The Multitasking Motorist

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In this chapter, we consider multitasking in the context of driving to involve the performance of two or more *functionally independent tasks* with separate goals, stimuli, and responses.[1] We contrast this definition with performing *functionally interdependent tasks* that serve common or overlapping goals. The concurrent use of a smartphone while operating a motor vehicle epitomizes everyday multitasking. At any given daylight moment, 9.7% of the driving public in the United States can be seen holding their smartphone to talk or text while operating a motor vehicle (DOT 2019). Drivers also use Bluetooth-enabled in-vehicle infotainment systems to perform a variety of secondary tasks (Strayer et al. 2019). This ubiquitous multitasking activity distracts drivers and leads to increases in injuries and fatalities on our roadways (WHO 2011). Note that the driving task and the smartphone task are functionally independent. They have separate goals (transportation vs. communication) with distinct stimuli (the driving environment vs. the content of the conversation) and responses (e.g., steering and braking vs. talking and listening). By contrast, interdependent tasks support the same overall goal (e.g., maintaining vehicle control through speed and space management by looking at the speedometer and adjusting the accelerator to control vehicle speed and making steering inputs to stay in the lane of travel).

[1] We use the terms multitask and dual task interchangeably in this chapter. A dual-tasking situation is one in which participants perform two functionally independent tasks. Multitasking is a more generalized term in which participants concurrently perform two *or more* independent tasks.

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The limits of human attention govern both functionally independent tasks and interdependent tasks. They also both can lead to impairments in driving performance when they are performed concurrently with the task of driving. Regan et al. (2011, p. 1776) defined the distraction created by performing functionally independent tasks (i.e., "*driver diverted attention*") as "the diversion of attention away from activities critical for safe driving toward a competing activity, which may result in insufficient or no attention to activities critical for safe driving." In the smartphone example described above, talking and texting are unrelated activities that divert attention away from the primary task of driving. Regan et al. (2011, p. 1975) defined the impairment from performing functionally interdependent tasks (i.e., "*driver misprioritized attention*") as "insufficient or no attention to activities critical for safe driving brought about by the driver focusing attention on one aspect of driving to the exclusion of another, *which is more critical for safe driving*." In the second example described above, looking at the speedometer (a less critical activity) may divert attention from the more critical task of lane maintenance. The essential difference between these two categories stems from whether attention is directed away from safety-critical aspects of driving to a secondary task that is unrelated to driving (i.e., an independent task) or to a secondary task that is related to driving but is less critical to roadway safety (i.e., an interdependent task).

Herein we consider the safety-critical aspects of driving to be the *primary task*. When performed concurrently, activities unrelated to or less safety-critical than driving become *secondary tasks*. However, this distinction is somewhat arbitrary, as one could easily imagine the perverse situation in which the driver considers the conversation to be the primary task and driving to be secondary. Some oblivious drivers may even think that the task of driving gets in the way of conversing when safety considerations, state laws (GHSA 2020), and common sense dictate that driving should be the primary task.

When motorists perform a secondary task, the attention allocated to the more safety-critical aspects of the driving task decreases. Given the limited pool of attentional resources (Kahneman 1973), there is a reciprocal relationship between the attention allocated to the primary and secondary tasks—as the cognitive demands of the secondary task increase, the allocation of attention to the core driving task decreases (Navon and Gopher 1979). Importantly, secondary tasks vary in both mental and temporal demand. Some secondary tasks are relatively easy and are performed quickly, whereas other secondary tasks are much more cognitively demanding and take considerably longer to perform. Consequently, there is a wide variation in the effects of multitasking on driving performance.

1 SPIDER

As motorists navigate their vehicle from one location to the next, they must maintain good speed and space management, identify and react to actual threats, identify potential hazards, and follow information governing traffic flow (e.g., obey traffic lights). Many of the essential activities that a driver performs depend on attention; to be safe, a driver must "pay attention" to the driving environment. Strayer and Fisher (2016) developed a model that summarizes the literature and characterizes many of the impairments to driving that occur when a driver multitasks. The model called SPIDER is an acronym that stands for **S**canning, **P**redicting, **I**dentifying, **D**eciding, and **E**xecuting **R**esponses. As illustrated in Fig. 1, the driving literature establishes that each of these cognitive operations is impaired when drivers multitask, and consequently, multitasking results in an impairment to the motorist's awareness of the driving environment (i.e., their situation awareness).

Scanning Drivers must visually scan the driving environment to navigate safely, stay in their lane of travel, and avoid obstacles. This term includes looking at the forward roadway, scanning the periphery, glancing at side and rear-view mirrors, and monitoring the instrument cluster. When a driver multitasks, they tend to narrow their gaze to a restricted region of the forward roadway, often neglecting the other sources of visual information that are critical to safe driving (e.g., Briggs et al. 2017; Engström et al. 2005; Harbluk et al. 2007; He et al. 2011; Horrey et al. 2006; Recarte and Nunes 2000; Reimer 2009; Reimer et al. 2012; Strayer et al. 2017; Tsai et al. 2007; Victor et al. 2005). Others have referred to this facet of driver behavior as *gaze concentration* or *visual tunneling* (e.g., Reimer 2009; Wang et al. 2014).

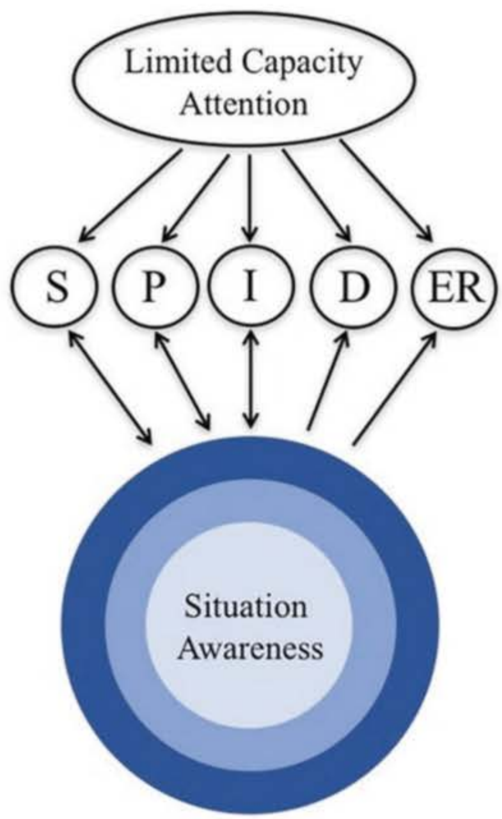

Fig. 1 The SPIDER model is an acronym for **S**canning, **P**redicting, **I**dentifying, **D**eciding, and **E**xecuting a **R**esponse. Multitasking diverts attention from driving, causing the motorist's situation awareness to be reduced. This is illustrated by progressively smaller and lighter-shaded concentric circles. The bidirectional arrows show that situation awareness is informed and updated by the SPIDER-related processes (i.e., scanning, predicting, and identifying) and facilitates expectancy-based processing of the driving scene. The loss of situation awareness impairs driving performance and increases the relative risk of a crash

Predicting Hazard prediction is an essential component of safe driving. To avoid being caught in the moment, motorists must use their driving experience to anticipate where potential threats might arise. For example, when passing a bus stopped adjacent to a crosswalk, an experienced motorist often looks at locations where pedestrians could cross in front of the bus. Notably, anticipatory glances associated with hazard prediction move to locations where a *potential* hazard may appear (i.e., these are glances to a location). Multitasking drivers show deficits in this anticipatory behavior, often exhibiting hazard prediction behavior more similar to that of a novice driver (Taylor et al. 2015). In an on-road study, Biondi et al. (2015) found that multitasking impaired the likelihood of making a glance to check for pedestrians in a crosswalk.

Identifying A driver must attend to the visual input to determine what they are looking at. Attention is necessary to transfer this information into working/short-term memory (e.g., Atkinson and Shiffrin 1968). Multitasking drivers often fail to see objects in their line of sight, leading to a phenomenon referred to as *inattentional blindness* (Mack and Rock 1998; Simons and Chabris 1999; Strayer et al. 2003; Strayer and Johnston 2001). For example, Strayer et al. (2004) found that drivers failed to identify up to 50% of the information they looked at (as verified using eye-tracking measures) when they were conversing on a hands-free cell phone.

