance were held constant and secondary task presentation and processing modes were manipulated. Individuals performed a simulated driving task. Directions for changing lanes were presented either as road signs (i.e., arrows) or as auditory commands (e.g., 'left'). Overall driving performance and the components that make up the overall driving measure (i.e., lane change initiation, lane maneuver quality, lane position maintenance) were assessed. In this chapter, I will first provide an overview of the experimental results. Second, I will discuss the results with respect to models of information processing, and finally I will discuss the generality and practical implications of the results.

Overview of Results

Visual presentation of secondary tasks disrupted overall driving performance more than auditory presentation, independent of whether lane changes were prompted by visual road signs (i.e., Experiment 3) or by auditory commands (i.e., Experiment 4). This result is consistent with Wickens' (1980) prediction that cross-modal presentation allows for better dual-task performance than intra-modal presentation. Consistent with many other findings (e.g., Consiglio et al., 2003; Lamble et al., 1999), the present results showed that although visual presentation of secondary tasks interfered more with driving performance than auditory presentation, auditory presentation of secondary task information also disrupted driving performance relative to driving without performing a secondary task. Thus, results of the present research suggest that the cognitive demands of *both* visual and auditory secondary tasks disrupt driving performance.

Most studies that have compared the effects of cognitive distraction on driving performance have not controlled or manipulated the type of processing involved in the mental tasks. Consequently, studies examining the effects of mental tasks on driving performance are based on poorly operationalized definitions of mental tasks and have yielded mixed results. Specifically, although some studies have shown that performance of mental tasks disrupts driving performance (e.g., Alm & Nilsson, 1995; Consiglio et al., 2003), others have failed to find such an effect (e.g., Rakauskas et al., 2004). In the present research, I operationalized the secondary task variables by selecting tasks that were shown (see Experiments 1 and 2) to require phonological, visual and spatial processing resources. Furthermore, I hypothesized that the mixed findings as to whether mental tasks disrupt driving performance were due to differences in the processing requirements of the secondary tasks. Results from the overall driving measure support this second hypothesis. Specifically, processing of all three secondary tasks disrupted overall driving performance relative to driving without performing a secondary task. Moreover, the visual and spatial processing tasks disrupted overall driving performance more than the phonological processing task, as expected given the visual and spatial nature of driving.

In sum, as predicted, visual presentation of secondary tasks disrupted overall driving performance more than auditory presentation. Furthermore, auditory presentation of secondary tasks disrupted overall driving performance relative to driving without performing a secondary task, suggesting that secondary task processing requirements also disrupt overall driving performance. Finally, secondary tasks requiring visual and spatial processing disrupted overall driving performance more than the secondary task requiring phonological processing. These latter two results support Recarte and Nunes' (2003) finding that tasks requiring visual and spatial processing interfere with driver visual behaviour, and add to these findings by linking the interference caused by visual and spatial processing to driving performance.

The current International Organization for Standardization (ISO) working draft (2006) proposes the use of the overall lane deviation measure when analyzing data from the Lane Change Test (LCT). An important finding in the present research was that breakdown of the overall driving measure into its three components (i.e., lane change initiation, lane maneuver quality, lane position maintenance) revealed that the effects of secondary task presentation and processing modes on driving performance varied as a function of the driving measure being assessed. Specifically, lane change initiation and lane maneuver quality were disrupted by secondary task perceptual and processing demands, whereas lane position maintenance was only disrupted by secondary task perceptual demands. Thus, the present findings suggest that all three driving measures require perceptual resources. Furthermore, lane change initiation and lane change quality require processing resources, whereas lane maintenance does not.

In the present research I focused on measures of lane change initiation and lane maintenance more so than lane maneuver quality, because the former two are key measures of driver performance, whereas the latter measure is less likely to allow generalization of the findings to a real driving situation. That is, the lane maneuver quality measure was rendered artificial due to the procedural instructions requiring participants to perform a sharp lane change maneuver rather than a smooth lane change maneuver. Under normal driving conditions, sharp lane change maneuvers are undesirable for safety reasons.

Lane Change Initiation

In the present experiments, lane change initiation (i.e., detection of and reaction to directional cues) was used as a measure of event detection. Detection of and reaction to visual directional cues (i.e., Experiment 3) was disrupted more by visual than by auditory presentation of secondary tasks. This finding is consistent with Wickens' (1980) theory that drivers can more easily perceive information presented cross-modally than intramodally. Despite the relatively greater disruption with visual presentation of secondary tasks, however, auditory presentation also disrupted lane change initiation performance relative to baseline driving, especially when tasks required spatial processing. These results suggest that the spatial demands of lane change initiation are particularly demanding of cognitive resources, and are consistent with Recarte and Nunes' (2003) finding that mental tasks requiring visual and spatial processing affect driver's capacity to process visual stimuli. Recarte and Nunes (2003) based their findings on measures of driver visual behaviour (i.e., allocation of looking time to different environmental areas), whereas the present results are based on a driving measure that is more directly related to safety (i.e., detection of and reaction to stimuli). Therefore, the present findings add a unique contribution to the literature by showing that driving performance measures, such as event detection, are sensitive to not only the presentation modality of the secondary task but also the processing requirements of that information. Thus, although visual presentation of secondary tasks disrupted lane change performance more than auditory presentation, auditory presentation was nonetheless disruptive, especially if the secondary task required that the driver process spatial information.

