A Comparison of Driver Alerting and Management Systems Through the Lens of Multiple Resource Theory

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Introduction

In a rapidly evolving world where human-machine interactions become increasingly dynamic and complex, understanding and leveraging Multiple Resource Theory (MRT) is essential for designing efficient and safe systems. When analyzing the effectiveness of different driver assistance designs through the lens of MRT, it is crucial to consider how each stage of information processing, modality, access, working memory, and responding can all create conflicts or synergies. Design 1 employs visual and auditory modalities to provide hazard alerts using color-coded visual displays and auditory tones, while Design 2 leverages tactile feedback through seat tactors to convey similar hazard information. These designs reflect divergent approaches to managing the driver's cognitive resources and minimizing interference during task execution. Wickens (2002) highlights that the potential for dual-task interference arises when tasks demand overlapping modalities or cognitive resources, which can compromise performance, particularly in high-stress or multitasking environments. By comparing the conflicts introduced at each stage of MRT, this essay aims to evaluate the advantages and limitations of these designs in supporting effective driver responses to hazards.

Multiple Resource Theory Background

Multiple Resource Theory, introduced by Wickens, provides a framework for understanding the way in which cognitive resources are allocated across multiple tasks simultaneously (Wickens, 2008). MRT illustrates that mental workload is distributed across resource blocks or pools, with each block dedicated to a specific modality (visual, auditory, or tactile), codes or access (spatial or verbal), and the stages of processing (perception, cognition, and responding). Tasks that use separate resource blocks are less likely to interfere with each other. In contrast, tasks that rely on the same resource blocks create competition for resources, resulting in a decline in performance across both (or all) tasks. Wickens' MRT offers important insight that can be applied to system designs, minimizing performance decrements and cognitive workload while maximizing multitasking efficiency.

MRT has been widely applied during the design and evaluation of alerting systems, which require efficient and proper allocation of an operator's attention to be effective (Wickens & Liu, 1988). Alerts, at least effective ones, are designed to draw an operator's attention to critical information while minimizing distractions from primary tasks. System designers can reduce interference and improve operator response times by designing alerts that use separate modalities, such as a system that combines visual and auditory stimuli (Sklar & Sarter, 1999). Prior studies have demonstrated the importance of using MRT to analyze the effectiveness of alerting systems during simultaneous tasks. Wickens et al. (1983) illustrate that auditory alerts complement visual monitoring in cockpits due to their use of separate resource blocks, leading to improved detection of hazards by pilots. A study by Bliss and Gilson (1998) investigated the implications of MRT in emergency signaling, with recommendations that a multimodal alert should be designed to improve and optimize operators' response. Applying MRT to alerting systems ensures that the alerts align with human perceptual and cognitive limitations, enhancing situation awareness in complex or dynamic environments.

MRT has proven to be a compelling framework for evaluating Driver Alerting, and Management system designs because it highlights how cognitive resources are allocated and potentially overloaded when dealing with multiple tasks. Distinguishing between resource blocks for modalities, codes, and processing stages allows designers to predict and minimize potential conflicts arising when multiple tasks use shared resources (Wickens, 2002). MRT is well suited to DAM systems, which are forced to balance the need for attention capture while minimizing interference in driving performance (Bliss & Gibson, 1998). MRT's use in designing and evaluating alerting systems, especially those used in high-demand contexts and systems, has highlighted its validity and adaptability (Dixon et al., 2003). The principles offered by MRT's structured approach to designing systems around a human's cognitive capabilities also make it an outstanding tool for finding the optimal DAM system (Bolton et al., 2013).

Design Comparison at Each Stage of MRT

To compare designs using MRT, it's essential to evaluate how each design interacts with drivers' cognitive resources across different stages of information processing. This requires examining the modalities employed by each design (visual, auditory, or tactile), the cognitive and physical tasks imposed on the user, and the potential for dual-task interference. Wickens (2024) emphasizes the importance of identifying shared versus separate resources in evaluating dual-task performance to understand how interference might occur. Considerations of workload, task difficulty, and environmental context are crucial, as these factors influence how effectively a driver can process, prioritize, and respond to alerts (Wickens, 2002). By addressing these dimensions, designers can predict how each system will perform under real-world driving conditions and identify the design that best balances safety and usability. The following sections will evaluate each of the designs at the perception, cognition, and responding stages of MRT, highlighting potential sources of interference within each design and addressing the pros and cons of each design at the various stages.

Perception

Design 1

Design 1 brings visual and auditory cues. Relying on two sets of audio signals and one colored outline to alert the driver to oncoming hazards. The audio signals will consist of an auditory message stating the alert's context, such as "Cyclist approaching from rear on the left", and a coded warning tone that repeats, with the repetition rate and intensity of the tone conveying the speed and proximity of the hazard. In addition to those auditory cues, a colored outline will highlight the oncoming hazard, with the possible colors of the outline being green for low risk, yellow for moderate risk, and red for an impending or high-risk hazard.

