The Effects of Cognitive Executive Load on Driving Crashes and Near-Crashes

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ABSTRACT

Previous naturalistic driving studies have shown that visual and manual secondary tasks increase driving crash risk. With the increasing use of infotainment systems in vehicles, secondary tasks requiring cognitive executive demand may increase crash risk, especially for young and older drivers. Naturalistic driving data were examined to determine if secondary tasks with increasing cognitive executive demand would result in increasing crash risk. Data were extracted from the Second Strategic Highway Research Program Naturalistic Driving Study, where vehicles were instrumented to record driving behavior and crash/near-crash data. Cognitive executive and visual-manual tasks paired with a second cognitive executive task were compared to the cognitive executive and visual-manual tasks performed alone. Crash/near-crash odds ratios were computed by comparing each task condition to driving without presence of any secondary task. Dual cognitive executive tasks resulted in greater odds ratios than those for single cognitive executive tasks. The dual visual-manual tasks odds ratios did not increase from single task odds ratios. These effects were only found for young drivers. These findings help validate that cognitive executive secondary task load increases crash/near-crash risk, especially in dual task situations for young drivers. Future research should be conducted to minimize cognitive task load associated with vehicle infotainment systems using such technologies as voice commands.

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GENERAL AUDIENCE ABSTRACT

Previous naturalistic driving studies have shown that visual and manual secondary tasks increase driving crash risk. With the increasing use of infotainment systems in vehicles, secondary tasks requiring cognitive demand may increase crash risk, especially for young and older drivers. Naturalistic driving study data were examined to determine if secondary tasks with increasing proposed cognitive demand would result in increasing crash/near-crash risk.   Cognitive and visual-manual tasks paired with a second cognitive task were compared to the cognitive and visual-manual tasks performed alone. It was found that dual cognitive tasks resulted in greater crash/near-crash risk than the single cognitive executive tasks. The dual visual-manual tasks did not show greater crash/near crash risk than the visual-manual tasks performed alone. These effects were only found for young drivers. These findings help validate that cognitive secondary task load increases crash/near-crash risk, especially in dual task situations for young drivers. Future infotainment systems and drivers' education programs should be designed to minimize cognitive loads.

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INTRODUCTION

Driver distraction may be more of a safety issue due to the influence in recent years of cell phones and the increasing use of infotainment displays and controls in vehicles. Distractions have always existed in vehicles, such as reaching for objects, glances away from the road, adjusting the radio and climate control, and eating and drinking. Cell phones and other technologies have added a new layer of distraction, and have been found to increase risk of vehicle crashes (Dingus et al., 2016).

Visual and manual distractions include those factors that may interfere with visual and manual tasks involved in driving a vehicle. Cognitive distractions have also been found to negatively affect driving performance measures such as braking reaction time (Strayer et al., 2015). Dingus et al. (2016) did a study analyzing naturalistic driving study (NDS) data where they found that visual and manual distractions such as reaching for an object in the vehicle had a higher risk of crash involvement than cognitive distractions such as passenger interactions.

It is not clear however, how greater degrees of cognitive distraction might affect crash risk. While conversing with passengers might present rather low cognitive interference with driving, tasks such as texting and dialing a cell phone, which certainly impose visual and manual distraction, also involve cognitive distraction   This cognitive distraction might be a component of the higher crash risks for these tasks.

Of particular interest is the executive function component of cognitive resources. Wickens' (2008) theory of multiple resources includes working memory verbal and spatial cognitive components but only accounts for a task switching component of executive processing component that manages verbal and spatial resources. There are executive functions beyond managing verbal and spatial resources that include “response inhibition, monitoring and regulating performance, updating task demands, and goal maintenance and planning” (McCabe et al., 2010). The driving task involves situational awareness where the driver must assess the current driving conditions and plan for future actions. Situational awareness involves executive attention, as do other secondary tasks. The variability of executive processing is of interest, as tasks that demand more executive resources would conflict with executive processing involved in the driving task.

Driver age and experience may also impact executive processing capability. Executive processing capabilities have been shown to mature up to age 25 (Ross et al. (2014) -and Spear (2000) found that brain development continues into the mid to late twenties. Further, driving experience results in the formation of mental models associated with driving tasks, freeing executive resources for other immediate processing needs (Wikman,1998). The ability to perform multiple tasks requiring executive processing may be more reduced with younger drivers, and increase with driving experience and age. Older drivers (e.g., 65 and older) however, may develop cognitive decline leading to impairment of executive processing.

Research Objectives

This study will examine NDS data to determine if paired tasks that both involve executive processing result in greater crash/near-crash (CNC) risk than when an executive processing task is paired with a purer visual or manual task. Executive processing tasks will be chosen so as to isolate the executive component as the varying factor. CNC risk for these tasks will be compared to tasks not heavily involving executive processing but rather are visual and manual in nature. It is expected that the highly executive processing tasks will cause higher CNC risk when paired with an executive task, but that there will be minimal increase in CNC risk for visual and manual tasks when paired with the same executive processing task. Further, it is expected that higher risk for the executive processing tasks will be found for young drivers with less developed executive capabilities and less driving experience, and for older drivers with possible cognitive impairment.

LITERATURE REVIEW

Multiple Resources and Executive Processing

Multiple Resource Theory

Wickens (2008) has proposed a multiple resource theory of capacity, where there exist multiple pools of resources used to perform tasks. Wickens developed a 3-dimensiona model of resource capacity that assumes separate resource pools. The model consists of three major dimensions. In the first dimension, perceptual and cognitive stages of processing draw upon different resources than the response stage. The second dimension assumes that spatial and verbal coding use separate resources. Finally, in the third dimension, visual and auditory processing draw upon separate resource pools. A fourth dimension was later added that involves focal (acuity) and ambient (peripheral) processing. According to Wickens' theory, tasks that draw upon different resource pools can be shared without performance decrement, while tasks that use the same resource pools will show a performance decrement.

Working Memory and the Executive Control System

The working memory components of Wickens' model were established earlier by Baddeley and others (Wickens et al., 2016). In Baddeley's model, verbal and auditory information is represented in the phonological loop. The phonological loop is thought to be responsible for maintaining verbal material in sequential order and is closely related to the speech system. Visual-spatial information, according to Baddely's model, is represented in the visuo-spatial sketchpad. The sketchpad has been shown to be involved with mental imagery and the planning of movements (Salway and Logie, 1995). Both the phonological loop and the visuo-spatial sketchpad store the information as codes, and these two components are thought to be separate from one another.

Multiple spatial and verbal tasks, however may be involved with a common component of working memory that can cause task interference. A third component of Baddeley's working memory model, the executive control system is involved in operations that may include both the phonological store and the visuo-spatial sketchpad. The functions of the executive control system are used in real-world tasks. Gathercole and Baddeley (in Shah and Miyake, 1996) have proposed for example, that complex language comprehension cannot be performed without the executive control system.

Several roles have been proposed for the executive control system. One is to coordinate multiple tasks which use the phonological loop and visuo-spatial sketchpad subsystems (Baddeley, 1996). Salway and Logie (1995) found evidence for separate verbal and visuo-spatial components, along with a central executive component that coordinates task performance. A second executive role proposed by Baddeley (1996) is selective attention. Baddeley found that ignoring irrelevant stimuli was involved in selective attention. Another key activity of the executive control system may involve the retrieval of information from long-term memory (Baddeley, 1996). Comprehension of verbal material for instance, may include setting up mental models by activating previously learned material from memory. A final executive role is the assignment of task resources. If multiple tasks share common resources, then the executive control system may give priority to one task over another and assign more resources to that task (Wickens et al., 2016).

Executive Functioning and Working Memory

Distinctions have been made between executive functions and working memory. Executive functioning is a broad classification of which working memory is thought to be a part. Among others, functions of executive memory include “response inhibition, monitoring and regulating performance, updating task demands, and goal maintenance and planning” (McCabe et al., 2010, p. 223). Working memory is responsible for maintenance and manipulation of information and includes the executive component as described by Baddeley (McCabe et al., 2010).

McCabe et al. (2010) provided evidence that executive functions and working memory share common attentional mechanisms. They found high correlations between measures of executive functions and working memory. They called the common ability shared by them executive attention. The shared nature of the Baddeley’s working memory components and executive functions provides a basis for common executive attention that would be drawn on in tasks such as driving.