Further, the present results show that when resources normally used to process driving-related information are re-directed towards the processing of spatial information, drivers are slower at reacting to information in the environment, such as road signs. From a design standpoint, results from the present research demonstrate that although hands-free and voice-based technology may eliminate the distraction caused by visual and manual interaction, they do not eliminate the interference resulting from cognitive processing requirements.

In Experiment 4, some of the visual perceptual load of the driving task was re-directed to an auditory perceptual load because the lane change directions were auditory instead of visual signs. I hypothesized that the auditory presentation of secondary tasks would interfere more with detection of and response to auditory directional cues relative to how much they interfered with detection of and response to visual directional cues (i.e., signs). This hypothesis was supported. Further, even though directional prompts were presented auditorily, visual presentation of secondary tasks still disrupted detection of and response to auditory directional cues more than auditory presentation, presumably because driving is primarily a visual/spatial task. Moreover, as in Experiment 3, auditory presentation of secondary tasks disrupted lane change initiation relative to baseline drives, suggesting that detection of and response to auditory directional cues required cognitive processing. The three types of processing requirements (i.e., phonological, visual, spatial) equally disrupted lane change initiations. Although these effects could be attributable to the fact that all three types of processing were required for detection of and response to auditory directional cues, it could also be argued that any additional processing load equally disrupted detection of and response to directional cues. This latter interpretation, however, is not adequate to explain the result that when participants were required to detect and respond to visual directional cues (i.e., Experiment 3), they showed significantly less evidence of a performance decrement when phonological interference was present. Thus, results suggest that detection of and response to auditory directional cues requires phonological, visual and spatial processing.

In sum, visual presentation of secondary tasks disrupted detection of and response to visual and auditory directional cues more than did auditory presentation of secondary tasks. This result suggests that detection of and reaction to directional cues requires visual perception regardless of the modality of the cue (i.e., visual or auditory). Furthermore, although processing of visual directional cues appears to require visual and spatial resources, processing of auditory directional cues appears to require a combination of phonological, visual and spatial resources.

Lane Position Maintenance

For both visual (i.e., Experiment 3) and auditory (i.e., Experiment 4) directional cues, visual presentation of secondary tasks disrupted lane position maintenance, whereas auditory presentation did not. This result supports other findings suggesting that lane position maintenance is dependent on visual perception (e.g., Burnett & Joyner, 1997; Hurwitz & Wheatly, 2002; Labiale, 1990; Srinivasan & Jovanis, 1997; Walker et al., 1990), and further suggests that lane position maintenance requires minimal cognitive processing. Methodologically, this latter result suggest that the effects of cognitive processing distractions on driving performance may be underestimated or overlooked in studies that only measure lane maintenance performance.

In sum, lane change initiation and lane maintenance performance results support Horrey and Wickens (2006) hypothesis that lane maintenance is a relatively automatic activity requiring minimal processing, whereas responding to road events or stimuli is a more demanding activity and requires cognitive processing.

Implications for Models of Information Processing

Wickens (1980) proposed that dual-task interference could occur at four stages, two of which were tested in the present experiments; perception and processing. According to Wickens' model, these two stages are independent. Interference at the perceptual stage occurs when secondary task information is perceptually the same (or identical) to primary task information. When two tasks are presented in the same mode (e.g., visual-visual) there is interference at the perceptual stage because the physical sensors (e.g., eyes) required to perceive the information are the same. This perceptual interference does not occur when different information presentation modes are used because the sensors required to perceive the information are different (e.g., eyes and ears).

In contrast, interference at the processing stage occurs when the limited cognitive resources used to process primary task information are the same as those used to process secondary task information (e.g., when both tasks require phonological resources) or when both tasks require central executive or general processing resources. According to proponents of the bottleneck model (Broadbent, 1958; Davies, 1965; Deutsch & Deutsch, 1963; Hendy, Liao & Milgram, 1997; Pashler, 1984, 1989; Welford, 1967), the limited resource is time (e.g., interference between two tasks arises when they occur at the same point in time). Proponents of the bottleneck model posit that performance of two tasks will never be as efficient as individual task performance because the human information processing system acts as a bottleneck that limits the ability to concurrently process two pieces of information. Therefore, according to the bottleneck model, all secondary tasks in the present experiments should have interfered equally with the driving task because secondary tasks were always performed concurrently with the driving task. Results from the present experiments do not support the bottleneck model as secondary tasks requiring various cognitive processing (i.e., phonological, visual, spatial) differentially disrupted the primary driving task. Thus, results from the present research suggest that other factors, besides time, account for dual-task interference at the processing stage.