With the audio message bringing verbal information and the repeating tone bringing spatial information, the driver can recognize and discriminate the location of the approaching hazard without taking their eyes off the road. Two separate sources of alerts aid this, each reinforcing the other due to them relaying the same information. The colored outline further allows the system to relay an alert without taking their immediate attention off of the navigation at hand. This is partly due to the outline functioning within the ambient field of vision, with the actual hazard maintaining its position in the driver's focal view.

Major concerns for the auditory alert system are the volume of each in relation to one another and how overwhelming hearing both audio signals at once would be. Depending on which signal is prioritized, the driver may find it hard to focus on the other, mainly when an immediate hazard is present. The intensity, as well as the repetition of the auditory alarms, will rise in relation to the proximity of the hazard, meaning if the driver is already trying to focus on avoiding an impending hazard or otherwise significant threat, they will have to deal with and process an onslaught of auditory information on top of the already panicking cab full of passengers. Another concern will arise with the presence of passengers, which is that of verbal noise within the vehicle. Suppose the driver and passengers are having a steady conversation at a volume high enough to overpower the vocal warning. In that case, it will only be heard once it is loud enough, which would mean the hazard is already too close for comfort. With the visual warning outlining an approaching hazard from the front, a concern would arise about how many would occur. If the outline were to only focus on the most significant threat in front of you, it would draw the driver's attention away from all the other hazards in front of them.

On the other hand, if the system were to outline every possible hazard in front of you, it would be so overwhelming that it would immediately snap them out of focus. Furthermore, if the driver suffers from color deficiency, the outline's color may be indistinguishable and lose meaning. If the thickness or gamma of the outline were to be altered along with the color, it would prove to be beneficial.

Design 2

Design 2 brings with it tactile vibratory cues. It relies on three sets of vibrating tactors located on the lower back, upper thigh, and back of the knee, emitting vibration patterns that indicate whether the hazard is in front of, beside, or behind the driver. The intensity of the vibration would convey the urgency/immediacy of the hazard, with the position of the vibration (left-right, front-back) conveying the direction from which the hazard is approaching. When it comes to detection, certain areas of the body are more sensitive to touch and vibration than others, particularly the locations with rigid, glabrous skin, like the palms and bottoms of feet, certain areas between hair follicles referred to as touch domes (Xiao et al., 2014), and at the roots of Velus hairs throughout the body (Halata et al., 2010). Velus hairs are the short, fuzzy hairs covering most of the human body. This is because of the presence of Merkel cells, sensory nerve endings that are essential for detecting touch and vibration (Xiao et al., 2014).

As the task of utmost importance while driving is the immediate handling and navigation of the moving vehicle, limiting alert notifications to a tactile modality, specifically within the femoral region, allows for less sensory processing on the driver (Wickens et al., 2013). The benefit of this is that the only status the driver must monitor regarding alerts is the presence of vibrations or lack thereof within their femoral region. In addition, it does not impact the driver's line of sight, allowing the driver to give their complete visual and auditory focus on the road and instrumentation in front of them. This tactile modality has three accesses: the verbal label given to the driver by the vibrating tactor, the vibratory pattern conveying the type of hazard, and the spatial location given by the vibrations of either the left or right sides. With the vibration's intensity varying depending on the hazard's proximity, one can assume that the vibration will continuously rise in intensity as the hazard approaches and that the vibrations will move from left to right or vice versa depending on the relative motion of the hazard. This would allow for a much more interactive alert system than one might assume due to the driver being able to track the location of the approaching hazard depending on how the vibrations move.

An issue for tactile feedback systems is found within the driver’s ability to sense and discriminate the different vibrations throughout their body. The human body has differing levels of touch sensitivity and touch discrimination, with the most sensitive areas being those of the hands and face. The typical rule of thumb when discussing touch discrimination is that the larger the surface area, the more difficult it is to discriminate between two points of touch. This concept is called the Two-Touch Threshold (Frahm & Gervasio, 2021). Room for three separate sets of tactors within the seat is limited, especially when considering the surface area of the seat bottom is only a few square feet. Depending on how the tactors are organized and stretched across the surface of the seat, another issue could come with the driver’s ability to discriminate the shifting movement of the vibrations, their intensity, and the various patterns of vibrations that could occur, all of which are crucial for the alert to benefit the driver. To aid in the driver's ability to discriminate vibrations, the tactors should be stretched along a portion of a limb, not concentrated in one specific area. To add to the concern about the driver's ability to discriminate the vibrations, one may be wearing clothing, such as thick gloves, pants, or coats, that could easily absorb the lighter end of the vibrational intensities.