The Driving Task

The driving task has been characterized by SAE J3016 (2021) as consisting of three major components. These components are illustrated in Figure 1. The first two components in the dynamic driving task (DDT) of the figure are lateral and longitudinal vehicle motion control and involve physical control of the vehicle in lateral and longitudinal directions, respectively. These operations would most certainly be affected by visual and manual distractions.

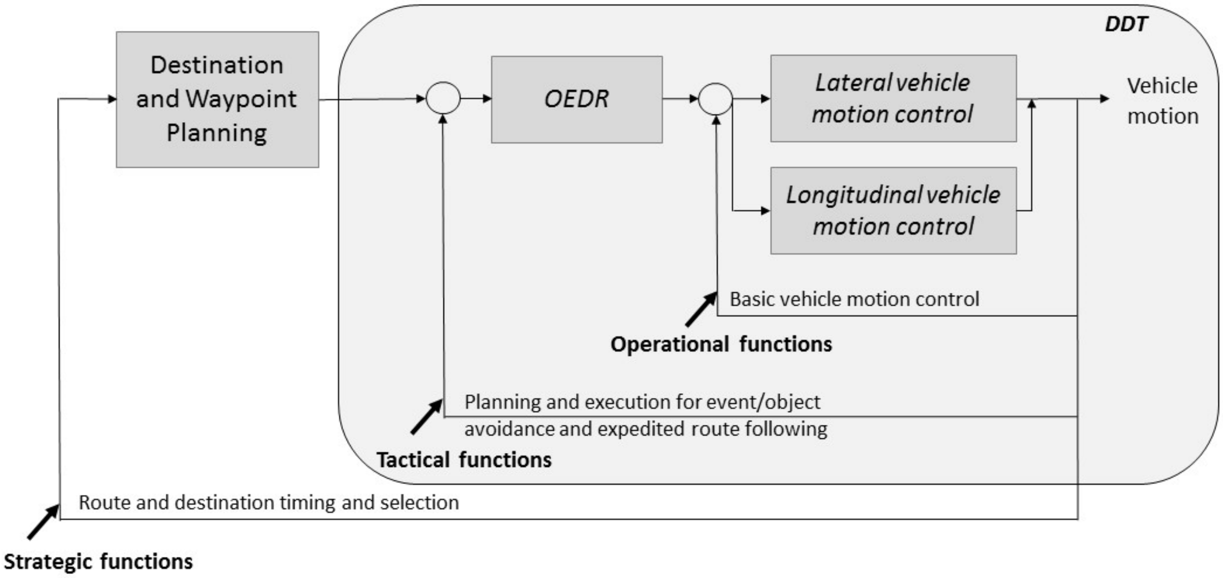
DDT
Destination and Waypoint Planning
OEDR
Lateral vehicle motion control
Longitudinal vehicle motion control
Vehicle motion
Basic vehicle motion control
Operational functions
Planning and execution for event/object avoidance and expedited route following
Tactical functions
Route and destination timing and selection
Strategic functions

Figure 1. Schematic view of driving task (From SAE J3016, 2021).

The third component is object event detection and response (OEDR) and involves detection, recognition and response by the driver. While this component affects vehicle control, it is a less direct factor than latitudinal and longitudinal control, since higher level human processes are required. Attention is required for this component, and so is more likely to be affected by cognitive distractions. OEDR includes driver monitoring and involves driver situation awareness (Calvert et al., 2020).

Situation Awareness

Endsley (in Wickens et al., 2016)) described situation awareness as consisting of: perception of critical visual and auditory information; comprehending the meaning of this information to form a representation of the surroundings; and projection of future events (e.g., future position of other vehicles) in order to determine how to alter driving behavior to accommodate these projections. Situation awareness is necessary for driving behaviors such as monitoring and updating vehicle positions, navigating the roadway, monitoring road conditions, and maintaining proper speed (Heenan et al. 2014). Awareness is an important component of executive attention (McCabe et al., 2010) so situation awareness should incorporate executive processes.

Cognitive Distractions

There is an increasing use of devices that can create cognitive distractions. Tasks involving cell phones may pose an executive processing demand and were found by Dingus et al. (2016) to increase crash risk. Additionally, talking and interacting with passengers were found to increase crash risk, and may also pose a cognitive executive demand that may impair driving performance. These tasks will be used for the present study, so previous evidence for their effects on driving performance will be discussed here.

Conversation

Studies have shown distracting effects of verbal information on driving. Rossi et al. (2012) found evidence that driver conversation and a braking task both required executive attention and interfered with each other when performed simultaneously. Further evidence comes from Heenan et al. (2014) who found that a task simulating conversation produced poor situation awareness in the form of speed monitoring and distance estimation of vehicles in front of the driver. As situation awareness requires executive attention, the results indicate driving interference at an executive processing level with the conversation task. Ma and Kaber (2005) also found evidence for a detrimental effect on driver situation awareness when engaging in a conversation task.

There is also evidence for the distracting effect of the information retrieval component of conversation. Iqbal et al. (2010) measured driving performance during three types of conversational tasks. A retrieval task resulted in the worst driving performance, including the most simulated collisions. Thus, there is evidence that retrieval from long-term memory is a highly attention-requiring task interfering with executive components of driving. The presence of simulated collisions is evidence of particular danger involved with retrieval.

Cell phones

Cell phone conversation would seemingly suffer from problems similar to passenger conversations. Caird et al. (2008) performed a meta-analysis of the literature that found slower reaction time (RT) when using either hand-held or hands-free phones. Additionally, drivers using cell phones tended to have more variable lateral positioning and gave greater headway. Giving greater headway is a compensation maneuver for distraction. There is a lack of evidence for differences between hand-held and hands-free driving in terms of performance and crashes (Caird et al., 2008, Horrey and Wickens, 2006, Redelmeier and Tibshirani, 1997). Thus, cell phones do not seem to impose physical impairment, but rather cognitive impairment like passenger conversations

Texting

Texting is largely a visual-spatial-manual task, much like driving. A meta-analysis by Caird et al. (2014) found the largest effects on driving performance were due to eye movements between the phone and the road when reading and typing text messages. These effects included more prolonged and frequent glances from the road, slower responses to hazards, less vehicle lane control, as well as a higher number of crashes

There are also certainly cognitive executive task components to the texting task however, which may also include a task switching component when combined with a task such as conversation. Texting involves retrieval of information from long term memory, much like conversation. This higher cognitive workload may detract from situation awareness and performance on the driving task. When switching between texting and conversation, drivers may hold information from the other task while performing the current task. Holding this information and protecting it from interference may increase cognitive executive load that further detracts from driving situation awareness and performance.

Dialing

The dialing process might be inferred from previous studies. Brumby et al. (2009) found that improvements in lane keeping performance only occurred between phone number chunks. These chunks corresponded to the area code, prefix and extension components of a phone number. From this, one might propose a possible scenario for phone dialing. When dialing a phone number, only one series of three or four digits is kept in working memory. Each series might be retrieved sequentially from long-term memory into working memory for dialing. While the number is dialed, active maintenance of each series might require executive processing to reduce interference from the driving task as well as other tasks, causing degradation of executive processing associated with the driving task.

Similar to texting, the driver may maintain the phone number in memory while conversing. This would produce a similar increased cognitive executive load that may impair driving performance. The driver may also maintain components of a conversation while performing the dialing task. This may produce increased executive load when combined with digit retrieval and holding the phone number in working memory that interferes with driving situations awareness. Additionally, a phone number requires fine discrimination unlike semantically related items and so requires greater attentional resources to maintain in memory (Unsworth an Engle, 2007).

Effects of Increasing Cognitive Load

The effects of cognitive load on driving performance have not been well quantified. Manual and visual distraction effects on driving have been well accepted and are probably the sources of the largest distractions. The National Highway Transportation Safety Administration has developed visual and manual distraction guidelines. No such guidelines however, exist for cognitive distractions. Cognitive distractions are obviously more difficult to assess due to the difficulty of measuring the effects of brain activity on driving (Strayer et al., 2015).

Strayer et al. (2015) developed a metric for determining the distracting cognitive effects of secondary tasks on driving. They correlated subjective workload measures via the NASA-TLX survey and P300 brain activity through EEG recording with brake reaction times and following distance. Results showed an increasing subjective cognitive workload and P300 latency with cognitive task difficulty. The subjective workload and P300 latency measures correlated well with brake response time and following distance, as greater numbers were associated with higher cognitive load. These results support increasing effects of cognitive load effect on driving performance.