Advocates of "general resource models" of information processing posit that interference is attributed to the difficulty (i.e., quantitative resource demands) of the tasks being performed. Therefore, according to general resource models, in the present experiments all secondary tasks should have interfered equally with the driving task because secondary tasks were designed to require equivalent quantitative resource demands. That is, preliminary testing was conducted (i.e., in Experiments 1 and 2) to ensure that secondary tasks did not significantly differ in terms of percent errors, subjective workload, and task completion times when performed without the primary driving task. Results of the present experiments did not support general resource models because although quantitative resource demands were controlled for, secondary tasks were not all equally disruptive to the primary driving task. Thus, dual-task interference could not be attributed solely to the quantitative resource demands of tasks. Rather, the present findings suggest that differences in qualitative task demands led to differences in dual-task performance.

Proponents of multiple resource models of information processing posit that short-term memory consists of qualitatively different limited resources (i.e., phonological, visual, spatial). Qualitative differences in task demands have been found to account for dual-task interference in many domains such as mental arithmetic and reading comprehension. The finding in the present research that visual and spatial secondary tasks interfered more with overall driving performance relative to phonological interference suggest that the internal processing resources required for performance of secondary tasks must be considered when assessing dual-task interference. The results relative to the distinction between the effects of phonological, visual and spatial processing tasks on driving performance suggest that there is a three part distinction and that Wickens' (1980) multiple resource model would benefit from these distinctions. Specifically, results suggest that initiation of lane change involves primarily spatial processing, whereas lane change maneuvers mainly involved phonological processing and lane maintenance performance required mostly visual processing. Therefore, different interference effects on driving performance were found when retaining visual and spatial information, thus indicating that these components are independent, rather than interdependent, components of working memory. In sum, the results of the present experiments support multiple resource models of information processing and add to the empirical validation of a multiple resource model in complex environments.

Generality and Practical Implications of Results

The present research has focused on the impact of secondary tasks upon driving performance. As automotive manufacturers continue to introduce in-vehicle devices, the disruptive influence of secondary tasks associated with these devices may increasingly impair primary driving performance. US statistics demonstrate that as identifiable groups, younger and elderly drivers account for a large portion of overall reported accidents (Lee, 2005). The causal factors for accidents associated with younger drivers differs from those related to elderly drivers. For young drivers, risk taking, skill deficiency, and poor judgment are amongst the primary factors leading to accidents (Evans, 1991). Alternatively, for elderly drivers, diminished perceptual and cognitive processing capabilities have been found to be primary causal factors contributing to their involvement in accidents (Ball & Owsley, 1991; Stutts, Stewart & Martell, 1998).

The participants in the present study were homogeneous with respect to age in comparison to the general population of drivers. Specifically, the majority of participants in this study were in their early twenties. The present experiment has clearly demonstrated the disruptive influence of secondary tasks on driving performance of this younger age group. It is likely that repetition of the same experiment involving a population of elderly participants would result in even more disruptive impacts of secondary tasks on driving performance. A sample of older drivers might produce more pronounced results because they tend to have poorer perceptual capacity and visual and spatial processing skills (McGwin & Brown, 1999). The question arises therefore whether inclusion of in-vehicle devices which introduce additional secondary task information processing should potentially be restricted in vehicles registered to elderly drivers. While provocative, this concept is not foreign to the requirement that the elderly must be re-tested to maintain their driving privileges, whereas younger and middle age drivers are not subject to such requirements. In considering such restrictions of motor vehicle registrations it should be emphasized that driving performance is more disrupted by visual and spatial secondary tasks than by phonological secondary tasks.

Detection of and response to environmental stimuli are important aspects of driver safety as they are often precursors to traffic crashes (Tijerina, 2000; Treat, 1980). That is, a high percentage of automobile accidents occur because of internal distractions rather than because drivers lacked skills in performing responses (Recarte & Nunes, 2000; Shinar, 1978). The most common type of crash is rear-end collisions, which account for approximately thirty percent of all crashes (Lee, 2005). Rear-end collisions are associated with breakdown in event detection and longitudinal control and have been found to be caused by distractions and driver tendency to follow too closely (National Safety Council, 1996). Researchers, however, do not specify the type of distractions that cause breakdown in event detection and longitudinal control. The present results add to the literature by demonstrating that qualitative differences in the processing resources (i.e., phonological, visual, spatial) required by the secondary tasks differentially affect measures of event detection. Specifically, the present results show that spatial information processing disrupts event detection more than do phonological and visual information processing. Thus, tasks that require spatial processing should be avoided when designing in-vehicle communication systems.