Deciding Drivers are often faced with deciding between two or more options. For example, in the lane change task (ISO DIS 26022 2010), drivers must decide when to shift from the center lane of travel to either the left lane or the right lane. When drivers multitask, they often fail to fully evaluate the alternative sources of information. Indeed, Cooper et al. (2009) found that multitasking drivers were more likely to make unsafe lane changes. Cooper and Zheng (2002) also found that multitasking drivers were more likely to misjudge the gap size and the speed of oncoming vehicles, and this deficit was most apparent on wet roadways.

Executing Response When faced with an unexpected event, motorists are often required to take evasive action (e.g., make steering or braking response). When drivers multitask, these actions often become delayed (Atchley et al. 2017; Caird et al. 2008; Horrey and Wickens 2006). Moreover, multitasking tends to positively skew the brake RT distributions so that late responses become particularly slow (Ratcliff and Strayer 2014). These sluggish brake reactions increase the likelihood and severity of crashes (Brown et al. 2001).

Situation Awareness A motorist's mental model of the driving environment—their situation awareness—is governed by the SPIDER-related processes (see Fig. 1). When drivers multitask, their situation awareness can become compromised (e.g., Durso et al. 2007; Endsley 1995, 2015; Horrey et al. 2006; Kass et al. 2007). The degradation of situation awareness depends upon both the mental and temporal demands of the secondary task being performed. Greater impact occurs with longer and more demanding secondary tasks. In Fig. 1, the bidirectional arrows from scanning, predicting, and identifying to situation awareness correspond to Endsley's (1995) three levels of situation awareness. Level 1 situation awareness relates to the perception of elements in the current situation. Level 2 situation awareness relates to comprehension of the current situation. Level 3 situation awareness relates to the prediction of the situation's future status. The bidirectional links indicate a recurrent process where scanning, predicting, and identifying update the driver's mental model, which can serve as a basis for adjustments in the amount of attention allocated to each of these processes. The fidelity of a motorist's awareness of the driving situation governs their decisions and the speed of their responses.

Endsley (1995) discusses how even small lapses in situation awareness result in poor performance. As illustrated in Fig. 1, greater demands on limited-capacity attention (caused by multitasking) result in impairments to the SPIDER-related processes and decrements in a motorist's situation awareness. Greater secondary-task demand results in lower levels of situation awareness. Figure 1 represents this effect with progressively smaller and lighter concentric circles. In their simulations, Fisher and Strayer (2014) found that a 5% decrease in the likelihood of any of the SPIDER-related processes being completed successfully would double the relative risk of a crash.

2 Measurement of Cognitive Distraction

Strayer et al. (2015) measured the effects of a variety of secondary tasks on a driver's workload. Simple tasks like listening to a radio or an audiobook were associated with low cognitive demand and did not adversely impair driving performance. By contrast, conversation tasks (e.g., talking to an interlocutor sitting next to the driver or conversing on a hand-held or hands-free cell phone) led to significantly higher levels of workload and greater impairments to driving than listening to the radio or audiobook.

Conversation is a dynamic process that involves both speech comprehension and speech production. Strayer et al. (2017) measured the cognitive workload of the conversational dyad (i.e., driver and non-driver) as they engaged in a natural conversation. The authors evaluated both an in-person (i.e., a passenger conversation) and a remote hands-free cell phone conversation. To obtain dynamic measures of workload, these authors used a specially configured version of the detection response task (DRT; International Standards Organization (ISO DIS 17488 2015)). Every 3–5 seconds, "yoked" DRT devices (one fitted to the driver and one fitted to the non-driver) flashed a light in the peripheral field of view of the left eye of each member of the conversational dyad. Both the driver and non-driver responded separately to the onset of the light by pressing a microswitch attached to their finger. Additionally, each DRT was equipped with a microphone to determine if the driver or non-driver was talking or listening at any point in time.

The DRT is very sensitive to dynamic fluctuations in mental workload; RT increases as the cognitive demands of a task increase.[2] In Fig. 2, the mental load of the driver is represented by the solid line. The "single task" refers to the DRT measurements obtained from the driver when they are performing the primary task of operating the vehicle (i.e., the driver was not multitasking). Note that when the driver begins to multitask by concurrently conversing with the non-driver, DRT reaction time systematically increases. Importantly, the increase in reaction time is the same for both the passenger conversation (i.e., when both the driver and non-driver are seated in the same vehicle) and cell phone conversation (i.e., when the conversational dyad is not in the same location).[3] Moreover, DRT reaction time is longer when the driver is talking (i.e., DT) than when they are listening (i.e., DL). A reciprocal pattern can be observed in Fig. 2 with the non-driver (depicted by the dotted line). Here again, DRT reaction time is equivalent for passenger and cell phone conversations, and it is longer when the driver is listening (and the non-driver is talking) than when the driver is talking (and the non-driver is listening).

The dynamic fluctuation in workload observed for both the driver and non-driver indicates that speech production is, on the whole, more demanding than speech comprehension. When the driver attempts to converse while operating their vehicle (i.e., when they multitask), their workload is higher than that of the non-driver. That is, the conversational dyad produces a pattern of resource reciprocity and the data indicate that driving competes for the same limited resources as the conversation. Also noteworthy is the ebb and flow of the multitasking costs with the dynamics of an unfolding conversation.

Subsequent research measuring the effects of a secondary task on a driver's workload has found that using a smartphone to interact with an intelligent personal

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[2] The DRT involves presenting a simple stimulus every 3–5 seconds and requiring drivers to make a simple button press (i.e., the DRT is a simple RT task). The DRT is an ISO protocol (ISO DIS 17488 2015) for measuring a driver's workload, but it clearly adds another unrelated task to the mix that has the potential to alter the driver's performance, thereby creating an example of the Heisenberg principle where measuring workload may alter the driver's behavior. In fact, Castro et al. (2019) found that the introduction of the DRT with an easily perceived light slightly degraded pursuit tracking performance, but not as much as a light that was more difficult to perceive or when the DRT task was changed from a simple RT task to a choice RT task. By contrast, Strayer et al. (2015) found that subjective workload was not altered with the introduction of the DRT and, in another context, Palada et al. (2019) found that the DRT did not interfere with the primary task of classifying maritime ships as friend of foe. On the whole, there is little evidence that the DRT significantly alters performance of the primary driving task. Nevertheless, care must be taken with the use of the DRT to ensure that the protocol does not introduce a confound in the experimental design.

[3] Despite the fact that the cognitive workload experienced by the driver is the same for cell phone and passenger conversations, the risk of a motor vehicle crash is considerably higher for the former (i.e., the odds ratio of a crash when conversing on a cell phone is 4.2; McEvoy et al. 2005; Redelmeier and Tibshirani 1997) than for the latter (i.e., the odds ratio of a crash is 0.7 when an adult passenger is in the vehicle; Rueda-Domingo et al. 2004; Vollrath et al. 2002). This discrepancy can be explained, in part, by the fact that adult passengers often support the driver by pointing out hazards and helping the driver to navigate (Drews et al. 2008).