Visual and Manual Distractions

In order to demonstrate the effects of cognitive executive distractions on crash risk, comparisons will be made in this study between conditions where there is greater and minimal executive load. Visual and manual distractions present the best candidates for minimal load. These risks will be discussed here.

Glances

Eye glances are an important measure of visual attention (Wong and Huang, 2013). Drivers will focus their longest glances on areas of most importance to them, generally as it relates to safety. Visual attention is directed to areas of current need, so glances to the front of the vehicle are most common. Drivers will also direct glances to the surrounding areas to maintain situational awareness.

Glances off the road that are too long however, pose a safety risk. Wikman et al. (1998) found that longer glance durations led to more lateral vehicle deviation. Novices tended to have longer glance durations, and they were also more prone to extreme lateral displacements, which increases the chance of running off the road (Wikman et al., 1998). Road signs may also pose a safety risk. While familiar traffic signs tend to receive shorter glances, advertising video signs have been found to receive more long duration glances (Beijer et al., 2004). The increasing use of such signs may pose more of an extended glance safety risk.

Manual Distractions

Manual distractions can have a large effect on driving performance. Dingus et al. (2016) found that the crash OR for reaching for an object was among the highest of all distraction ORs. Also having high ORs were texting and dialing. Although these distractions are proposed to have cognitive and executive processing elements, they undoubtedly present a risk due to the manual nature of the tasks.

Distraction and Crashes

Much of the literature concerning driver distractions uses laboratory and driving simulation experimentation. A way to gather data on the effects of distractions on actual crashes is through the use of naturalistic driving studies. Dingus et al. (2016) conducted the Second Strategic Highway Research Program Naturalistic Driving Study (SHRP 2 NDS) sponsored by the Transportation Research Board of the National Academy of Sciences. This study used video, kinematic and audio recordings to gather data on driving risks, e.g., distraction factors such as cell phones. Dingus et al. (2016) included only crashes involving injury or property damage, so this is the most direct link between distracting factors and actual crashes.

The data in the Dingus et al. study found that visually and manually distracting tasks had greater odds ratios (ORs) of being associated with crashes. Reaching for an object, looking outside the vehicle, texting, dialing, and reading/writing had higher ORs. Tasks involving more cognitive factors including talking on a cell phone and interaction with a passenger had lower ORs.

Although the cognitive tasks had lower ORs, the tasks of texting and dialing a phone also have cognitive components required to perform these tasks. The finding of the highest OR for dialing is particularly interesting, as there might be less visual-manual distraction than for other tasks such as texting. Dialing has been shown to have greater effects on driving performance than cell phone conversations. In Caird et al.'s (2008) meta-analysis, dialing was found to show a greater increase in reaction time over baseline than either hand-held or hands-free cell phone use.

Both texting and dialing involve retrieval from long-term memory. The dialing task is a non-semantic digit retrieval task that may be more cognitively difficult than semantic texting and may also involve holding those digits in memory. It is unclear from these data how much of a role cognitive distraction plays in the crash risk of texting and dialing a cell phone, but higher crash ORs for dialing may indicate greater cognitive interference with driving.

Experience and Age

As drivers gain experience, they become more skilled in their performance by learning the driving task. Driving proceeds from a controlled, effortful process to an effortless automatic one. Cognitive resource workload decreases with practice from novice to experienced driver (Paxion, 2014). Resources can be freed with practice for more executive driving tasks as well as executive components of secondary tasks.

Skilled, effortless processing occurs primarily through learning of consistent stimuli. When stimuli are consistently presented as target stimuli, or stimuli to be learned, they require fewer resources to process. When stimuli are variably mapped, meaning they sometimes appear as targets or as distracters, more attention is required to process them (Shiffren and Schneider, 1977).

Driving with practice develops learned patterns that free resources for other tasks. At a high level these tasks may include supervisory tasks such as monitoring, planning routes, and executing novel maneuvers. Remaining resources may be available for tasks that that are more immediate or are secondary to the driving task. Learned driving include lower level learned processes such as manual vehicular control and visual recognition. These patterns use multiple resource components in a coordinated and more automatic fashion as experience develops. (Paxion, 2014).

Young Drivers and Executive Development

Young drivers account for a disproportionate number of crashes. Crash rates have been found to be highest during the first month after getting a license, and to decline notably during months thereafter (McCartt et al., 2003). A higher crash rate is specific to young drivers (e.g., teens) (Simons-Morton et al., 2011). This higher rate may be due to less experience, limited cognitive development, emotional immaturity, and increased risk-taking behavior

Development of the prefrontal cortex (PFC) and parietal lobes starts at age 11 and has been shown to continue until age 24 (Ross et al., 2014). Spear (2000) further found that brain development continues through the mid to late twenties. The PFC is responsible for the development of cognitive and emotional development and serves management functions. It also contributes to regulatory functions, leading to judgment despite the presence of distractions. Further it helps to regulate emotions, which may not be under complete control in adolescents. The PFC also helps to avoid risk taking, a behavior associated with lack of forethought (Keating, 2007). Maintaining and shifting attention, planning, goal setting and strategy are also associated with the PFC (Heck and Carlos, 2008).

There is further evidence that executive processing associated with the PFC is less well developed in adolescent drivers. Mantyla et al. (2009) measured executive driving task processing in drivers aged 15 to 19 years old. They found that a working memory updating task was associated with more lateral driving deviations in drivers with less efficient working memory. Lack of executive processing development in adolescents may have been mirrored in those drivers with less efficient working memory.

Older Drivers and Executive Impairment

"Older drivers have a higher accident rate than any other age group except teenagers, and incur more fatalities per mile driven than any other adult age group" (Daigneault et al., 2002, p. 221). Reasons for this increase may include physical problems such as eye health (Daigneault et al., 2002), but much of the research literature has identified cognitive functioning as a factor, especially executive processing.

Reuter-Lorenz et al. (2001) examined executive processing in older adults (aged 65-75). They found evidence that older adult brains employed more bilateral processing of both verbal and spatial memory tasks for simpler tasks than younger adults. They put forth that verbal and spatial storage functioning may be diminished in older adults, and that executive processing resources may compensate for this memory component loss. Thus, older drivers may have fewer available executive processing resources when driving and performing other tasks.

Further evidence of limited executive processing resources in older drivers comes from a study comparing older drivers with accident records to drivers without records (Daigneault et al., 2002). Comparisons revealed that older drivers (aged 65 and older) with accident records had lower scores on cognitive tests measuring speed and accuracy of planning or executing tasks. Poorer executive functioning as measured by these tests may play a role in accidents involving older drivers.

There is empirical evidence that older adults are less able to perform executive processing tasks while driving. Verwey (2000) found that older drivers (aged 60 to 79 years) were less able to perform a secondary verbal mathematical task while performing a driving task. Additionally, Makishita and Matsunaga (2008) found that older drivers (aged 61 to 64) had longer response time to signaling detection of a buzzer sound while driving and performing a secondary mental calculation task than younger drivers.

Distraction Effects and Age

Distractions affect all drivers but in different degrees. Guo et al. (2017) examined crash ORs for various distractions for different age groups. Large distraction effects were found for visual and manual distractions across all age groups. These included looking outside the vehicle and reaching for an object in the vehicle. There were age differences for looking outside the vehicle, with middle aged drivers (aged 30-64) having low ORs. This may be indicative of visual strategy learning in middle aged drivers and reaction time differences in older drivers. Reaching for objects showed OR decreases with age that may be indicative of manual learning in the driving task.

ORs for cell phone distractions of talking, texting and dialing were lower for middle aged adults than for teens (aged 16-20), younger adults (aged 21-29) and older drivers (aged 65-98). The lower ORs for middle aged groups may indicate that they have the best development, judgement, and/or capability to perform better with all cell tasks. Lower ORs for cell talking is consistent with better executive development and learning as compared to young drivers, and better cognitive functioning as compared to older drivers. Cell phone texting is consistent with manual and visual learning as well as executive development and learning as compared to younger drivers, and better cognitive functioning as compared to older drivers. There were striking differences between middle aged and both young and older drivers in the cell dialing task, with young and older drivers having considerably higher ORs. Although the prevalence of cell phone dialing was rather low, especially among older drivers, the pattern is consistent with executive development, learning, and functioning differences in the cell dialing task that may detract from the driving task. Manual and visual differences may also be a factor. Finally, there would probably be experience effects for cell phone tasks, with younger and middle-aged drivers being more experienced in these tasks than older drivers.