One possible limitation of this study is that the secondary tasks used to assess mental processing are not exactly the same as tasks that might be involved in in-vehicle devices. Specifically, the typical mental activities that drivers pursue while they are driving (e.g., conducting business transactions, listening to music, discussing workday events) are somewhat different from the artificial mental tasks used in the present experiments. Furthermore, it is difficult to assess how the effects of requiring participants to constantly and repetitively perform the mental tasks in the present experiment relate to the spontaneous nature and frequency of normal mental activities. Characteristics of these typical activities suggest that distraction and disruption would be even greater than observed in this study, because they are more variable. Despite these unresolved issues, this much needed research on the differential effects of phonological, visual and spatial task processing on driving performance provide an important perspective on the consequence of internal distractions on driving performance.

The present research demonstrated that the Lane Change Test (LCT) technique is a good tool to aid developers in the identification of distracting tasks. Specifically, use of the LCT has permitted evaluation of secondary task distraction on driving performance. The results of the present research demonstrate that LCT is a good method for assessing the impact of qualitatively different tasks on key measures (i.e., event detection and lane maintenance) of driving performance. LCT could also be used as a screening mechanism to prevent the inclusion of distracting tasks in the design and development of new in-vehicle devices. There are two ways of using the LCT paradigm to screen out distracting tasks. The first is to benchmark performance on a new task relative to that of control performance (i.e., no secondary task), the second is to compare performance on a new task to that of a conventionally accepted in-vehicle task such as the radio tuning task.

The current International Organization for Standardization (ISO) working draft (2006) proposes standards for the use of the Lane Change Test (LCT) in the design and development of in-vehicle systems. Presently this draft standard recommends use of the overall lane change deviation measure. In contrast, the results of the present research suggest that use of breakdown measures (i.e., lane change initiation, lane maneuver quality, lane position maintenance) would be preferable. Breakdown of the overall measure into these individual components revealed the differing impacts and contributions of these components to the overall measure. Therefore, breakdown measures permit more precise determination of secondary task impact upon key measures of driver distraction. As revealed in the present study, event detection and lane position maintenance measures of driving performance were differentially disrupted by secondary tasks. Thus, summarizing component measures into an overall measure fails to account for the differential impacts of secondary task on event detection and lane position maintenance, which are two key measures of driver distraction.

In conclusion, the present research supports findings that although visual presentation of secondary task information disrupts driving performance more than auditory presentation, performance of auditorily presented secondary tasks impairs driving performance relative to driving without a secondary task. Impairments were larger when the secondary tasks involved spatial processing than when they required phonological or visual processing. Furthermore, impairments were primarily manifested in measures of detection and response time to stimuli such as the directional cues used in the present experiments. Conversely, impairments associated with lane maintenance were much smaller. The present results support Horrey and Wickens's (2006) hypothesis that event detection and lane position maintenance depend on separate dimensions of Wickens' (1980) four-dimensional multiple resource model. Specifically, event detection is primarily dependent on the "processing codes" dimension, whereas lane position maintenance is mainly dependent on the "perceptual modalities" dimension. Thus, secondary task perceptual demands disrupt event detection and lane position maintenance, whereas secondary task processing demands mainly disrupt event detection.

Although the results of the present thesis suggest that auditory presentation of secondary tasks was less disruptive of overall lane change performance than was visual presentation of secondary tasks, it would be useful to explore why visual presentation is worse. Specifically, results from the overall lane change performance measure suggested that secondary tasks that draw driver's visual attention away from the road substantially disrupt driving performance. According to Wicken's (2002), a potential explanation for the later result may be that both the secondary task and the driving task compete for the same limited visual perceptual resources within the brain. Wickens, however, also offers another potential explanation. Specifically, secondary tasks that draw driver's visual attention away from the road may disrupt driving performance because the two competing visual channels (i.e., the road display and the secondary task display) are far enough apart from each other to require visual scanning.

In the present experiments, the demand associated with visual scanning may be sufficient to disrupt concurrent performance of the driving and secondary tasks. The degree to which the advantage of cross-modal over intra-modal presentation is due to separate auditory and visual perceptual resources within the brain, or related to the added demand of visual scanning in the two visual display case is unclear. Future research could examine the issue further by comparing conditions in which the secondary tasks are presented on the same display as the driving simulation (low visual scanning demand), to conditions in which separate displays are used to present the secondary tasks and the driving simulation (high visual scanning demand).

The results of the present study provide information concerning the potential for secondary tasks to interfere with driving, when the secondary tasks have demands comparable to those in the experiment. Performance of more complex tasks requiring information processing, such as using an electronic map to navigate in the real-world, are also expected to interfere with event detection tasks (e.g., hazard detection). Future research could improve our understanding of the effects of internal distraction on driver performance by examining other important driving performance measures such as loss of control and collision frequency.