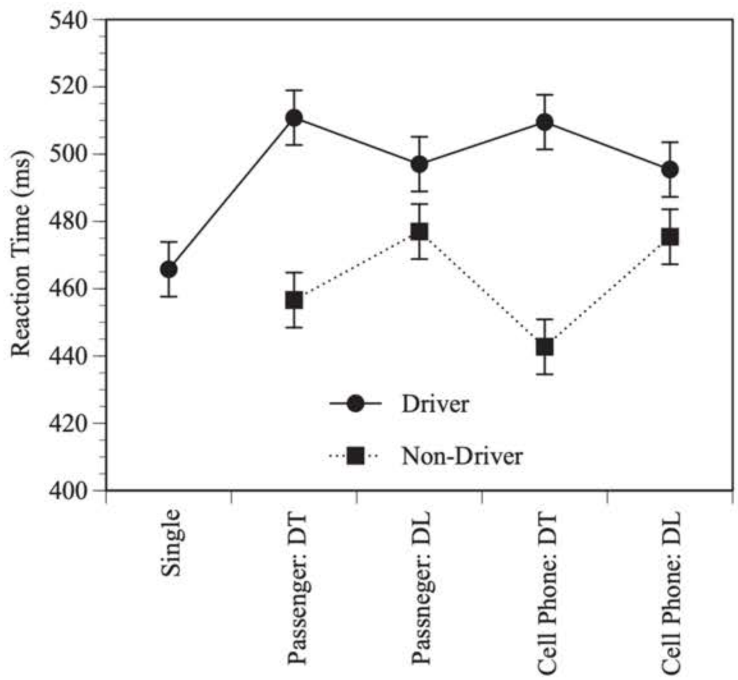

Fig. 2 Reaction time for the driver and non-driver when they respond to the DRT. Error bars reflect the standard error of the mean. The single-task condition reflects performance when the driver is driving and not conversing. The "passenger" conditions reflect a conversation when both members of the dyad were seated in the same vehicle. The "cell phone" conditions refer to a remote hands-free cell phone conversation. DT refers to situations when the driver is talking and the non-driver is listening. DL refers to situations where the driver is listening and the non-driver is talking

assistant (e.g., Apple's *Siri*, Google's *Google Now,* and Microsoft's *Cortana*) resulted in even higher levels of cognitive workload than conversation tasks (Strayer et al. 2017). In fact, using an intelligent personal assistant to send simple text messages resulted in the same cognitive load as performing an auditory version of the mind-numbing Operation Span (OSPAN) Task[4] while driving (Watson and Strayer 2010), well above any reasonable red line of workload (Grier et al. 2008). Taken together, there is considerable variability in the mental workload associated with different multitasking operations.

When motorists multitask, their awareness of the driving environment degrades over time (e.g., for a review, see Strayer and Fisher 2016), and they are less able to react to unexpected events. Figure 3 depicts a model of the loss and recovery of attention to driving across a multitasking episode.[5] In the figure, the diameter of the

[4]The OSPAN task is a complex memory span task developed by Turner and Engle (1989) that requires participants to hold items in memory while concurrently solving simple math problems and then to recall the memorized items in the order that they were presented.

[5]Figure 3 presents a conceptual depiction of the bandwidth of the information processing system of the driver based upon the mathematical framework of signal processing developed by Claude

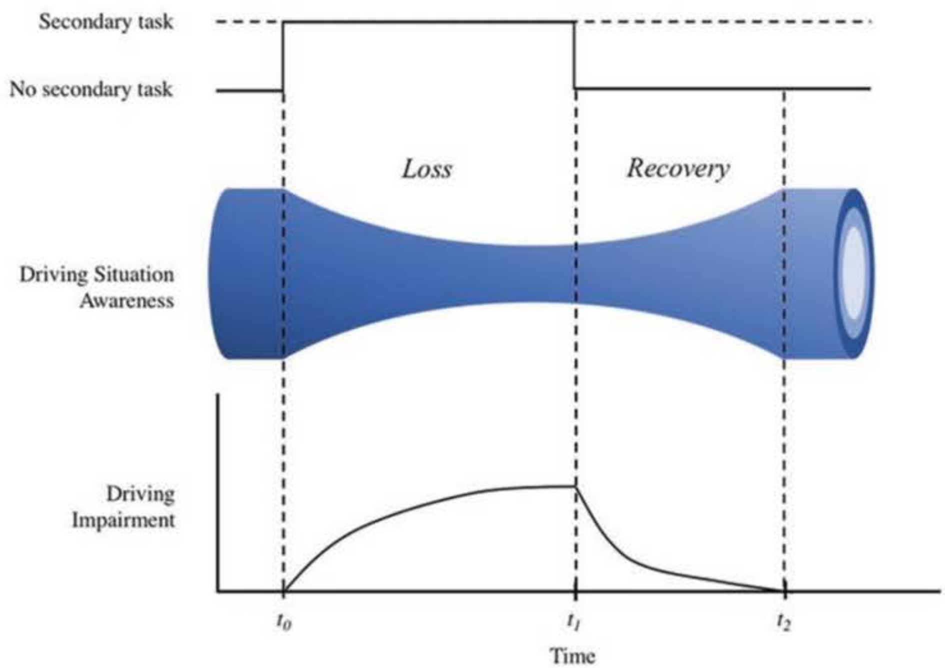

Fig. 3 Dynamic fluctuations in attention plotted as a function of a multitasking episode. The diameter of the cylinder reflects the amount of attention allocated to the driving task. The larger the diameter, the greater the amount of attention allocated to the driving task

cylinder represents the moment-to-moment level of capacity allocated to driving, with a larger diameter indicating more attention to the driving task. In the period preceding t_0, the motorist is shown performing the single-task of driving and attention allocated to the task is high. At t_0, the driver begins to engage in an attention-demanding secondary task (i.e., they begin to multitask), and attention is diverted from the processes requisite for safe driving. Driving impairments from multitasking grow between t_0 and t_1. At t_1, the motorist stops performing the secondary task, and attention is redirected to the primary task of driving. Impairments to driving dissipate between t_1 and t_2. At t_2, attention has been fully returned to the driving task (i.e., performance has returned to single-task levels). The model shown in Fig. 3 has symmetrical loss and recovery functions; however, this is not a requirement of the model.

Shannon (1948). The greater the bandwidth or channel capacity of a system (depicted in Fig. 3 by the diameter of the cylinder), the more information that can be processed per unit time. Information theory (e.g., Hick 1952; Hyman 1953) describes the relationship between bandwidth, processing speed, and also the loss of information due to capacity limits (e.g., bottlenecks in information processing due to multitasking that can lead to impaired driving). In Fig. 3, the bandwidth of processing of the driving task is reduced between t_0 and t_2 because attention has been diverted to a secondary task.

3 Persistence of Distraction

The recovery from multitasking can be empirically determined by plotting the residual costs following a multitasking episode. Strayer et al. (2016) used the DRT procedure described above (i.e., probing randomly every 3–5 seconds) to measure the residual costs after a driver issued a voice command to tune the radio or to place a phone call. These voice-based features are common in new automobiles and often involve pushing a button on the steering wheel and then speaking a command (e.g., tune the radio to 90.1 FM). Figure 4 presents the residual costs plotted in 3-second intervals across the post-multitasking window. For comparison, the red "O" represents DRT performance when participants were driving and concurrently performing the OSPAN task and the red "S" indicates DRT performance in the single-task driving condition. The red dotted line marks the level at which DRT performance was significantly greater than the single-task baseline. The best-fitting power function, plotted in blue, shows large costs immediately after the multitasking episode had finished. These costs dissipate as a negatively accelerated function of time over the 30-second post-multitasking window. In fact, 3 seconds after multitasking stopped, the residual costs were the same as when drivers had been concurrently performing the OSPAN task. The residual costs were significantly different from single-task baseline 27 seconds after multitasking had terminated. It is noteworthy that the residual costs observed in this study lasted longer than the actual multitasking episode.