Research Approach and Hypotheses

This study examined effects of cognitive distractions on crash risk. While the results from Dingus et al. (2016) seem clear that visual and manual distractions have a large effect on the risk of crashes, the effects of cognitive distraction from secondary tasks are less clear. Although cognitive distraction may have a less severe penalty on driving performance than visual and manual tasks, there may be cognitive conflicts between multiple secondary tasks that more severely impair performance and cause crashes. Additionally, the effects of cognitive conflicts for tasks such as texting and dialing with driving on crash risk have not been well established

Of particular interest in the driving task is demand for executive processing resources. One might suppose that texting and dialing with a cell phone might impose higher executive demands. Texting may involve retrieval of verbal information from memory, and dialing may involve retrieval and holding arbitrary digits in working memory. A third task that may impose executive demands is adjusting/monitoring in-vehicle devices. All three tasks have been shown to have elevated ORs from previous studies and so may indeed be associated with crash risk due to executive demands as well as visual and manual distractions. This task may involve high level executive monitoring and retrieval. All three tasks may involve holding information in working memory when switching between a second task involving executive demand.

Of further interest are the effects of age and experience on executive performance and resulting crash ORs. Younger drivers may have more limited executive processing development and so the driving task may be more impaired by the presence of secondary tasks requiring executive attention. Additionally younger drivers are less experienced than older drivers and may not have learned as much about the driving task, which will reduce executive attention for secondary tasks. Finally, older drivers (e.g., 65 and older) may have developed cognitive impairments, limiting their ability to share executive attention required for secondary tasks and the driving task.

This study will examine CNC ORs for tasks with cognitive executive components when paired with more pure executive functioning tasks and compare them to visual and manual tasks paired with the same second executive tasks. These task pairing conditions will also be compared between age groups.

Hypothesis 1: Tasks with more executive demands will produce greater CNC OR increases than tasks with less executive demand when paired with a second executive processing task.

Hypothesis 2: The effects shown by Hypothesis 1 will be greater for drivers aged 16-29 and drivers aged 65 and older.

METHODS

Materials

Data were acquired from the SHRP 2 NDS database, from a study conducted from 2010 to 2013. Data were collected from drivers in six sites: Buffalo, NY, Tampa, FL, Seattle, WA, Durham, NC, Bloomington, IN, and State College, PA. A Data Acquisition System (DAS) system was developed by the Virginia Tech Transportation Institute to record driving data. The DAS collected 3D accelerometer data, global positioning system data, forward radar and vehicle network data. Four cameras continuously recorded views of the forward roadway, the driver's face and driver-side roadway, the right rear window, and the driver interactions with the steering wheel and center stack display. (Guo et al., 2017).

Participants

The participants' ages ranged from 16 to 98 years. Participants were paid $500 per year of data collection, and signed an informed-consent form that was approved by the Institutional Review Boards of all data-collection sites. Primary participants' vehicles were instrumented. Secondary participants were family members and others who consented to data collection and regularly drove the instrumented vehicle (Guo et al., 2017).

Data Collection

In the NDS study, vehicle sensor data (e.g., accelerometer) were used to identify potential crashes. "A crash was operationally defined as any physical contact between the vehicle and another object" (Guo et al., 2017, p. 260). Crashes ranged from minor curb strikes to severe-injury results. Near crashes were also identified, and "are operationally defined as having the observable factors that could lead to a crash" (Dingus et al., 2016, p. 2636). The present study combined both crashes and near-crashes (CNC) due to the limited amount of crash data.

Executive Conflict Prediction

In order to calculate CNC ORs with higher executive demand, distraction tasks with proposed higher executive demand were paired with a second task of proposed lower executive demand. Cell phone texting and dialing, and adjusting/monitoring in-vehicle devices were chosen as executive distraction tasks, as they would involve executive components and have been found to have high crash ORs (Dingus et al., 2016, Guo et al., 2017). Passenger interaction and talking/singing were chosen as second executive tasks because they involve executive components and have been shown to have high prevalence (Guo et al., 2017). Cell phone dialing was paired with cell phone talking as there were too few cases for which dialing with passenger interaction and talking/singing were paired. Cell phone talking involved holding a cell phone to the driver's ear, and so is not a pure cognitive executive task. Cognitive executive pairings were compared to the pairings of distracting visual and manual tasks with the same second executive tasks. Reaching for objects and looking outside the vehicle were chosen as they have been shown to have high crash ORs (Dingus et a., 2016, Guo et al., 2017) and should have very limited executive demand. All task pairings are presented in Table 1.

Table 1. Single and dual distraction tasks, second tasks, and dual conflict

Distraction Task Single and Dual	**Second Task Dual Only**	**Dual Conflict**
Executive	Executive	Executive
Adjusting/Monitoring	Talking/Singing and Passenger Interaction	2
Texting	Talking/Singing and Passenger Interaction	3
Dialing	Talking on Cell Phone	4
Visual-Manual	Executive	
Reaching	Talking/Singing and Passenger Interaction	1
Looking	Talking/Singing and Passenger Interaction	1

The predicted executive conflict levels are listed in the table. Higher numbers indicate greater executive conflict. According to these predictions, dialing should show the greatest conflict with cell phone talking and driving. Holding arbitrary digits in memory would create an increase in executive load when conversing, and holding verbal information from a conversation would increase executive load when retrieving and holding the digits of a phone number. Texting should show the next greatest conflict due to the increased executive load of holding verbal information when retrieving information for the texting or second executive task. Texting is proposed to have lower executive conflict than dialing because holding phone numbers in working memory should require greater attentional resources than semantic information associated with texting. Adjusting/monitoring is assumed to have the least executive demand due to task switching and retrieval so should have less conflict with the second tasks. The visual and manual distraction tasks should have little executive demand, and should otherwise have minimal conflict with the second executive tasks.

The conflict differences for the distraction tasks can be primarily explained by executive demands. Although the distracting executive tasks also have visual and manual components, the distracting visual and manual tasks are primarily visual and manual in nature. Thus, elevated conflict for the distracting executive tasks should represent a more cognitive conflict with the second executive tasks and driving. While one would expect verbal and spatial working memory components to be part of the distracting executive tasks, there should be lack of these cognitive conflicts with the driving and second executive tasks. The driving task contains little or no verbal components (Horrey and Wickens, 2003), and so no conflict would exist there to explain conflict with the distracting executive tasks. As for the spatial component, little or no spatial demand for the second executive tasks is assumed, so there would be little or no spatial conflict with the distracting executive tasks to explain conflict differences. Thus, the cognitive conflicts should be primarily executive ones.

Data Preparation

CNC cases were analyzed in the NDS study in relation to baseline (control) segments. Baseline segments are driving samples where no safety-critical events occurred in the presence of secondary task conditions. Both CNC and baseline time segments were 6 seconds in length. This was the time taken to determine secondary task engagement for CNCs. A stratified random-sampling scheme was used to select baseline segments. First, the number of baseline segments was determined for each driver based on the proportion of non-safety-critical segments driven over 5 mph. In the second stage, the baseline segments were randomly selected for each driver based on the number of segments determined from the first stage. Secondary task prevalence was determined from the percentage of control segments in which the task was present.

The data were divided into three age groups: young (16-29 years), middle (30-64 years), and older (65-99 years). Only three groups were selected so that more CNC data would be available for each group. The young group was chosen based on limited PFC and brain development (Ross et al., 2014, Spear, 2000) and the relatively higher number of crashes that occur during this period (McCartt et al., 2003). The older group was based on high crash rates (Daigneault et al., 2002) and literature demonstrating deterioration of executive capability after age 65 (Reuter-Lorenz et al., 2001, Verwey, 2000, Makishita and Matsunaga, 2008). The middle group was allowed to have the greatest span possible to incorporate the most number of CNCs.

Task Selection

All task data were from the event table of the data set from a SHRP 2 NDS study by Sears et al. (2019). Appendix A contains descriptions of the tasks used for analysis.

For each crash, near-crash, or baseline segment, trained data coders could record up to three secondary tasks for a single 6 second time period. For the single task analysis, single tasks were selected when there were no additional second or third secondary tasks coded. This was done to control for the influence of any other secondary tasks on CNC data. For the dual task analysis, dual tasks were selected where there were no third secondary tasks coded for the same reason. Dual tasks could be in either order, with the distraction task (cognitive or visual-manual) as the first or second task, or the second executive task (passenger interaction, talking/singing, or cell phone talking) as the first or second task. In all task conditions, no CNC or baseline segments where driver fatigue or sleepiness was coded were included in the selection. All other driver impairments and behaviors were allowed. For the model driving task condition, no secondary tasks, driver impairments, or driver behaviors were included (secondary tasks, driver impairments, and driver behaviors are defined in the SHRP 2 Event Detail Table Data Dictionary). There were multiple selection criteria from the data set for the visual-manual tasks of reaching, looking, and for the second task of passenger interaction as shown in Table 2.