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Appendix A-1: Items used in the phonological secondary task

COLLEGE VILIFY	BICYCLE COLOURING	PENCIL FAME	DISSUADE **WAIT**ING	**DREAM** **THEME**
LAVENDER COLONE	**WID**OW SQU**ID**	**NEAR**SIGHTED **CHEER**LEADER	ORNAMENT FUGITIVE	NEIGHBOUR CHIMPANZEE
FURTHER CHILDREN	DEMANDING RAILWAY	SQU**AT**TING **WHAT**EVER	SQUIRREL WARM	MULE HATING
RICHNESS **ITCH**ING	DE**LETE** E**LITE**	CREAM RATE	ST**ORM**Y SW**ARM**ING	DE**RAN**GED **RAIN**BOW
SURE WA**SHER**	**SUIT**CASE RESO**LUTE**	STRAIN FLIRT	B**OY**COTT B**UOY**ANCY	LULLABY COLONY
OBSOLETE CURTAIN	ALLIGATOR SWIMMING	**METER**ING **NEAT**NESS	TELEVISION CENTURY	UNITARY TIGER
MILLIONNAIRE FITNESS	PURE WHALE	**GAIN** R**EIN**DEER	SQUIRMY **WORM**	SEATING DIFFERENT
DEEM **SEAM**STRESS	**KER**NEL **CUR**FEW	BLOWING ASSURANCE	DIME SLEEVELESS	**MEET**ING **DEFEAT**
RADAR DE**RAIL**ED	**STAIN** **REIGN**	SYLLABUS CELERY	BOYSCOUT WONDERFUL	NURSE SWINE
BUSY CUCUMBER	STORAGE TRICEP	DIAL POP	DE**LAY** **LATE**	CLOUDY DISSA**LLOWED**
BOATING RE**MOTE**	**RAIS**IN **GREAT**NESS	CLOWN CABBAGE	**STEAM**SHIP RE**DEEM**ING	B**LOOM**ING AS**SUME**
DISGUST LEVERAGE	SLATE TRICYCLE	COM**PUTE** **PEW**TER	REASON LATENESS	CHANGING DEVILS
SOFA VALLEY	STEAMER QUALIFIES	P**UR**SE WH**IRL**	SIDECAR STIGNING	SEASON DESTROY
ISLANDER RE**VILE**	HE**IGHT**EN POL**ITE**NESS	CREATURE PROPOSAL	PACK**AG**ING MIL**EAGE**	**BAY**ONET DISSO**BEY**
UN**TID**Y **THAI**LAND	TRANS**LATE** **EIGHT**EEN	DISCUSS REPELLENT	WINDOW STUFFY	**WOOD**WORK P**UDD**ING
DOUGHNUT REIMBOURSE	DEMANDE SUNSCREEN	**FOUGHT** DISTR**AUGHT**	CHARC**OAL** **BOWL**ING	ROTATE FOURTEEN
COMPUTER CRADDLE	WELCOME CHECKBOARD	**FUEL** **FEWER**	DEM**EAN**ING SCR**EEN**PLAY	
OB**SCENE** **SEA**SHORE	STR**EET**CAR UN**BEAT**ABLE	DECANTER ROOKIE	WHENEVER BEATLE	
FEATURE **FLEET**	**BOARD**ING **CORD**IAL	BORING CARDINAL	PANICKING MILESTONE	
TIGHTEN AIRPLANE	LEVEL MISERY	**GREY**ISH **CRATE**	**VESSEL** **WRESTLE**	