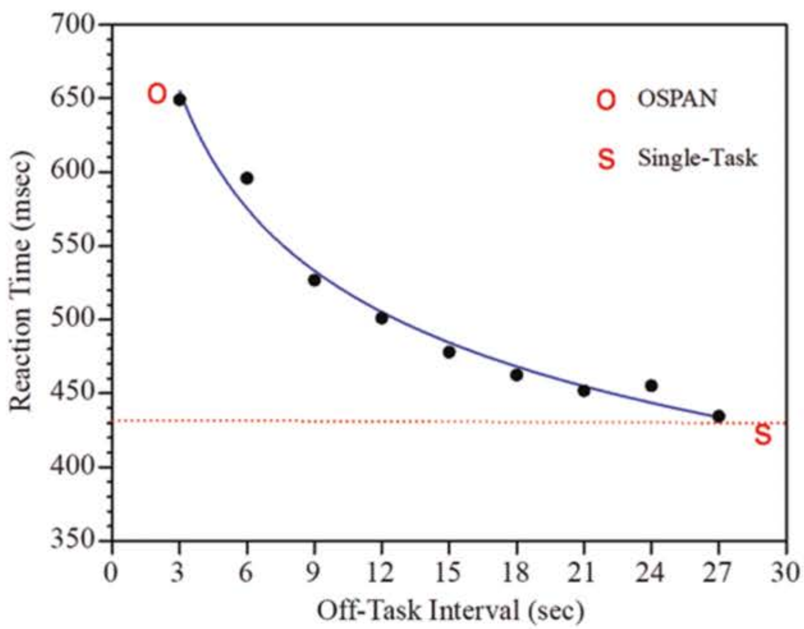

Fig. 4 Residual costs as measured by the DRT following a multitasking episode. For comparison, O indicates performance when concurrently performing the OSPAN task and S reflects performance on the single-task of driving

In reference to Fig. 3, the interval between t_1 and t_2 was 27 seconds for drivers using these common in-vehicle voice commands. These multitasking costs were hidden because there was no overt secondary task being performed by the driver when they were obtained. The DRT methodology provides a valuable tool to unveil these hidden multitasking costs by probing throughout the drive. However, Jenness et al. (2015) reported a similar recovery pattern with measures of driving performance (e.g., steering inputs and driving speed) and Turrill et al. (Submitted) observed residual costs in eye-tracking measures (e.g., pupil diameter, which has been found to vary with mental workload; Ahern and Beatty 1979; Beaty and Lucero-Wagoner 2000; Kahneman and Beatty 1966).

These behavioral and physiological measures establish that the residual costs are not an artifact produced by the DRT methodology. Turrill et al. (Submitted) also found that the duration of the residual costs following a multitasking episode (i.e., the interval between t_1 and t_2 in Fig. 3) was modulated by driving difficulty (manipulated by traffic density in a driving simulator) and secondary-task load (manipulated by counting backward by 1s or 3s). By contrast, Turrill et al. (Submitted) found that the impairments were apparent shortly after initiating the multitasking episode (i.e., the interval between t_0 and t_1 in Fig. 3). This demonstrates that the loss and recovery functions depicted in Fig. 3 are, in fact, asymmetrical. The impairments are manifested soon after multitasking begins whereas the recovery from multitasking takes about half a minute (or more) to dissipate.

It is worth considering the mental operations associated with starting and stopping a multitasking episode. When starting to multitask, motorists must load the secondary-task goals and procedures into working memory and then hold and manipulate that information (Baddeley and Logie 1999; Engle 2002). They must juggle the two tasks, switching between them to support the task demands (e.g., Salvucci 2006; Salvucci and Taagen 2008). Turrill et al. (Submitted) found that it took just a few seconds for participants to get a secondary counting task going. For simple dual-task combinations (e.g., counting backward by 1s while performing a simple pursuit tracking task), the dual-task costs were apparent within 3 seconds (i.e., within the resolution of the DRT measurement procedure). With more complex dual-task combinations (e.g., counting backward by 3s while driving a simulated vehicle in high-density traffic), dual-task costs were fully apparent by 6 seconds. A reasonable interpretation of these data is that the goals and procedures supporting counting backward by 3s take longer to load and manipulate in working memory than counting backward by 1s. This interpretation is supported by subjective reports from participants that it took longer and was harder to get the more demanding counting task underway.

As of 2020, 48 states prohibit texting while driving (IIHS 2020). Although the laws vary state by state, the majority prohibit texting while driving, even if stopped at a red light. Motorists may wonder why smartphone use is prohibited when the vehicle is stopped. What could possibly go wrong if the vehicle is stopped? The residual costs shown in Fig. 4 provide a rationale for why texting at red lights is unsafe. When the light turns green, drivers may proceed into the intersection with impaired situation awareness (Strayer and Fisher 2016) and the residual costs from multitasking are likely to persist for the duration of the transit through the intersection. The impaired situation awareness means that multitasking motorists are often unaware of pedestrians, bicycles, and other obstacles on the roadway and in the crosswalk. Rates of injuries and fatalities to pedestrians and bicyclists have seen a sharp uptick in recent years, due at least in part to drivers multitasking at intersections. In fact, since 2009, pedestrian fatalities have risen by 53% (IIHS 2018). A portion of the increase in fatalities is also likely due to multitasking pedestrians who also use their smartphones when crossing the road. They also suffer from a loss of situation awareness and may step into the crosswalk without looking to see if it is safe to do so. Indeed, in 2017, the city of Honolulu enacted a prohibition of pedestrians using their smartphones while crossing the street (Honolulu 2017).

4 Threaded Cognition

Salvucci and Taagen (2008) developed a *threaded cognition* theory of multitasking to account for the costs incurred when people concurrently perform unrelated tasks such as driving and counting backward (or conversing on a smartphone). Based on the ACT-R (Adaptive Control of Thought-Rational) architecture, threaded cognition assumes that a serial cognitive processor coordinates the multiple task "threads" associated with currently active tasks. The theory instantiates an "exclusive-use" rule whereby requests for processing for other threads must wait until the completion of the current process. A procedural bottleneck arises when competition for the exclusive-use cognitive processor occurs. The exclusive-use rule causes behavior to be restricted to a single thread, a feature of cognition likely to minimize crosstalk between multiple task threads (e.g., Bergen et al. 2013). Threaded cognition posits that task threads acquire processing resources in a "greedy" fashion and release them "politely." A greedy thread requests processing resources as soon as possible when they are needed, although the thread may have to wait its turn because of the exclusive-use rule. A polite thread releases resources for other threads as soon as its processing is no longer required. Finally, the task threads are prioritized so that the least recently processed thread receives priority.

Because the cognitive processer operates on an exclusive-use rule, combining an attention-demanding secondary task with driving results in contention for cognitive processes and suboptimal driving performance (as well as suboptimal performance on the attention-demanding secondary task). Effectively, the current task thread locks out other threads from the central processor until processing on the current thread has been completed. An example of this bidirectional interference is apparent in Fig. 2. Relative to the single-task driving condition (i.e., that of the driver) and the single-task conversation (i.e., that of the non-driver), performance on both tasks was degraded when the driver attempted to combine them. This pattern in Fig. 2 is consistent with the prediction that the conversation thread locks out the driving thread and the driving thread locks out the conversation thread.[6]

The robust residual costs following a multitasking episode depicted in Fig. 3 are much larger than would be expected from the psychological refractory period (PRP; Pashler 1994, 2000) or task switching (e.g., Rogers and Monsel 1995) literature. It is noteworthy that these residual costs were observed with DRT measurements (both RT and hit rate to the DRT stimulus) when a real-world driving task was paired with voice-based interactions in the vehicle. They were also observed with a simple pursuit-tracking task and with a high-fidelity driving simulator when participants drove and performed a backward counting task. Additionally, they were observed with measures of driving performance and with physiological measures.

The residual costs presented in Fig. 3 are inconsistent with the concept of a "polite" thread that releases resources as soon its processing is no longer required (Salvucci and Taagen 2008, p 110). It would appear that the threads are anything but polite, with residual costs persisting for half a minute or more. It is possible that the DRT measures reflect the motorists "catching up" on driving threads that have been neglected during multitasking. For example, a driver's situation awareness degrades over the multitasking episode (Strayer and Fisher 2016). Once the secondary-task thread has terminated, processing resources may be returned to the driving task to refresh the mental model of the driving environment.

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[6] The pattern presented in Fig. 2 was obtained using the DRT protocol. This protocol involves presenting a simple stimulus and requiring the driver to make a simple button press (a simple RT task) and, as discussed above, the procedure causes little or no interference with other ongoing tasks. How would threaded cognition account for the sensitivity of the DRT to primary and secondary-task demand? One possibility would be that a DRT thread gets added to the goal buffer. For example,

IF the goal buffer contains a triple task (e.g., the driving task, a secondary-task, and the DRT task)

THEN add the goal to perform the driving task
and add the goal to perform the secondary task
and add the goal to perform the DRT task.

…

If the goal buffer contains the DRT task
and the DRT stimulus has been presented
Then issue the DRT motor response.