Table 2. Multiple selection criteria for reaching, looking, and passenger interaction

TASK	SELECTION CRITERIA
Reaching	Reaching for food-related or drink-related item Reaching for cigar/cigarette Reaching for personal body-related item Reaching for object, other
Looking	Looking at previous crash or incident Looking at pedestrian Looking at animal Looking at an object external to the vehicle
Passenger Interaction	Passenger in adjacent-seat interaction Passenger in rear-seat interaction

Hypotheses

All of the analyses were conducted with CNC probability as the dependent variable. Independent variables were the distraction task conditions. Table 3 represents the components of the ORs. ORs may be represented by the following equation:

$$OR = A*D/B*C$$

Table 3. Odds ratio table

	Crash	No Crash
Secondary task present	A	B
Model driving	C	D

ORs were computed for both single and dual secondary task conditions. The single task ORs were produced for each distraction task group presented in Table 1. Dual task ORs were computed for each distraction task condition paired with the second tasks as listed in the table. In the case of dual tasks, secondary task present in the OR equation represents the presence of both tasks. In model driving, no secondary tasks, driver impairments, or driver behaviors were present.

Hypothesis 1: Tasks with more executive demands will produce greater CNC OR increases than tasks with less executive demand when paired with a second executive processing task.

ORs for the executive tasks were compared. It was predicted that there would be a difference in ORs between the single task and dual task conditions that would increase with predicted executive demands of the distracting executive task. Thus, adjusting/monitoring should show the least OR increase, with texting showing a greater increase, and dialing showing the greatest OR increase. ORs for the visual and manual distraction conditions should show little or no increase from single to dual task.

Hypothesis 2: The effects shown by Hypothesis 1 will be greater for drivers aged 16-29 younger and drivers aged 65 and older.

The OR differences for Hypothesis 1 should be greater for young and older drivers. ORs for all three age groups were compared with each other. It was expected that the predicted pattern of OR increase from single to dual task executive distraction conditions would be greater for the young and older driver groups. Thus, the OR differences between single to dual task would increase in the order of adjusting/monitoring, texting, and dialing, and these increases would be greater for the young group and the older group than for the middle group. Little or no differences between single and dual task ORs were expected between age groups for the visual and manual distraction conditions.

Analysis Approach

Data were analyzed using the R programming language. CNC and baseline frequencies and baseline prevalence percentages were found for each condition. In order to analyze the single and dual task conditions for each of the five tasks, single and dual tasks were compared to model driving. Comparison to model driving allows for the added increments of single and dual tasks to be compared to each other against a common reference involving no secondary tasks, driver behaviors or impairments.

Mixed-effects logistic regression models were used to analyze single-model and dual-model conditions for each task for the overall data and for each age group. The random effect was participant (driver), and the fixed effects included the categorical indicator variables task, gender, lighting, weather, and traffic density. CNC probability was the dependent variable, with baseline values representing the absence of a CNC. The indicator variable of primary interest was task (single or dual condition vs. model). The generic model for these analyses is:

$$\text{Logit}(P(\text{CNC} = 1)) = b_0 + b_1T + b_2G + b_3L + b_4W + b_5TD + d$$

Where: $P(\text{CNC}=1)$ = probability of a CNC, b_0, b_1, b_2, b_3, b_4, and b_5 are regression coefficients, T = task variable, G = gender variable, L = lighting variable, W = weather variable, TD = traffic density variable, and d = driver random term. $\text{Exp}(b_1)$ = OR for the task variable.

Levels of indicator variables with confidence intervals of extremely wide ranges, or from 0 to infinity were discarded from analyses.

RESULTS

Task Frequencies and Prevalence

Tables 4 and 5 display the CNC frequency, baseline frequency and baseline prevalence data for each task overall and for each age group. Table 4 shows frequencies and prevalence percentages for each of the five tasks performed alone, and the second tasks to be paired with these tasks in the dual task conditions, as well as the model driving condition. Table 5 shows frequencies and prevalence percentages for each of the five tasks when paired with their respective second task. Note that the overall frequencies in both tables do not represent the sum of the age groups precisely, as there were null values for age, and so are not represented in the age group frequencies.

Table 4. Single task CNC and baseline frequencies and baseline prevalence percentages

Overall				Young			Middle			Older		
	CNC	Baseline	Prevalence	CNC	Baseline	Prevalence	CNC	Baseline	Prevalence	CNC	Baseline	Prevalence
Adjust	47	87	0.44	19	33	0.37	16	29	0.46	11	24	0.54
Text	86	287	1.44	69	227	2.52	14	60	0.96	1	0	0
Dial	5	11	0.05	2	5	0.06	3	5	0.08	0	1	0.02
Reach	85	79	0.40	44	29	0.32	29	31	0.50	11	19	0.42
Look	141	116	0.58	70	37	0.41	30	40	0.64	40	37	0.83
Interact/ Talk/Sing	1136	3272	16.36	737	1678	18.63	254	884	14.15	133	658	14.70
Cell Talk	165	541	2.70	113	335	3.72	50	176	2.82	1	25	0.56
Model	2142	8642	43.21	965	3363	37.35	723	2708	43.33	427	2445	54.62

Table 5. Dual task CNC and baseline frequencies and baseline prevalence percentages

Overall				Young			Middle			Older		
	CNC	Baseline	Prevalence	CNC	Baseline	Prevalence	CNC	Baseline	Prevalence	CNC	Baseline	Prevalence
Adjust + ST1	23	21	0.11	12	8	0.09	5	6	0.10	6	7	0.16
Text + ST1	14	15	0.08	13	13	0.14	1	2	0.03	0	0	0
Dial + ST1	11	9	0.05	9	6	0.07	1	1	0.02	0	0	0
Reach + ST1	10	16	0.08	5	8	0.09	4	3	0.05	1	5	0.11
Look + ST1	26	21	0.11	14	10	0.11	6	6	0.10	6	5	0.11
Model	2142	8642	43.21	965	3363	37.35	723	2708	43.33	427	2445	54.62

ST1: Front-seat passenger interaction, rear-seat passenger interaction, and talking/singing
ST2: Cell phone talking

CNC and baseline frequencies for dual task conditions were generally much lower than those for the single task conditions. Frequencies for the dial task were low in both the single and dual task conditions. The young group had high baseline prevalence for the texting task in both single and dual task conditions, and greater prevalence for the dialing task in the dual task condition than the other age groups. The young group however, had lower prevalence than the other two groups for the adjusting/monitoring task in both single and dual task conditions. For the visual-manual tasks of reaching and looking, baseline prevalence percentages were fairly consistent in the dual task conditions, whereas young drivers tended to have lower prevalence for these tasks than the other age groups in the single task condition. Both the passenger interaction/talking/singing and the cell phone talking task baseline prevalence decreased with increasing age group. Model driving prevalence increased with increasing age group

Baseline prevalence percentages were found for all task combinations in order to demonstrate that cognitive tasks can be shared with one another, whereas visual-manual tasks have modality limitations that make it difficult to share tasks. Appendix B presents prevalence tables for combinations of all tasks used in this study. Visual-manual task pairs had extremely low prevalence. There was some age effect however, in that young drivers shared more of these task pairs than the other age groups, indicating some inclination towards greater prevalence of performing multiple secondary tasks for young drivers.