Appendix A-2: Items used in the visual secondary task

STICKY	SILK	**RESIST**	**STIFF**	**TEMPT**	EVIL	**PRESENT**
WILD	SHEET	**SHUT**	**FIRM**	**SEEK**	CULT	**GIFT**
RICE	LINEN	**QUIT**	**FIXED**	**TRY**	CLUB	**KID**
SLIGHT	**NEED**	SWEET	NICELY	**QUICK**	SINUS	MICE
WIND	**CHUM**	SPICE	FIT	**WIT**	MEDECINE	PINCH
GUST	**BEST**	NICE	TILES	**MIND**	FLU	CHEESE
BUSY	**BUN**	SERVE	**BIKE**	STYLE	MUSIC	**THREE**
TIME	**CHILI**	CHILL	**HELMET**	GIRL	FIRST	**RING**
MINUTE	**DISH**	WINE	**BELL**	GUY	HIT	**CIRCUS**
NURSE	FLEX	**NIGHT**	UGLY	NICK	**JUICE**	**STING**
SICK	MUSCLE	**SLEEP**	WITCH	SLIT	**QUENCH**	**BITE**
FEVER	LIFT	**REST**	STICK	CLIP	**THIRST**	**HURT**
LUCKY	CHIN	LICK	CLIMBS	**MILK**	**STILL**	EYES
FURRY	CHEEK	WET	HIKE	**BUTTER**	**DULL**	BLINK
DICE	LIP	HUMID	HILL	**WHIP**	**NUMB**	WINK
SINK	**MICE**	GUN	**PURE**	HUGE	TEETH	STIFF
JUMP	**BLIND**	RIFLE	**INFECT**	BULK	PICTURE	NECK
SWIM	**THREE**	HUNT	**GERM**	MIGHTY	SMILE	HURT
ICICLE	**LIMB**	**BUSH**	SUMMER	EJECT	SHELL	**BEGIN**
SHINE	**KNEE**	**STEM**	JUNE	EMIT	FISH	**NEW**
SUN	**JUMP**	**HERB**	JULY	EVICT	DISH	**FRESH**
CRY	SLIM	**FLUB**	**CHURCH**	**INDEED**	**REDUCE**	**CHILD**
YELL	THIN	**MIFF**	**CHIME**	**YES**	**TICKET**	**SULK**
UTTER	SKINNY	**RUIN**	**PEW**	**TRULY**	**PRICE**	**CRIB**
RIDE	SELF	JEWEL	MYTH	**PILE**	**PIN**	WHITE
SHUTTLE	HELP	WINNER	LEGEND	**MESS**	**SUIT**	PICKET
BUS	HINT	GEM	LIES	**BUNCH**	**STRIPE**	FENCE
EVIL	**PRESENT**	**IGNITE**	**TINY**	**CHEW**	LITTLE	NIGHT
CULT	**GIFT**	**BURN**	**MIDGET**	**FRUIT**	LESS	TIME
CLUB	**KID**	**FIRE**	**RUNT**	**PLUM**	NIL	FILM
TINY	**FULL**	**BEEF**	STICK	SEGMENT	JET	TIFF
MIDGET	**ENTIRE**	**STEW**	PUTTY	PRUNE	THRUST	FIGHT
RUNT	**BIT**	**LIVER**	CEMENT	MINCE	ENGINE	FELL
VELVET	**VERY**	**DESSERT**	WHISKEY	LIME	**INVENT**	INTELLIGENT
SUEDE	**KEEN**	**ICING**	GIN	GREEN	**DESIGN**	NERD
MINK	**LUCID**	**CRUMB**	RYE	MINT	**ERECT**	WISE
CHIP	**IGNITE**	**CLUE**	**WRITE**	VEHICLE	FINISH	**DECIDE**
FRENCH	**BURN**	**MYSTERY**	**LETTER**	DRIVE	CHEER	**ISSUE**
FRIES	**FIRE**	**SECRET**	**SEND**	WHEEL	LINE	**DEDUCE**
EMIT	**BEND**	**CIRCLE**	MINE	**BELCH**	**CUCUMBER**	
FUME	**TWIST**	**CUBE**	NICKEL	**SWIG**	**NUT**	
SMELL	**TURN**	**CURVE**	DIG	**BEER**	**EDIBLE**	

Appendix A-3: Items used in the spatial secondary task

3:30 & 5:00	1:30 & 11:00	1:00 & 7:00	11:00 & 4:00	10:00 & 3:00
8:30 & 10:30	3:00 & 7: 00	10:30 & 1:00	5:00 & 4:00	1:00 & 8:30
2:30 & 5:30	10:30 & 10:00	8:30 & 1:30	5:00 & 9:30	4:00 & 4:30
10:00 & 3:00	5:30 & 10:30	4:00 & 7:30	4:30 & 1:30	9:30 & 11:30
2:30 & 11:30	5:30 & 2:00	7:30 & 4:30	5:00 & 1:00	8:30 & 8:00
7:30 & 5:00	3:30 & 1:30	3:30 & 11:30	7:30 & 3:30	11:30 & 3:00
7:30 & 1:30	7:00 & 4:30	1:00 & 3:00	7:00 & 7:30	3:30 & 4:00
11:30 & 1:00	8:30 & 3:30	7:00 & 5:30	2:00 & 7:00	1:30 & 2:30
10:30 & 9:30	7:30 & 11:30	4:00 & 7:00	7:00 & 10:30	10:30 & 10:00
1:30 & 2:00	1:00 & 5:00	4:30 & 4:00	5:00 & 11:00	5:00 & 10:00
8:00 & 1:00	11:30 & 4:30	11:00 & 11:30	9:30 & 11:30	1:00 & 3:30
8:30 & 8:00	10:00 & 1:00	8:30 & 11:00	9:30 & 8:30	5:00 & 2:30
7:00 & 9:00	11:30 & 2:00	11:30 & 3:30	7:00 & 3:30	8:30 & 3:00
2:30 & 5:30	10:00 & 1:00	4:00 & 7:30	7:00 & 10:30	5:00 & 9:30
9:00 & 10:00	11:00 & 3:30	7:30 & 4:30	8:00 & 2:00	7:30 & 3:30
2:30 & 11:30	4:30 & 8:00	2:30 & 10:00	3:00 & 2:30	8:00 & 9:00
11:30 & 8:00	7:00 & 8:30	9:00 & 11:00	11:00 & 10:30	
8:30 & 5:00	5:30 & 2:00	1:00 & 10:30	3:00 & 10:30	
1:30 & 3:00	5:30 & 10:30	8:30 & 11:00	1:30 & 10:00	
2:30 & 11:00	1:30 & 4:00	9:00 & 5:00	9:30 & 8:30	