Cognition

Design 1

Design 1 uses visual and auditory cues to alert the driver to hazards in the surrounding environment. This multimodal approach offers several benefits in terms of redundancy and reliability. For example, the auditory alert provides a secondary warning in case the visual cue is missed or obscured, such as when a driver's view is momentarily blocked by another vehicle. The auditory signal, such as a clear message stating ensures the driver is informed even if the visual cue on the windscreen is not immediately visible. Research shows that using both visual and auditory signals can improve hazard detection and reduce response time (Wickens, 2013). For instance, if a vehicle is approaching rapidly from behind, an auditory alert with a high-pitched tone that repeats rapidly can effectively communicate urgency, helping the driver to prioritize and react to the situation faster. Moreover, using color-coded visual cues allows the driver to immediately assess the potential severity of a hazard without needing to cognitively process detailed information, making it easier to prioritize responses during high-stress driving situations (Wickens, 2013). This form of redundancy offers a quick, intuitive response, allowing drivers to make decisions faster.

However, Design 1 has notable disadvantages, particularly regarding cognitive overload and auditory masking. When both visual and auditory alerts are presented simultaneously, the cognitive load may increase, mainly if there are multiple simultaneous alerts or complex visual stimuli. For instance, in a busy traffic scenario where the driver receives multiple overlapping warnings (e.g., visual cues for pedestrians, auditory cues for a cyclist, and a red warning for a nearby car), the overload can slow down decision-making, leading to slower responses or failure to prioritize threats effectively. As Norman (2004) points out, "excessive sensory information can overwhelm the user's cognitive resources," leading to reduced performance and potential errors in hazard detection. Additionally, auditory masking can diminish the effectiveness of the auditory warning in noisy driving environments, such as on highways or in urban traffic. In these conditions, drivers may fail to hear the warning message, especially if environmental distractions such as engine noise or other vehicles' horns exist. The design might also become a distraction in itself—frequent or highly dynamic visual alerts on the windscreen could take the driver's focus off the road, increasing the risk of accidents. For example, if too frequent or complex, flashing visual alerts could distract the driver at critical moments, such as when navigating a sharp curve or overtaking another vehicle.

Design 2

Design 2 uses tactile vibratory cues to inform the driver of potential hazards by vibrating in different parts of the seat based on the hazard's location. This design expresses that tasks using different sensory modalities reduce cognitive overload by spreading demands across distinct resources. Wickens (2008) explains that "the use of separate resources from visual or auditory channels reduces competition and overload in the cognitive system". By using tactile feedback, the driver can maintain focus on the road and avoid the cognitive load typically associated with processing auditory or visual alerts (Wickens, 2008a). A significant advantage of tactile cues is that they provide spatially intuitive feedback. For example, a vibration on the left thigh signals an approaching hazard from the left side, while vibrations on the back indicate a hazard approaching from behind. This allows for a rapid, instinctive response without requiring drivers to shift their focus or mentally process the meaning of visual or auditory cues (Norman, 2004).

Moreover, tactile cues are not affected by environmental noise, such as road sounds or engine hums, making them ideal for use in noisy conditions like construction zones or crowded city streets, where auditory and visual cues may be less effective (Van Erp & Van Veen, 2004).

However, Design 2 also presents challenges. One major disadvantage is habituation, which happens when drivers get used to repeatedly hearing the same warnings. As a result, they may stop paying attention to the cues, making them less helpful over time. As Norman (2004) said, "If cues are repeated too often, they may lose their urgency or meaning to the driver", leading to slower reactions in critical situations. Another concern is the potential for interpretation difficulty. Although tactile cues are spatially intuitive, they may become confusing if the patterns are too similar or not distinct enough. Wickens (2008) notes, "If the tactile patterns are too subtle or similar, it may be hard for the driver to distinguish between them, especially under stress". Moreover, tactile feedback needs to be clear and distinct to prevent misinterpretation. If the vibration patterns are too similar, drivers may fail to respond correctly, especially in urgent situations. NASA’s study emphasizes that well-calibrated, intuitive tactile signals are essential to ensure the system’s effectiveness and avoid driver confusion (NASA, 2021).