The exclusive-use rule would cause the DRT thread to wait its turn in the goal buffer until other threads had been completed. Consequently, the more demanding the driving task and/or the more demanding the secondary task, the longer the latency of the DRT response. Note that because of the simplicity of the DRT task, the DRT thread should take few processing resources and would therefore produce little interference with the primary and secondary tasks. However, the rule that the least recently processed thread receives priority would seem in need of modification to a first-in, first-out rule. Otherwise, the intermittent DRT task would take priority over the continuous driving and secondary tasks. This follows because, when paired with continuous tasks (e.g., driving and conversing), the DRT would often be the least recently processed thread and would take priority over the other tasks. Under such a scenario, the DRT would be insensitive to primary- and secondary-task difficulty. Because the DRT is very sensitive to primary- and secondary-task difficulty, the DRT thread must wait its turn in the goal buffer.

One potential source of evidence for enhanced driving-related processing in the post-multitasking interval could come from eye-tracking measures. It is well established that drivers concentrate their gaze toward the center of the roadway when they perform a cognitively demanding secondary task (e.g., Harbluk et al. 2007; Victor et al. 2005). Informative glances to side mirrors and to the periphery decrease while multitasking. Turrill et al. (Submitted) examined visual scanning patterns in the pre-multitasking, multitasking, and post-multitasking intervals (i.e., prior to t_0, from t_0 to t_1, and from t_1 to t_2 in Fig. 3, respectively) to see if there was an increase in peripheral scanning once the secondary task had terminated. However, instead of enhanced peripheral visual scanning, the pattern revealed was that of a gradual return to single-task levels similar to the pattern in Fig. 3. No evidence appeared in the eye-tracking measures that drivers attempted to "catch up" with enhanced visual scanning in the periphery once the secondary task had stopped. Moreover, the residual costs were also observed in a simple pursuit-tracking task where there was little, if any, situation awareness to regain after multitasking. Although the absence of evidence is not evidence of absence, we found no direct evidence to support the "catch-up hypothesis."[7]

If motorists are not catching up on driving threads neglected while multitasking, what is the source of the residual costs? One possibility is that there is a passive decay of the information held in working memory associated with the completed secondary task. Whereas Turrill et al. (Submitted) found that loading information into working memory occurred relatively quickly, the purging of this information appears to be more gradual (i.e., similar to that of the Brown-Peterson short-term memory forgetting functions, Brown 1958; Peterson and Peterson 1959). This now irrelevant information continues to occupy valuable space in working memory and cause interference and crosstalk with the information necessary for driving. Evidence supporting the passive decay hypothesis comes from eye-tracking measures that show a gradual decrease in pupil dilation over the post-multitasking interval (Turrill et al. Submitted). The eye-tracking measures suggest a gradual decrease in cognitive interference as the secondary-task information decays.

5 Crosstalk Hypothesis

William James was one of the first to comment on the fact that the more similar two tasks are, the more they are likely to interfere with each other when they are performed concurrently (James 1890). The crosstalk hypothesis suggests that dual-task

[7] The residual costs were observed in the DRT and in measures of pupil diameter. Importantly, Jenness et al. (2015) reported residual costs in steering inputs and driving speed, measures of performance obtained with the primary task of driving. Perhaps the strongest evidence that more than "catching up" is happening in the post-multitasking interval comes from the fact that similar residual costs are observed in a simple pursuit-tracking task where there is little if any situation awareness to recover.

interference occurs when two tasks use similar or overlapping information that come into conflict (e.g., Bergen et al. 2013; Navon and Miller 1987; Pashler 1994). Crosstalk, sometimes described in the literature as "code conflict," can occur in perception, in working memory, and in motor output. Similar (but functionally independent) tasks using similar information can be confusing for the information processing system to sort out. For example, in threaded cognition (Salvucci and Taagen 2008), the different task threads could act upon the wrong information held in working memory. When multitasking stops, the (now) irrelevant secondary-task information slowly fades from working memory and crosstalk diminishes.

Bergen et al. (2013) differentiated between *domain-general interference*, brought about by a competition for limited attentional resources (e.g., Kahneman 1973) and *domain-specific interference*, brought about by concurrent demands on the "mental machinery." Crosstalk is an example of domain-specific interference. Bergen et al. (2007) provide an example of crosstalk where the spatial and linguistic aspects of visual imagery compete because they place demands on the same neural hardware. Crosstalk occurs while multitasking when the specific mental representations and procedures conflict—the greater the overlap, the greater the potential for crosstalk.

From the perspective of crosstalk, driving and conversing on a hands-free cell phone would seem to be an example of two tasks that could be combined with little dual-task interference. Driving is thought to be a task that uses visual information, spatial codes, and manual responses. By contrast, conversation is thought to be a task that uses auditory information, verbal codes, and vocal responses. Multiple resources accounts would suggest little competition between the two tasks because they use different modalities of input, different mental codes, and different response types (Wickens 1980, 1984, 2008). However, there is abundant evidence that these two tasks compete on a variety of levels (cf., Strayer and Fisher 2016).

Bergen et al. (2013) point out that comprehension and production of language often involve mental simulation. In their study, they had participants characterize the veracity of sentences with motor content (e.g., "To open a jar you turn the lid counterclockwise"), visual content (e.g., "The letters on a stop sign are white"), and abstract sentences with no clear motor or visual context (e.g., "The capital of North Dakota is Bismarck"). The different sentences, thought to elicit different patterns of mental simulation, resulted in different patterns of dual-task interference when they were paired with driving. One the one hand, brake reaction time was found to be equally impaired by all sentence types, providing support for domain-general interference. On the other hand, processing sentences with visual scenes produced more interference on measures of following distance than abstract sentences, providing support for domain-specific interference. The lesson from this research is that language with different content recruits different neural hardware and produces different patterns of dual-task interference.

It may not come as a surprise that the destination-entry features supporting navigation found in many new vehicles produced the greatest potential for distraction (Strayer et al. 2019). There are high levels of crosstalk between programming a GPS navigation system and operating a motor vehicle because of the overlapping visual, cognitive, and manual demands of the two concurrent tasks. In fact, the National

Highway Traffic Safety Association's visual-manual guidelines (NHTSA 2013, p. 116) recommend against in-vehicle electronic systems that allow drivers to interact with a navigation system supporting destination entry when the vehicle is moving.

6 Hierarchical Control and Driving

Surprisingly, some aspects of driving significantly improve when drivers multitask. For example, a number of researchers have found that drivers maintain better lane position when they engage in a demanding cognitive secondary task (Atchley and Chan 2011; Becic et al. 2010; Beede and Kass 2006; Brookhuis et al. 1991; Engström et al. 2005, He and McCarley 2011; Horrey and Simons 2007; Horrey and Wickens 2006; Jamson and Merat 2005; Knappe et al. 2007; Liang and Lee 2010; Östlund et al. 2004; Reimer 2009).[8] This counterintuitive finding was initially chalked up to the fact that drivers tend to concentrate their gaze on the forward roadway when multitasking (e.g., Briggs et al. 2017; Engström et al. 2005; Harbluk et al. 2007; He et al. 2011; Horrey et al. 2006; McCarley et al. 2001; Recarte and Nunes 2000; Reimer 2009; Reimer et al. 2012; Strayer et al. 2017; Tsai et al. 2007; Victor et al. 2005). In fact, there is a tight coupling between where a driver looks and their steering inputs (Readinger et al. 2002; Rogers et al. 2005; Wilson et al. 2008).

To test the hypothesis that increasing cognitive load leads to a concentration of gaze that results in reduced lane position variability, Cooper et al. (2013) independently manipulated eye movements and cognitive load. They found that eye movements had only a modest impact on lane position variability, whereas the cognitive load had a much greater impact. Cognitive load reduced variability in lane position even when the eyes were not concentrated on the forward roadway. These data are in line with Logan and Crump's (2009) hierarchical control theory that suggests that complex skills, such as driving, are governed by an "outer loop" that is dependent on limited-capacity attention and an "inner loop" that is more automatic and does not place demands on attention. In fact, paying attention to the inner loop interferes with performance, whereas attention is necessary for efficient outer loop performance. The distinction between outer and inner loops has been applied to typing, golfing, soccer, and playing a musical instrument where paying attention to keystrokes on a typewriter, swings of the golf club, footwork when dribbling a soccer ball, or fingering on a guitar disrupts skilled performance (e.g., Beilock et al. 2002; Logan and Crump 2009).