Appendix B: ***Table 1. Experiment 1: Mean latencies, standard deviations, and error scores at each level of secondary task and interference***

	Type of Interference											
	Control			Phonological			Visual			Spatial		
Secondary Task	M	SD	%	M	SD	%	M	SD	%	M	SD	%
Phonological	1.8	1.7	15.7	1.8	1.7	25.0	1.9	1.8	19.9	1.9	1.7	26.9
Visual	2.6	0.7	12.5	2.6	0.8	16.7	3.6	1.1	18.1	3.4	1.4	15.7
Spatial	2.6	0.7	12.5	2.9	1.0	16.7	3.4	1.2	16.7	3.7	1.5	17.1

Table 2. Experiment 2: Mean latencies, standard deviations, and error scores at each level of secondary task and interference.

	Type of Interference											
	Control			Phonological			Visual			Spatial		
Secondary Task	M	SD	%	M	SD	%	M	SD	%	M	SD	%
Phonological	3.2	1.1	19.4	4.1	1.0	21.3	3.7	1.1	20.4	3.3	1.2	20.4
Visual	3.8	1.4	12.5	3.2	1.1	12.5	4.4	1.3	16.2	4.0	1.7	11.6
Spatial	3.4	1.2	10.6	3.1	0.7	15.7	3.5	1.2	17.1	3.8	2.1	18.5

Appendix C: Driving questionnaire

Driving Experience Questionnaire

Instructions: The purpose of this questionnaire is to assess your driving experience and general background. Your personal identity will not be associated with any of your responses. Only a unique number will be recorded and will be used by the researchers. Please complete each question by responding in the space provided or selecting either Yes or No.

Part I. Demographic Information

1. Are you? ☐ Male ☐ Female

2. Age:____________

Part II. Driving Experience

4. Do you have a valid driver's license? ☐ Yes ☐ No

5. How many years have you had a driver's license? _______ year(s)

6. On average, how many kilometers do you drive per year?_______ km / year (e.g. 50,000km/year)

7. How many accidents as a driver (including fender benders) have you had since you began driving? _________

   Of these, how many were considered your fault? _____

   How many were considered the other driver's fault? ______

8. If any of the accidents were considered your fault, list what type of accident it was? (e.g., roll over, rear-end collision, failure to give right of way) (If more than one accident was considered your fault, please list the type for each one.)

9. Do you usually wear a seatbelt while driving: ☐ Yes ☐ No

10. Do you usually drive: ☐ Automatic ☐ Standard

11. How many moving violations have you had since you started driving? ___________ (E.g., speeding tickets, reckless driving, violating a stop sign or light. Do **not** include parking tickets.)

    Please list each type of violation (e.g., speeding) and the number of tickets you have had for that type (e.g., 2) in the past 2 years.

    a)____

    b)____ c)____

Appendix C (continued): Driving questionnaire

12. Have you had previous experience driving this PC-based driving simulator?
☐ Yes ☐ No

Part III. Medical Information

13. Do you use glasses (or contact lenses) for distance? ☐ Yes ☐ No

14. Do you use glasses (or contact lenses) for reading? ☐ Yes ☐ No

Appendix D: Experiment 3, *Table 1. Mean lane change deviations (in m) and standard deviations (in m) on lane change test for each level of secondary task presentation (auditory vs. visual) and processing (phonological, visual, or spatial)*

	Processing Mode							
	Control		Phonological		Visual		Spatial	
Presentation Mode	M	SD	M	SD	M	SD	M	SD
Auditory	1.28	0.29	1.43	0.30	1.49	0.35	1.51	0.37
Visual	1.32	0.24	1.60	0.36	1.67	0.44	1.68	0.34

Table 2. Mean latencies (in s) and standard deviations (in s) on secondary tasks for each level of secondary task presentation (auditory vs. visual) and processing (phonological, visual, or spatial)

	Processing Mode								
	Phonological			Visual			Spatial		
Presentation Mode	M	SD	%	M	SD	%	M	SD	%
	Single Task (secondary tasks without driving)								
Auditory	1.66	0.68	11.90	2.85	1.54	9.23	2.57	1.09	11.31
Visual	2.13	0.95	13.69	3.71	1.70	7.14	3.77	1.01	12.80
	Dual-Task (secondary tasks with driving)								
Auditory	2.65	1.04	14.36	3.36	1.82	8.73	2.81	1.68	14.01
Visual	3.57	0.98	14.91	4.20	1.82	8.73	4.14	1.20	16.62