Responding

Design 1

Design 1 relies on visual and audio cues to alert the driver of potential hazards. This requires the driver to perceive, process, and respond to the visual and audio inputs while safely operating the vehicle. The main task is safely operating the vehicle, which often requires the usage of visual, audio, and tactile modalities. According to MRT, two types of responses are manual and vocal. Manual responses, such as computer mouse movements, are often spatial, whereas vocal responses are often verbal or spoken (Wickens, 2002). Driving responses are generally manual, as the driver must move their hands and legs to execute specific actions based on the sensory input. When using Design 1, additional incoming visual and audio information can interfere with the primary task because the secondary task's responses and input modalities are very similar to the main task (Hagiwara et al., 2014). Interference may lead to task decrement, which may lead to task prioritization that will determine the performance decrement among the tasks (Horrey & Wickens, 2003). In situations where multiple alerts are present simultaneously, the driver may experience cognitive overload, resulting in task shedding, where the driver focuses entirely on the immediate driving task (i.e., avoiding the car in front) and ignores the cyclist warning provided by Design 1. Additionally, if environmental noises mask the auditory cues, this may lead to delays in recognition and response. While this design has the potential to prevent accidents by capturing the attention of distracted drivers, it may also increase distractions by increasing cognitive demands placed on drivers. For instance, navigating a visually complex environment while processing overlapping auditory alerts may cause a driver to misinterpret or overlook critical safety information (Norman, 2004).

Design 2

Design 2 relies on tactile cues to alert the driver of any potential hazards. Once the tactile system gives an alert, the driver must perceive and process the information and respond while maintaining the vehicle's safe operation. The driving response is typically manual and tactile, and Design 2's input is tactile. Given the tactile nature of Design 2, this means it does not require the driver to move their eyes away from the main driving visual scans nor listen for additional audio cues. However, the tactile nature of driving and Design 2's alert system may have a higher chance of interference as the modality and response are similar (Horrey & Wickens, 2003). In practical scenarios, such as detecting a hazard approaching from behind while navigating a busy highway, the spatially intuitive vibrations could help drivers quickly orient to the threat without diverting their attention from the road. For example, left thigh vibration indicates a cyclist approaching from that direction, allowing drivers to check their mirrors and adjust their position instinctively. However, suppose multiple hazards occur simultaneously, such as vibration on the back for a tailgating vehicle and another on the left for a cyclist. In that case, the driver may struggle to discriminate between the cues if they are not distinct enough (Wickens, 2024). Drivers new to the system may find it challenging to interpret tactile patterns accurately, leading to delays or incorrect responses during critical moments (Meng & Spence, 2015). By avoiding visual and auditory modalities, Design 2 minimizes the risk of interfering with the primary driving task when these resources are highly taxed.

Recommendation

As shown above, both designs have a benefit; however, there might be a different use case for each depending on the longevity of use. Design 1 may be advantageous for short-term interactions with the vehicle, such as rental car use. The dual-modality approach lets drivers quickly grasp hazard information even if one modality is temporarily ineffective. For example, visual color-coded outlines on the windscreen provide intuitive, non-verbal cues about hazard proximity and risk level, while auditory messages explicitly state the hazard's nature and location. This design aligns with Wickens' (2002) MRT, suggesting that distributing information across separate modalities can reduce competition for cognitive resources during task execution. However, auditory masking from environmental noises (i.e. traffic, engine sounds, music, etc.) may compromise the effectiveness of audio cues, especially in extra noisy environments (Athar, 1996). Simultaneous visual and auditory alerts risk cognitive overload in high-density traffic scenarios where multiple hazards may compete for drivers' attention (Norman, 2004). While Design 1 supports rapid comprehension and response, its susceptibility to environmental distractions and cognitive load challenges design reliability in complex and long-term use cases. This is where Design 2 might be better suited for long-term vehicle ownership due to the potential to integrate seamlessly into the drivers' habitual response patterns over time. Unlike Design 1, tactile alerts are unaffected by visual or auditory distractions and allow drivers to focus on the road, aligning with MRT's emphasis on minimizing intermodal competition (Wickens, 2008). Tactile feedback offers spatial intuitive hazard information. However, the tactile systems require a learning period for users to familiarize themselves with the mappings of the vibration patterns to specific hazard locations, which could pose challenges for new or infrequent users (Gallace & Spence, 2009). Habituation and clothing interference further complicate the effectiveness of tactile alerts, emphasizing the need for clear and distinct feedback patterns (NASA, 2021). Despite these drawbacks, Design 2's resilience to environmental distractions and reduced cognitive demands make it ideal for regular users who can leverage its benefits after overcoming the initial learning curve.

Both designs offer unique benefits and challenges, the design choice ultimately depends on the intended use case and userbase. While Design 1's multimodal approach allows for quick and intuitive hazard recognition without requiring prior system knowledge, the design's reliance on auditory cues risks interference in noisy environments and the potential for cognitive overload. In contrast, Design 2's tactile feedback system excels in long-term applications, where drivers can acclimate to its intuitive spatial cues, it ensures hazard alerts are unaffected by environmental distractions. Given the long-term reliability, reduced cognitive load, and adaptability of Design 2, this design is the better overall choice for a car manufacturer to prioritize, particularly for enhancing safety and usability for regular vehicle owners.

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