[8] The improved lane keeping observed under higher levels of cognitive load is not found with higher levels of visual load. This fact makes it easy to differentiate a cognitively distracted driver from a visually distracted driver. In the latter case, higher visual load (e.g., reading a text message) impairs lane keeping behavior.

Hierarchical control theory predicts that paying attention to the outer loop should improve the attention-demanding components of driving, whereas attending to the inner loop should degrade the more automatic components of driving. Conversely, because multitasking diverts attention from driving, it should cause outer loop components to suffer and inner loop components to prosper. Medeiros-Ward et al. (2014) examined lane maintenance while factorially manipulating secondary task load and driving predictability. When driving became less predictable due to wind gusts, more attention was required to maintain lane position. Under this circumstance, performing a cognitively demanding secondary task degraded lane maintenance. However, with predictable driving (i.e., no wind gusts), performing a cognitively demanding secondary task actually improved lane maintenance. Essentially, multitasking has differential effects on outer and inner loop performance. Counterintuitively, multitasking can actually improve the more automated components of driving that are not dependent on limited-capacity attention.

7 Neural Basis for Individual Differences in Multitasking

In the process of examining individual differences in multitasking ability, a handful of individuals were identified who, quite unexpectedly, showed no decrements when combining driving in a simulator with conversing on a hands-free cell phone (Watson and Strayer 2010). Measures of driving performance (i.e., brake reaction time and following distance) and performance on a cognitively demanding conversation surrogate (i.e., an auditory/vocal version of the OSPAN Task with measures of math accuracy and memory recall) were either unchanged or actually improved when the two tasks were combined. Approximately 2.5% of participants tested in this dual-task combination were identified as *Supertaskers*, individuals with extraordinary multitasking ability. Watson and Strayer (2010) used Monte Carlo simulations to show that this pattern of dual-task performance could not be explained by chance variation.

Subsequent testing of these Supertaskers used fMRI measures obtained while participants performed a very challenging version of the dual N-back task (Jaeggi et al. 2007). Compared to age, gender, and working memory capacity matched controls, Supertaskers exhibited patterns of greater neural efficiency while performing the dual N-back task (Medeiros-Ward et al. 2015)[9]. When multitasking, Supertaskers brains were characterized by more efficient recruitment of the anterior cingulate cortex (ACC, Broadmann areas 24 and 32) and the frontopolar prefrontal cortex

[9] The dual n-back task involves the performance of two functionally independent tasks. This dual-task combination involved the simultaneous presentation of visual/spatial and auditory/verbal stimuli. Participants processed both modalities independently and responded if the visual/spatial or auditory/verbal stimuli matched the stimulus N-times back (e.g., 1-, 2-, or 3-back). The vast majority find the dual n-back task to be impossibly hard; however, Supertaskers perform the task at near perfect levels of performance.

(FP-PFC, Broadmann area 10). While performing this challenging multitasking combination, Supertaskers performed better than the controls despite these brain regions being significantly *less* metabolically active, as measured by the Blood-Oxygen-Level-Dependent (BOLD) signal.

The ACC and FP-PFC brain regions of the prefrontal cortex play an important role in cognitive control and appear to be critical for efficient multitasking. The ACC is a subcortical structure that is involved in attentional control (Bush et al. 2000) and is considered to be an integrative hub involved in prioritizing what information in the environment to attend to and what information to ignore (Holroyd and Coles 2002). The ACC is also thought to play a prominent role in conflict monitoring (Botvinick (2007) and the detection of errant behavior (Gehring and Fencsik 2001; Gehring et al. 1993). The FP-PFC is an area of the brain found exclusively in primates that is thought to play an important role in managing competing secondary-task goals and switching between them (Braver and Bongiolatti 2002; Mansouri et al. 2017). Patients with damage to this part of the brain often have particular difficulty with multitasking (Burgess et al. 2000; Dreher et al. 2008).

Coming full circle, the fMRI data suggest that the prefrontal cortex is actively engaged when humans attempt to concurrently perform multiple tasks, such as driving and conversing on a hands-free cell phone. The fMRI BOLD signal shows high levels of metabolic activity in the ACC and FP-PFC for 97.5% of participants who are not Supertaskers. We suggest that the ACC plays a critical role in integrating and prioritizing the primary task (i.e., driving) and secondary-task information and that the FP-PFC helps manage the task goals and switch between the driving task and any concurrent secondary task.

A specialized version of the dual N-back task used to identify Supertaskers is available online at www.supertasker.org. Like Jaeggi et al.'s (2007) task, the online version presents visual and auditory streams of information and the participant must process the information independently to make a classification.[10] The cover story for the Supertasker test is that participants act as a bouncer at a nightclub and only let "cool people" into the club. Cool people do not try to enter recently used doors or use recently used passwords (i.e., the doors and passwords are the visual and auditory streams of information that form the backbone of the N-back task). After completing the Supertasker test, participants are given a score based on the formal measures of capacity (e.g., Heathcote et al. 2015). Try the test and let us know how you do.

[10] One of the volunteers who received a perfect score in the online version of the Supertasker task contacted the software developers to inquire about his perfect score (he actually received a perfect score twice, once in the initial test and again on a subsequent retest). This individual reported that he is considered to be one of the top sight-readers in the classical piano industry. Another volunteer who was rated as a Supertasker was on the British Olympic team. We believe that it is likely that Supertaskers, who represent approximately 2.5% of the population, excel at all sorts of real-world tasks that involve high levels of multitasking.

8 Who Multitasks and Why?

On the other end of the ability continuum are individuals who persist in multitasking even though they are bad at it. Sanbonmatsu et al. (2013) examined the relationship between *self-perceived* multitasking ability, impulsivity, sensation-seeking, and *actual* multitasking ability. These authors obtained self-reported measures of cell phone usage while driving along with measures from the media multitasking inventory (Ophir et al. 2009). Participants also performed a computerized version of the OSPAN task (Unsworth et al. 2005) and completed personality inventories assessing impulsivity, sensation-seeking, and self-perceived multitasking ability.

Chronic multitaskers were found to be the least capable of multitasking. This is a remarkable finding because people often frequent activities in which they excel. In fact, those with lower executive control, as measured by the OSPAN task, were more likely to use their cell phone while driving and they also scored higher on measures of impulsivity and sensation-seeking. These individuals also scored high on media multitasking, a pattern that is consistent with previous research by Ophir et al. (2009). There was a positive correlation between an individual's self-perception of their multitasking ability and their actual usage of a cell phone while driving. In fact, 70% of those sampled believed that their ability to multitask was better than average, a statistical impossibility. This shows a disconnect between *perceived* multitasking ability and *actual* multitasking ability. Drivers who had lower working memory capacity and scored higher in attentional impulsivity and sensation-seeking, particularly those scoring high in the disinhibition component of sensation-seeking, were more likely to use their cell phone while driving.

One paradoxical finding is that the vast majority of the public favor legislation that would prohibit using a cell phone while driving. For example, a survey by the AAA Foundation for Traffic Safety (2013) found that 88.6% of respondents felt that cell phone use while driving was a very serious or serious threat to their personal safety. This survey also found that 70% of respondents supported law that would restrict hand-held cell phone use while driving and 45% supported a total ban on cell phone use while driving. Nevertheless, recent sensor data obtained from over 3 million motorists found that drivers were using their phone on 88% of their trips (Zendrive 2017). Moreover, at any given daylight moment, 9.7% of the public can be seen using their cell phone to talk or text while operating their vehicle (DOT 2019).