Appendix D (continued): ***Table 3. Mean distance (in m) and standard deviations (in m) on lane change initiations for each level of secondary task presentation (auditory vs. visual) and processing (phonological, visual, or spatial)***

	Processing Mode							
	Control		Phonological		Visual		Spatial	
Presentation Mode	M	SD	M	SD	M	SD	M	SD
Auditory	14.25	4.27	16.18	5.72	16.17	4.13	18.13	4.99
Visual	13.38	2.46	17.46	4.11	18.48	3.49	18.47	3.98

Table 4. ***Mean distance (in m) and standard deviations (in m) on lane change lengths for each level of secondary task presentation (auditory vs. visual) and processing (phonological, visual, or spatial).***

	Processing Mode							
	Control		Phonological		Visual		Spatial	
Presentation Mode	M	SD	M	SD	M	SD	M	SD
Auditory	34.00	9.08	38.83	11.76	36.91	10.77	35.00	9.47
Visual	37.43	11.07	43.78	10.31	43.05	9.37	43.58	10.32

Appendix D (continued): ***Table 5. Mean lane change deviation (in m) and standard deviations (in m) on lane maintenance performance for each level of secondary task presentation (auditory vs. visual) and processing (phonological, visual, or spatial)***

	Processing Mode							
	Control		Phonological		Visual		Spatial	
Presentation Mode	M	SD	M	SD	M	SD	M	SD
Auditory	0.65	0.20	0.61	0.21	0.62	0.22	0.63	0.23
Visual	0.56	0.14	0.71	0.26	0.77	0.29	0.71	0.28

Appendix E: Experiment 4, *Table 1. Mean lane change deviations (in m) and standard deviations (in m) on lane change test for each level of secondary task presentation (auditory vs. visual) and processing (phonological, visual, or spatial)*

	Processing Mode							
	Control		Phonological		Visual		Spatial	
Presentation Mode	M	SD	M	SD	M	SD	M	SD
Auditory	1.31	0.23	1.58	0.29	1.59	0.34	1.60	0.32
Visual	1.28	0.22	1.65	0.31	1.73	0.36	1.69	0.38

Table 2. Mean latencies (in s) and standard deviations (in s) on secondary tasks as a function of secondary task presentation (auditory vs. visual) and processing (phonological, visual, or spatial) for baseline and dual-task runs

	Processing Mode								
	Phonological			Visual			Spatial		
Presentation Mode	M	SD	%	M	SD	%	M	SD	%
	Single Task (secondary tasks without driving)								
Auditory	1.56	0.91	16.22	2.71	0.95	10.63	2.67	1.06	13.61
Visual	2.88	1.93	13.18	3.17	1.48	13.94	2.99	1.43	17.30
	Dual-Task (secondary tasks with driving)								
Auditory	2.38	1.02	13.18	3.66	1.26	13.94	3.77	1.45	17.30
Visual	3.76	1.84	18.10	4.23	1.56	18.33	4.96	2.29	24.03

Appendix E (continued): ***Table 3. Mean distance (in m) and standard deviations (in m) on lane change initiations for each level of secondary task presentation (auditory vs. visual) and processing (phonological, visual, or spatial)***

	Processing Mode							
	Control		Phonological		Visual		Spatial	
Presentation Mode	M	SD	M	SD	M	SD	M	SD
Auditory	16.77	2.49	20.86	3.42	21.80	4.10	21.86	3.71
Visual	17.23	2.46	22.60	3.36	22.91	4.20	24.93	4.88

Table 4. Mean distance (in m) and standard deviations (in m) on lane change length for each level of secondary task presentation (auditory vs. visual) and processing (phonological, visual, or spatial)

	Processing Mode							
	Control		Phonological		Visual		Spatial	
Presentation Mode	M	SD	M	SD	M	SD	M	SD
Auditory	35.88	10.50	39.10	11.12	40.93	12.40	40.18	12.08
Visual	30.81	6.92	37.25	11.53	38.03	11.18	37.79	9.55

Appendix E (continued): ***Table 5. Mean lane change deviation (in m) and standard deviations (in m) on lane maintenance performance for each level of secondary task presentation (auditory vs. visual) and processing (phonological, visual, or spatial)***

	Processing Mode							
	Control		Phonological		Visual		Spatial	
Presentation Mode	M	SD	M	SD	M	SD	M	SD
Auditory	0.55	0.14	0.58	0.21	0.57	0.18	0.61	0.27
Visual	0.56	0.20	0.66	0.24	0.73	0.25	0.67	0.27