Single and Dual Task Effects

Tables 6 and 7 present the single-model and dual-model results respectively, overall and for each age group. As seen in Table 6, neither single-texting nor single-dialing reached significance in the overall data or in the young and middle groups. There was not sufficient data to analyze texting and dialing for the older group. Adjusting/monitoring, reaching and looking

Table 6. Single-model results

	Overall			Young			Middle			Older		
	OR	**CI**	**p-value**	**OR**	**CI**	**p-value**	**OR**	**CI**	**p-value**	**OR**	**CI**	**p-value**
Adjust	3.25	2.15-4.93	<.001	3.02	1.56-5.86	<.001	3.34	1.63-6.84	<.001	2.99	1.29-6.93	.011
Text	1.22	0.91-1.62	.180	1.20	0.87-1.65	.278	0.77	0.38-1.54	.455	N/A	N/A	N/A
Dial	2.27	0.65-7.90	.198	1.72	0.24-12.52	.595	3.02	0.59-15.54	.186	N/A	N/A	N/A
Reach	5.31	3.66-7.70	<.001	6.50	3.68-11.48	<.001	4.62	2.53-8.44	<.001	4.21	1.70-10.41	.002
Look	7.01	5.20-9.45	<.001	8.26	5.15-13.25	<.001	3.70	2.08-6.56	<.001	10.35	5.95-18.01	<.001
Interact/ Talk/Sing	1.53	1.39-1.68	<.001	1.77	1.56-2.02	<.001	1.16	0.96-1.39	.125	1.23	0.97-1.57	.094
Cell talk	1.21	0.98-1.49	.078	1.28	0.99-1.66	.062	0.99	0.68-1.44	.971	0.27	0.03-2.18	.221

Table 7. Dual-model results

	Overall			Young			Middle			Older		
	OR	**CI**	**p-value**	**OR**	**CI**	**p-value**	**OR**	**CI**	**p-value**	**OR**	**CI**	**p-value**
Adjust + ST1	6.91	3.44-13.86	<.001	7.47	2.61-21.42	<.001	6.16	1.63-23.27	.007	8.64	2.31-32.36	.001
Text + ST1	4.20	1.75-10.08	.001	4.80	1.92-12.01	.001	1.03	0.07-15.83	.984	N/A	N/A	N/A
Dial + ST2	14.68	4.85-44.46	<.001	11.80	3.53-39.42	<.001	6.26	0.25-155.92	.26	N/A	N/A	N/A
Reach + ST1	3.39	1.33-8.62	.01	2.84	0.78-10.31	.113	5.08	0.83-30.87	.078	2.80	0.27-29.49	.392
Look + ST1	6.83	3.45-13.55	<.001	5.39	2.06-14.06	.001	5.40	1.38-21.03	.015	13.24	3.27-53.63	<.001

ST1: Front-seat passenger interaction, rear-seat passenger interaction, and talking/singing
ST2: Cell phone talking

were all highly significant with respect to model data, both overall and for all age groups. The second tasks were also tested against model driving. Interaction with passengers and talking/singing were significant overall and for the young group, but not for the middle group. The older group approached significance for these second tasks (p=.094). Cell phone talking was not significant overall or for any age group, but approached significance overall (p = .078) and for the young group (p =.062).

Table 7 presents the dual-model results for the five tasks paired with their second task against model driving. Texting and dialing dual tasks were highly significant overall and for the young group, but not the middle group. Again, there was not data to analyze the older group. Adjusting/monitoring and look were significant in all cases. The reach task was significant overall, but not for any age group, although it did approach significance for the middle group (p = .078).

Confidence intervals did not overlap between single and dual task for the texting task, both overall and for the young group, providing evidence for an OR increase between single and dual task in these cases. For the dialing task, confidence intervals did overlap between single and dual task, both overall and for the young group, although the ORs were higher for dual task than singe task in both cases. Confidence intervals for the adjusting/monitoring task overlapped to a large degree between the single and dual task condition overall and for the young and middle age groups, and completely overlapped for the middle group. Odds ratios however, were larger for the dual task than the single task both overall and more so for the young and older group. Confidence intervals overall and for the young group between the texting and dialing tasks overlapped in the dual task condition, failing to show a clear OR difference between the tasks. ORs were however much higher for the dialing than the texting task.

Confidence intervals between the single and dual task conditions for the look tasks completely overlapped overall and for all age groups. Thus, there was no evidence of difference between single and dual task conditions for this task. Confidence intervals overlapped completely between single and dual conditions for the reach task overall and for the middle and older groups, but less so for the young group. ORs were actually smaller for dual task than single task overall and for the young and older groups.

DISCUSSION

The significant CNC ORs for texting and dialing in the dual task condition, but not in the single task condition, combined with the lack of evidence for OR increases from single to dual conditions for the visual-manual tasks supports an overall effect of cognitive executive load on crash risk, partially supporting the first hypothesis. Cognitive load effects are particularly supported in the case of texting, where confidence intervals between single and dual task did not overlap. The overlapping confidence intervals between single and dual task conditions for the adjusting/monitoring task, along with the differences between single and dual task conditions for texting and dialing support an increase in cognitive executive load for the texting and dialing tasks but not for the adjusting/monitoring task. Overlapping confidence intervals between the texting and dialing task in the dual task condition do not support a difference in cognitive executive load on crash risk between these two tasks, although the OR was larger for the dialing than the texting task.

Visual-manual explanations for increases in ORs for cognitive executive tasks are not supported by the data. Although the second cognitive tasks were presumed to be primarily cognitive in nature there are possible visual-manual elements of these tasks that could interfere with the visual-manual components of the cognitive tasks. Interaction with passengers might include glancing or gesturing towards the passenger, while cell phone talking includes holding the cell phone (see Appendix A). The lack of increases in ORs when the visual-manual tasks are paired with the second cognitive tasks however, suggests little or no visual-manual interference of the second cognitive tasks with either the visual-manual tasks or the cognitive tasks.

The effects of increasing cognitive load on ORs were supported for the young group but not the middle group, partially supporting the second hypothesis. The young group demonstrated the patterns shown by the overall data, with evidence of increasing ORs for the texting and dialing tasks with proposed increasing cognitive executive load when paired with the second cognitive tasks, particularly for the texting task. Additionally, the overlap between single and dual task confidence intervals for the adjusting/monitoring task fails to support an effect of cognitive executive load for this task. The middle group showed no evidence of OR increase with proposed increasing executive task load. Although there was not sufficient data to analyze the texting and dialing tasks for the older group, the adjusting/monitoring task showed an OR increase similar to the young group and greater than the middle group, despite overlapping confidence intervals between single and dual task. Perhaps with more CNC data, there would be better evidence of a cognitive executive load effect on crash risk for this group, as well as the young group. As with the overall data, there was no evidence of visual-manual interference leading to increased CNC ORs in any age group, since pairing the second tasks with the visual-manual tasks resulted in little evidence of increases from single task.

The prevalence data provides more insight into age differences and crash risk due to cognitive load. Young drivers engaged in more passenger interaction and talking/singing than older age groups, indicating they may take greater risk with respect to cognitive tasks. Prevalence percentages for dual tasks were rather low in general, but there were age differences. Texting and dialing dual task prevalence was greater for younger drivers, indicating a tendency for them to engage in greater cognitive task loads when using infotainment devices. Although the prevalence for adjusting/monitoring in-vehicle devices was actually lower for the young age group, they might actually engage in more communication and entertainment functions when using in-vehicle systems. Adjusting/monitoring in-vehicle devices only involved navigation functions for this study (see Appendix A). With newer in-vehicle systems that contain more infotainment functions, young drivers may engage in more cognitive load multitasking.

The cognitive executive load imposed by the dual cognitive tasks may be due to holding of information in memory while another cognitive task is performed. In the texting task, drivers may hold information from a conversation while composing a text message, or conversely, hold texting information while engaging in a conversation. Additionally, the specificity or type of information held may add to the cognitive executive load. In the adjusting/monitoring task, more abstract information about a navigation display may be held while engaging in a passenger conversation, whereas in the texting task, more specific verbal information that may interfere with the verbal information of a passenger conversation may add to executive load.

The dialing task is of particular note as it involves specific arbitrary digit information that is held in working memory. In a dual task cell phone conversation situation, drivers may be getting an unfamiliar number from someone on the phone. An unfamiliar number would be much more difficult to hold in working memory than one that has been memorized.

The results demonstrate an effect of dual cognitive tasks on CNC risk. Balint et al. (2020) found considerably higher ORs for multiple secondary tasks as compared to single secondary tasks. Dingus et al. (2019) found significant ORs for the combined singe hand-held tasks of texting, dialing and browsing, but non-significant ORs for passenger interaction and talking/singing. Differences between odds ratios for the hand-held tasks and cognitive tasks however, decreased with decreasing crash severity. So hand-held single tasks may pose an increased risk of more severe crash incidents in single task situations. Greater effects of cognitive task distraction on crash risk may be found in dual task situations, but it is unclear from the present study whether these effects would be found with more severe crash data. Sufficient data would be needed to test whether there are increasing effects of cognitive load from single to dual task on more severe crash risk.