Sanbonmatsu et al. (2016a) examined the disconnect between support for legislation restricting cell phone use while driving (62% in their sample) and actual use of a cell phone while driving (78% in their sample). The correlational study found that motorists perceived the benefits of *their* usage to outweigh the perceived risks to them of crashing. Participants were overconfident in their own ability to multitask relative to others. However, they did not believe that *others* were capable of driving safely while talking on a cell phone. That is, they considered *others*' use as a threat to *their* safety. Moreover, the survey found that motorists did not perceive a benefit from others' usage, whereas they felt that they did benefit from their own usage.

This hypocrisy in the form of "do as I say, not as I do" demonstrates that people want the laws to apply to other distracted drivers.

As discussed earlier in this chapter, multitasking motorists often fail to notice things in the driving environment (i.e., they have poor situation awareness). Supporting this notion, a study by Sanbonmatsu et al. (2016b) found that multitasking diminished motorist's self-awareness of their impaired driving. The decrease in performance monitoring caused participants to be less aware of their actual driving errors, an unfortunate consequence of inattentional blindness. Consequently, motorists may persist in the belief that they can multitask while driving. These authors note that the multitasking "drivers who made the most errors exhibited a pattern similar to the fictional character Mr. Magoo, who was blithely unaware of his driving impairments" (p. 622).

Taken together, the studies by Sanbonmatsu et al. (2013, 2016a, b) paint an alarming picture of the multitasking motorist. Those most likely to multitasking while driving have lower working memory capacity, score higher in impulsivity and sensation-seeking, are overconfident in their abilities, and are often blind to the errors that they do make. Nevertheless, they engaged in this multitasking behavior because they feel that the benefits outweighed the risks, yet they did not feel the same about other multitasking motorists.

9 Multitasking and Device Addiction[11]

An incoming call or text is often a rewarding social stimulus that is difficult for motorists to ignore because it stimulates the dopaminergic reward network in the brain. The dopaminergic mesolimbic system is composed of the ventral tegmental area (VTA), the amygdala, and the nucleus accumbens (NAc). This primitive brain network helps the organism to pay attention to the features of a rewarding experience so that it can be repeated (Banich 2004). The reward circuits exert powerful control over behavior. The prefrontal cortex provides top-down control of the subcortical brain regions associated with reward and emotion regulation (Heatherton and Wagner 2011; Uncapher et al. 2017). Self-regulatory failure occurs if the balance is tipped in favor of the reward circuits due to the strength of a stimulus (e.g.,

[11] It is hotly debated whether smartphone use rises to the level of a "true" behavioral addiction, similar to a gambling disorder (e.g., Griffiths 2013; Roberts 2016). The question of whether smartphone use is a behavioral addiction conforming to the Diagnostic and Statistical Manual for Mental Disorders (DSM-5) criteria or just "problematic smartphone use" that is "distinct from other addictions that merely use the smartphone as a medium" (Yu and Sussman 2020, p. 422) is beyond the scope of this chapter. However, a comprehensive review of 108 peer-reviewed articles generally supports the conclusion that smartphone addiction is a genuine addictive disorder (Yu and Sussman 2020).

a rewarding text message) or a failure to exert executive control (e.g., due to fatigue associated with excessive multitasking).

Like the ringing bell for Ivan Pavlov's classically conditioned dogs, the driver has been classically conditioned to *their* ringing cell phone. When their phone rings (i.e., the conditioned stimulus), the driver may reflexively answer the call and connect to their social network. The dopamine reward-learning network has been implicated in this sort of cue-reward pairing (Pan et al. 2005). Whereas a driver's cell phone is a rewarding conditioned stimulus, people often find other ring tones aversive and annoying. That is, a ring tone is not an inherently rewarding stimulus. The ring tone must be paired with a user's own smartphone for it to acquire this property.

Motorists may acknowledge that they should not use their smartphones while driving, yet they do it anyway. Using the smartphone to interact with a motorist's social network is a very powerful and rewarding stimulus. In fact, the author DS knows several people who have lost loved ones in a distracted driving crash. These individuals, who were not in the vehicle when it crashed, now lock their smartphones in the trunk so that they are not tempted to use their devices while driving (an example of *proactive* self-regulation).[12] They report that if the smartphone is in the car, they are drawn to it. Because driving places demands on the prefrontal attentional network, self-regulatory failure often occurs when the motorist's phone rings.

Based on estimated crash risk, Strayer (2017) developed a 6-item scale to determine the level of risk associated with using a smartphone while driving. Points are assigned based on whether a driver engaged in the activity while driving in the last week. A score between 1 and 3 was considered to be a moderate level of risk, a score between 4 and 6 would be considered a high level of risk, and a score greater than 6 would be considered an extreme level of risk. It is noteworthy that the National Transportation Safety Board (NTSB 2011) and the National Safety Council (NSC 2010) consider that driving is compromised if the obtained score is greater than 0.

- Accepting a phone call while driving (1 point)
- Placing a call (including dialing) while driving (2 points)
- Reading a textual message while stopped at a traffic light (1 point)
- Sending a textual message while stopped at a traffic light (1 point)
- Reading a textual message while driving (2 points)
- Sending a textual message while driving (2 points)

[12] Strayer and Cooper (2015) distinguished between proactive and reactive self-regulation of smartphone use while driving. Drivers may *proactively* self-regulate their multitasking activities to periods when they are stopped at a traffic light (e.g., Huth et al. 2015), even though the persistent costs described earlier make this less than an optimal strategy. Drivers may also attempt to *reactively* self-regulate their multitasking activity to periods when driving demands and consequences for distraction are higher (e.g., when driving in a work or school zone); however, the inattentional blindness caused by such activities often renders this strategy ineffective.

10 Attention and Vehicle Automation

The recent introduction of automated vehicles poses new attentional challenges for motorists. The Society of Automotive Engineers categorizes six levels of automation in vehicles, from Level 0, meaning no automation, to Level 5, meaning full automation (SAE 2016). Presently, vehicles with Level-2 automation, henceforth referred to as semiautomated vehicles, are publicly available and are equipped with systems that employ lateral and longitudinal control. These vehicles enable adaptive cruise control and lane-centering technology to be engaged simultaneously. The technology is not perfect, and in accordance with the SAE guidelines for semiautomated systems, drivers are required to remain vigilant and be able to take back manual control of the vehicle at any time.

In semiautomated vehicles, the primary task of the driver changes. Rather than being in full control of the vehicle, the driver instead takes on the role of passively monitoring the vehicle for rare technological failures. The driver must also monitor the environment for instances that the automated system is not designed to handle. Even though there is a shift from the active controller to the passive monitor, the demands illustrated in the SPIDER model still exist (e.g., scanning, predicting, identifying, deciding, executing responses) and the driver must maintain situation awareness at all times. However, researchers are still trying to understand how this new role of monitoring affects the allocation of attention to the primary driving task and willingness to engage in secondary tasks (i.e., multitask).[13]

One concern regarding the automation of vehicles is that passive monitoring might make it difficult for motorists to maintain optimal levels of arousal, which can lead to fatigue and impairments in situation awareness. Some believe automation might impair situation awareness due to changes in vigilance and complacency (Endsley and Kiris 1995), while others believe automation may potentially improve situation awareness by decreasing the workload placed on the driver (Billings 1991). In terms of multitasking, researchers have found that drivers who are performing a secondary task take longer to take back manual control of the vehicle if the automated features deactivate (Vogelpohl et al. 2018).

The Yerkes–Dodson model describes the relationship between arousal, attention, and task performance (Yerkes and Dodson 1908). Optimal levels of performance on a task occur when there is a moderate level of arousal, as depicted by the mid-point of the inversed-U shaped function (Cohen 2011, p. 2737; Yerkes and Dodson 1908). Attention affects arousal levels such that high demands can increase arousal to detrimental levels, resulting in poor task performance (Derakshan and Eysenck 2009). For example, driving that demands high and sustained attention can increase stress and lead to detriments in driving performance (Langner and Eickhoff 2013). In

[13] In the future, when Level-5 automation becomes commonly available, the safety-related concerns regarding multitasking motorists becomes moot. Until that time however, multitasking is likely to compete with a driver's ability to monitor the semi-automated vehicle and maintain good situation awareness.

terms of arousal, some researchers have found that over-arousal when monitoring semiautomated vehicles can lead to faster onset of fatigue and decrements in vigilance (Greenlee et al. 2019). Others have found that under-arousal might also lead to fatigue and disengagement from the environment (Manly et al. 1999, p. 661). The degree to which driving semiautomated vehicles may lead to over- or under-arousal is not well understood.

Physiological measures can be used to assess motorist arousal and engagement with the driving environment in real-time (see Lohani et al. 2019). For example, electroencephalography (EEG) measures the summated electrical activity in the brain from electrodes on the scalp. It is noninvasive and mobile and allows for direct recording of neural activity in response to the demands of an environment. EEG can be decomposed into various frequency bands (Delta ~0.5–4 Hz, Theta ~4–8 Hz, Alpha ~8–12 Hz, and Beta ~12–30 Hz) using Fourier analysis (Cohen 2014). These frequency bands are studied in relation to different cognitive functions. For example, alpha power in parietal regions of the brain is reflective of visual attention, such that higher alpha power indicates lower visual engagement with the environment and lower alpha power is indicative of higher visual engagement (Bowman et al. 2017; Foxe and Snyder 2011). Alpha power is greatest when an individual's eyes are closed (Berger 1933). Additionally, fatigue and under-arousal have been shown to increase alpha power (Chuang et al. 2018; Käthner et al. 2014), while an increase in cognitive workload and arousal has shown to decrease alpha power (Mun et al. 2017). Therefore, power in the alpha frequency band is a useful metric to assess visual engagement and arousal while driving.

Strayer et al. (2020) recorded EEG when motorists operated Level-0 (no automation) and Level-2 (semiautomation) vehicles on a network of interstate highways. It was hypothesized that if driving semiautomated vehicles leads to a decrease in arousal and task engagement, there would be an increase in alpha power, whereas if driving semiautomated vehicles leads to an increase in arousal and task engagement, there would be a decrease in alpha power. Contrary to popular concern about threats of fatigue and disengagement associated with automated vehicles, Strayer et al. (2020) found a slight *decrease* in alpha power with semiautomated driving (compared to manual driving). This is consistent with the SAE guidelines that drivers must remain engaged with the primary driving task even when driving in semiautomated mode.

Presently, it is unknown how the development of trust in semiautomated vehicles over the long haul might affect attention (and driver's situation awareness), arousal, and the willingness to multitask. It is possible that as a driver becomes more comfortable with the technology, they may become more likely to disengage from the environment, or "zone out". As automated technology continues to develop, it will become increasingly important to assess driver arousal and attention with sensitive, real-time measures.

11 Red Line of Workload

Finally, it is important to establish a red line of workload (Grier et al. 2008), a level at which the task demands exceed the capacity of an individual and where performance degrades to unacceptable and/or unsafe levels. In the context of driving, multitasking activities that cross the red line increase the risk of crashes and fatalities (WHO 2011). Strayer et al. (2019) compared a driver's workload when performing four different task types. These task types are commonly available in new vehicles via the embedded in-vehicle infotainment system (IVIS). The four task types were (a) *audio entertainment* (e.g., selecting different sources of music), (b) *calling and dialing* (e.g., placing an outgoing call from a contact list or dialing a number), (c) *text messaging* (e.g., listening to short text messages and replying from a list of predetermined messages), and (d) *navigation* (e.g., initiating GPS route guidance to different locations). These task types were compared to the single-task (driving) baseline and to a high-demand benchmark (i.e., the red line of workload).

The red line of workload was established by applying the NHTSA's (2013) upper limit for total task time (e.g., 24 seconds, using a visual occlusion testing procedure). The general principle was that IVIS interactions should be performed in 24 seconds or less when paired with the task of operating a moving motor vehicle. The red line of workload was also calibrated by having drivers concurrently perform a cognitively demanding auditory N-back task (Mehleret al. 2011) or a visually demanding visual/manual search task (i.e., the SuRT task, ISO TS 14198 2012). The red line of workload shown in Fig. 5 reflects the driver's workload when they concurrently performed either the N-back or SuRT task (i.e., the red line represents the average workload for the N-back and SuRT tasks, each done separately, scaled by 24 seconds, see Strayer et al. 2019 for additional details).

The on-road evaluation of the IVIS interactions performed by Strayer et al. (2019) found that the audio entertainment and calling and dialing features were significantly below the red line of workload (approaching but not exceeding the red

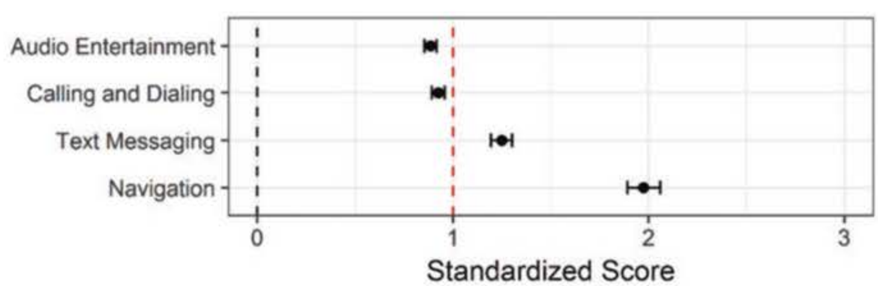

Fig. 5 The overall demand as a function of secondary-task type from Strayer et al. (2019). The dashed vertical black line represents workload in single-task driving, and the dashed vertical red line represents the "red line" of workload. Error bars represent 95% confidence intervals

line of workload). By comparison, both the text messaging and navigation task types significantly exceeded the high-demand baseline. Notably, the navigation task type was associated with *twice* the demand of the red line of workload. Given the observed high level of workload, it is not surprising that NHTSA's (2013) visual-manual guidelines recommend against enabling this feature when the vehicle is in motion. Unfortunately, these guidelines are voluntary (i.e., left to the discretion of auto manufacturer), and it was enabled in 40% of the test vehicles when participants were driving.

12 Summary

Multitasking in the automobile is ubiquitous. This concurrent performance of a secondary task that is unrelated to driving has been shown to divert attention from the primary task of operating a motor vehicle. Multitasking impairs SPIDER-related activities (e.g., scanning, predicting, identifying, deciding, executing responses) and compromises a motorist's situation awareness. There is considerable variability in the mental workload associated with different multitasking activities. Some concurrent tasks, like listening to the radio or audio book, have little impact on driver workload and driving performance. Tasks involving a conversation with another person impose a higher mental load than listening to the radio or audio book. Multitasking with more complex in-vehicle information systems (e.g., voice-based or multimodal visual, manual, and cognitive interactions) is associated with surprisingly high levels of driver workload and impairments to driving. When motorists terminate a multitasking operation, there is a persistence in distraction that lasts for at least 27 seconds. The secondary-task threads appear to be "impolite" and suggest that the information supporting the abandoned secondary task decays gradually from working memory. In part, impairments to driving from multitasking stem from crosstalk between two tasks that use similar or overlapping information that come into conflict. Indeed, not all conversations are equivalent, and language with different content recruits different neural hardware and produces different patterns of interference with driving. Counterintuitively, whereas multitasking clearly impairs higher-level cognition, some of the lower-level automated aspects of driving, such as maintaining lane position, may actually improve under cognitive load. Multitasking places heavy demands on the prefrontal cortex, particularly the frontopolar and anterior cingulate cortices. For most drivers, these brain regions show high levels of metabolic activity whilst multitasking. However, Supertaskers, thought to comprise about 2.5% of the population, are able to multitask at high levels without overloading these neural circuits. On the other end of the continuum are those who persist in multitasking and are bad at it. Intriguingly, individuals most likely to multitask while driving have lower working memory capacity, score higher in impulsivity and sensation-seeking, are overconfident in their abilities, and are often blind to the errors that they do make. These drivers also felt that the benefits of multitasking outweighed the risks; however, they did not feel the same about other multitasking motorists. There is evidence that many drivers suffer from problematic smartphone use, reflexively answering a call when the phone rings. Future advancements in vehicle automation may make the safety-related concern regarding multitasking motorists moot. Until that day, multitasking is likely to compete with a driver's ability to monitor the vehicle and maintain good situation awareness.

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