A couple of unexpected results merit discussion. The first is that both the texting and dialing tasks did not show significant single-model results. There may be at least two contributing factors for this finding. First, CNC data were used in this study. In the Dingus et al. (2019) study, more severe crash incident data were used, without near-crash data. As previously indicated, visual-manual distractions may pose a greater risk for more severe crashes. The use of near-crash data in this study therefore, may have lowered risk, resulting in non-significance. The second factor is that these tasks were performed in isolation, without any additional secondary tasks present. Previous studies (e.g., Dingus et al., 2016, Guo et al., 2017) have allowed other secondary tasks to be present in conjunction with the task of interest. This may have reduced the CNC ORs, contributing to a lack of significance.

A second unexpected finding was that the reaching task showed an OR decrease from single to dual task overall and for the young and older groups, although confidence intervals did overlap. There is the possibility that interaction with passengers helps lower crash risk. When drivers reach for something, a passenger may assist the driver by looking for potential danger. Drivers may tell the passenger to monitor the road while they are reaching.

Limitations

The results of this study are based on rather low CNC and baseline frequencies for dual task conditions, very low in the case of dialing. Perhaps with more CNC data, other differences might have been found, such as a greater single to dual task effect for the dialing versus the texting task and a single to dual task effect for adjusting/monitoring, especially for young and older drivers. The low CNC data also made analyzing the effects of cognitive executive load very limited for older drivers.

The low baseline frequencies of dual task conditions indicate that dual tasking with the tasks examined do not generally occur often. Although dual tasking may occur more often with the introduction of more functionality for in-vehicle systems, future studies would need to bear that out. And, although it is speculated that holding information in working memory was responsible for the increased cognitive loads in dual task conditions, this study cannot rule out alternative explanations. As such, proposed increases in cognitive load in single task situations where drivers hold voice commands in memory cannot necessarily be linked to the crash risk shown in the dual task conditions of this study.

There are possible alternative cognitive as well as visual-manual explanations for the OR increases from single to dual task for the cognitive executive tasks. An alternative cognitive explanation could be that drivers switched completely between cognitive distraction tasks and the second tasks without holding information in working memory between the two tasks. This task switching may have resulted in decreased switching between both secondary tasks and the driving task. That is, less attention may have been devoted to the driving task due to drivers switching between the secondary distraction task (e.g., texting) and the second cognitive task (passenger interaction or talking/singing).

A possible visual-manual explanation for OR increase from single to dual task for the texting task is that drivers were glancing back and forth between cell phones and passengers, or were switching manual interactions between the tasks. This increased visual and/or manual distraction may have led to more time of eyes off the road, or hands on the steering wheel. As for the cell dialing task, drivers holding the phone in the dual task condition would have to switch between holding the phone in hand to dial a number and holding the phone to the ear to engage in talking or listening. This increased visual-manual distraction could have contributed to an increase in OR from single to dual task.

An additional limitation may stem from the use of less severe incidents, including near-crash data. Dingus et al. (2019) found non-significant ORs for cognitive tasks when using more severe crash data. The use of less severe crash data and near-crash data may reflect an increased risk for less severe incidents (e.g., curb strikes and near-crashes), but not for more serious crash incidents. Analysis of more severe crash incidents would need to be done to test this possibility

Finally, the discrete grouping of ages does not allow for a statement on any continuity of crash risk due to cognitive executive load with respect to age. A continuous analysis of data based on age was not performed due to the low CNC frequency counts as age increased. Future studies where more data is available might address this issue.

Implications for Future Research and Design

While physical (e.g., visual and manual) distractions have been clearly shown to have negative effects on crashes, this study has supported the effects of greater cognitive executive processing loads on crash risk. As texting and dialing have been shown to have high cognitive loads in vehicle systems (Strayer et al., 2019), the results of this study can help to validate the effects of those loads on crash risk. Although the prevalence of cognitive dual tasking was low, and prevalence of cognitive disengagement from the driving task has been shown to be low compared to visual-manual task distractions (Wotring et al. (2018), the current results may be more applicable to an increasingly complex in-vehicle environment. With more infotainment functions being included that require the driver's cognitive resources, the potential for increases in crash risk with executive load may be increasing. Additionally, voice commands that can allow visual-manual distraction to be minimized may pose greater cognitive loads (Strayer et al., 2017). This study may be useful in stressing the need to develop vehicle infotainment systems so that they can be operated with less executive load.

Characteristics of the executive distractions may indicate particular executive operations that need consideration. Holding information in working memory and protecting it from interference may be an executive task that is responsible for higher workload and greater crash risk. In voice command systems, the driver may "load and hold" a command to be executed. (Strayer et al., 2017). Designs that seek to minimize holding information in working memory may reduce crash risk. Menu systems have been used as a means of reducing cognitive workload by limiting the amount of information in commands, although deeper menus may actually increase workload (Strayer et al., 2014, Biondi et al., 2019).

A second characteristic that may affect executive load is retrieving and holding precise or arbitrary information in memory. A cognitive executive effect for cell phone dialing and texting would be consistent with the position that arbitrary and precise information is more difficult to retrieve and hold in working memory and protect from interference. Strayer et al. (2019), in finding high cognitive workload ratings for voice entry systems, used commands from vehicle systems that were specific in their format and wording. If voice entry systems can use more intuitive commands (Strayer et al., 2017) that are more flexible, cognitive load might be lower, lowering crash risk.

Cell and smart phones pose a visual-manual risk, and hand-held use while driving is banned in most states, but they could still be used in vehicles. Voice command-operated phones are now available and may provide a way to minimize visual-manual distraction. The need is now to minimize cognitive load associated with using voice commands in order to minimize crash risk with their use.

Since the results of this study have provided evidence that younger drivers tended to have a greater crash risk with greater cognitive executive load, drivers' education program could incorporate cognitive strategies in their training. Young drivers could be taught to not to dual task, but to engage in a single task at a time. Although there may be young drivers who choose to ignore this training, it may have a general effect on reducing crash risk.

CONCLUSIONS

This study has provided evidence that greater cognitive executive load results in increased crash risk. Pairing cognitive executive tasks with a second cognitive executive task resulted in greater CNC ORs over single task conditions. Visual-manual tasks paired with the second cognitive executive task on the other hand, showed no overall increase in ORs over single task conditions, indicating no CNC risk due to little or no increase in cognitive executive load. These effects were shown only for young (16-29 years) drivers.

These findings link cognitive executive workload crash risk to real-world CNC data via the use of the NDS data. Although the effects of increased workload were supported through dual-task conditions, they may indeed apply to single task situations where cognitive executive workload is higher due to holding information in working memory. Such situations may include voice commands, where drivers hold commands in memory prior to speaking them.

Additionally, holding more specific, less intuitive information may pose a greater CNC risk. Future research and design of infotainment systems should limit cognitive executive load, and driver education programs could include cognitive executive task management.

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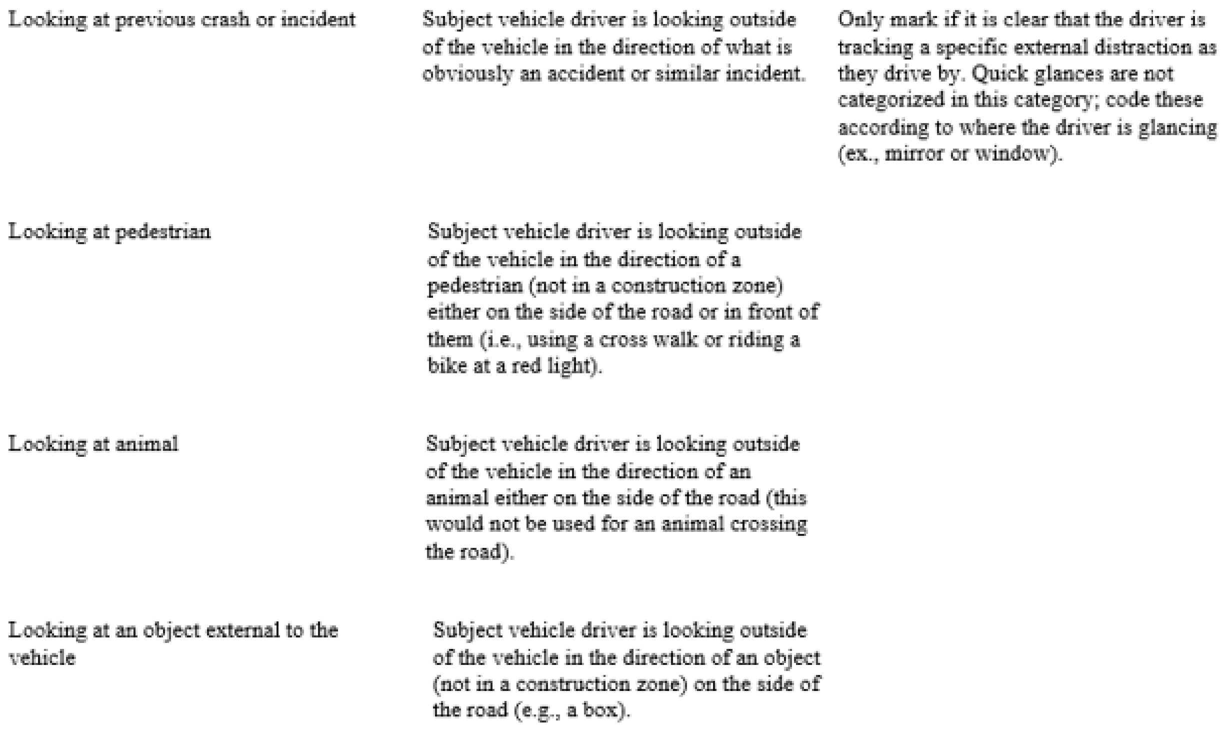
APPENDIX A

Secondary Task Definitions from SHRP2 Event Detail Table Data Dictionary

SECONDARY TASKS

Talking/singing, audience unknown	Subject vehicle driver is moving lips as if talking or singing, the interaction is not believed to be with a passenger. This category includes whistling, and also includes possible or suspected cases of hands-free cell phone use. (See "Cell phone, Talking/listening, hands free" category for further information.) This category does not include the driver talking to a pedestrian or other known party outside the vehicle, which should be coded as the appropriate external distraction.	Driver may or may not also be interacting with a passenger, but this Secondary Task involves singing with radio, talking to self, using a cell phone through a hands-free medium, etc.
Passenger in adjacent seat - interaction	A front seat passenger is visible or not visible, but the subject vehicle driver is clearly interacting with a passenger (other than a child) in the adjacent/front seat. This could be talking, listening, reacting to (i.e., laughing), gesturing towards, moving toward or away from the passenger, or reaching to take something from or give something to the passenger. If age of passenger is unable to estimate, use this category.	Use this distraction if you can see the front seat passenger (other than a child) in the camera or the driver is talking and looking in the direction of the front passenger seat. Entire trip file or segment may be used to look for evidence of passenger. Consider this distraction as long as the driver and passenger both remain in the vehicle (even if the car stops or is idling).
Passenger in rear seat - interaction	A rear seat passenger (other than a child, or age unable to estimate) is visible or not visible, but the driver is clearly interacting with a passenger (other than a child) in the rear seat. This could be talking, listening, reacting to (i.e., laughing), moving toward or away from the passenger, or reaching for the rear seat passenger. If age of passenger is unable to estimate, use this category.	Use this distraction if you can see the rear seat passenger (other than a child) in the camera or the driver is talking and looking in the direction of the rear seat. May also use the rear view to view the rear seat passenger. Entire trip file or segment may be used to look for evidence of passenger. Consider this distraction as long as the driver and passenger remain in the vehicle (even if the car stops or is idling).
Cell phone, Talking/listening, hand-held	Subject vehicle driver is talking on a handheld phone or has phone up to ear as if listening to a phone conversation or waiting for person they are calling to pick up the phone. If driver has an earpiece or headset, the driver must be observed talking repeatedly.	

Cell Phone, Texting	Subject vehicle driver is pressing buttons or a touch screen on the cell phone to create and/or send a text message.	
Cell Phone, Dialing hand-held	Subject vehicle driver is pushing number buttons on a cell phone or touch screen to dial a number or browse/check something else on their cell phone (this would also include reading the phone number from a sheet of paper).	If unsure whether driver is texting or dialing/browsing, code as dialing.
Adjusting/monitoring other devices integral to vehicle	Subject vehicle driver interacts with a manufacturer-installed device other than those listed in other categories, either by touching or glancing at the device. Does not include driving-critical tasks, such as turn signal, wipers, headlights, gear shift, speedometer.	Includes interaction with seat belt, door locks, window controls, Navigation system, sun visors, rear view mirror, etc. Does not include retrieving objects inside storage compartments.
Reaching for food-related or drink-related item	Subject vehicle driver is looking for or reaching for any item related to eating or drinking. If the driver is already in the process of eating, and is just picking up food repeatedly to put in mouth, code as the appropriate eating category. This reaching task is for the initial locating, reaching, and preparing food or drink to be eaten.	Ex. reaching for cup, utensils, plate, food. Once the item is in hand and being moved with the intent to use, code as appropriate usage category (e.g., eating).
Reaching for cigar/cigarette	Subject vehicle driver reaches or starts to glance around for cigar/cigarette or related items.	Once the item is in hand and being moved with the intent to use, code as appropriate usage category (e.g., lighting).
Reaching for personal body-related item	Subject vehicle driver is reaching for any item related to personal hygiene, health, or adornment.	Ex. reaching for comb, brush, makeup, razor, dental floss, contact lenses, glasses (not currently being worn), hat (not currently being worn). Once the item is in hand and being moved with the intent to use, code as appropriate usage category.
Reaching for object, other	Subject vehicle driver reaches for an object not described in any other category. Includes objects in storage compartments.	Once the driver has finished reaching for the object and has it in hand (if not being moved for intended usage), then it becomes "object in vehicle, other," as long as it doesn't fit into any of the other categories (e.g., eating, drinking, etc.)



Looking at previous crash or incident	Subject vehicle driver is looking outside of the vehicle in the direction of what is obviously an accident or similar incident.	Only mark if it is clear that the driver is tracking a specific external distraction as they drive by. Quick glances are not categorized in this category; code these according to where the driver is glancing (ex., mirror or window).
Looking at pedestrian	Subject vehicle driver is looking outside of the vehicle in the direction of a pedestrian (not in a construction zone) either on the side of the road or in front of them (i.e., using a cross walk or riding a bike at a red light).	
Looking at animal	Subject vehicle driver is looking outside of the vehicle in the direction of an animal either on the side of the road (this would not be used for an animal crossing the road).	
Looking at an object external to the vehicle	Subject vehicle driver is looking outside of the vehicle in the direction of an object (not in a construction zone) on the side of the road (e.g., a box).	

APPENDIX B

Prevalence Data for all Task Combinations

Table 8. Overall prevalence percentages

TASK	SINGLE	ADJUST	TEXT	DIAL	REACH	LOOK
IINTERACT/ TALK/SING	16.36	0.11	0.08	0	0.08	0.11
CELL TALK	2.70	0	0.005	0.05	0	0.02
ADJUST	0.44		0.01	0	0.01	0.01
TEXT	1.44			0	0.01	0
DIAL	0.05				0	0
REACH	0.40					0.005
LOOK	0.58					

Table 9. Young group prevalence percentages

TASK	SINGLE	ADJUST	TEXT	DIAL	REACH	LOOK
IINTERACT/ TALK/SING	18.63	0.09	0.14	0	0.09	0.11
CELL TALK	3.72	0	0.01	0.07	0	0.02
ADJUST	0.37		0.02	0	0.01	0.01
TEXT	2.52			0	0.02	0
DIAL	0.06				0	0
REACH	0.32					0.01
LOOK	0.41					

Table 10. Middle group prevalence percentages

TASK	**SINGLE**	**ADJUST**	**TEXT**	**DIAL**	**REACH**	**LOOK**
IINTERACT/ TALK/SING	14.15	0.10	0.03	0	0.05	0.10
CELL TALK	2.82	0	0	0.02	0	0.02
ADJUST	0.46		0	0	0	0
TEXT	0.96			0	0	0
DIAL	0.08				0	0
REACH	0.50					0
LOOK	0.64					

Table 11. Older group prevalence percentages

TASK	SINGLE	ADJUST	TEXT	DIAL	REACH	LOOK
IINTERACT/ TALK/SING	14.70	0.16	0	0	0.11	0.11
CELL TALK	0.56	0	0	0	0	0.02
ADJUST	0.54		0	0	0.02	0.02
TEXT	0			0	0	0
DIAL	0.02				0	0
REACH	0.42					0
LOOK	0.83					