THESIS

TIME SHARING PERFORMANCE OF EGOCENTRIC AND ALLOCENTRIC FRAMES OF REFERENCE AS AN INDICATOR OF RESOURCE POOL

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ABSTRACT

TIME SHARING PERFORMANCE OF EGOCENTRIC AND ALLOCENTRIC FRAMES OF REFERENCE AS AN INDICATOR OF RESOURCE POOL

The Multiple Resource Model (MRM) sets forth groups of cognitive resources and is used to predict dual task interference. Recent updates to the model suggest that it may not be all encompassing. The current studies aim to determine the resource use of egocentric and allocentric frames of reference (FoR) within the criteria of the MRM.

Egocentric and allocentric FoR have been widely studied for their use in navigation aids, especially in aviation, and a plethora of neurological research has attempted to determine the neural correlates of each FoR. These two bodies of literature support the first two criteria of being considered separate resources, but the time sharing capabilities (the last criterion) have not been investigated. The current research used a dual task paradigm under intermediate and heavy resource use to determine how these FoR can be time shared. Results between experiments conflicted but indicated a stronger tendency toward improved performance under conditions in which the FoR being used for both tasks was the same. This was unexpected and does not fit into the MRM. Improved performance may be a result of task similarity, which can improve performance according to the shared processing routines hypothesis. Implications for navigation aid design are discussed.

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INTRODUCTION

Time sharing is done often by people in everyday life. From events as mundane as driving a car and listening to a podcast, or feeding your baby and talking with your spouse, to more specialized tasks such as pilots communicating with air traffic control while flying their plane, or soldiers driving a Humvee while reading bomb detecting radars; time sharing is everywhere. The advantages and disadvantages of this phenomenon, also colloquially referred to as multi-tasking, have always been apparent in some respects. While there are some individual differences, we can typically time share activities like driving a car and listening to an audiobook with reasonable efficiency, but we cannot effectively drive a car and read a book. The theory behind why multi-tasking or efficient time sharing is possible, and how to use these abilities advantageously, has proven very helpful in the design of dual task environments.

Multiple Resource Theory

Early Attention Theories. During the 1950s, fixed capacity theories of attention surfaced as the search for a "human capacity limit" became a focus of psychological research. These theories quickly faded due to an inability to account for skill acquisition (Sanders, 1997), but over the years other theories came to light, generally suggesting a variation of a single resource model or general pool of resources (Kahneman, 1973; Sanders, 1997). These models supported the idea of a limited but sharable capacity and have been termed "resource models." However, the idea of a single resource did not account for all of the differences in dual-task performances and the associated decrements. Research began to provide evidence that differences in demands of information processing structures led to differences in time sharing efficiency (i.e. Kantowitz & Knight, 1976). This understanding of processing structures as resources, along with research that laid out the intersection of multiplicity and resource necessity in economics (Navon & Gopher, 1979), led Wickens (1980) to conduct a meta-analysis of attention studies and propose the Multiple Resource Model, which is now widely adopted and used in the design of multi-modal displays (Sarter, 2007).

The Multiple Resource Model

The Multiple Resource Model (MRM) proposes that humans have separate "resources" used for information processing (Wickens, 2002). The first of these, *stages of processing*, posits that perceptual and cognitive tasks use different resources than selecting and executing actions. *Codes of processing* accounts for the way that spatial activities use different resources from verbal activities. The final dichotomy, *modalities*, accounts for the fact that auditory perception is a different resource from visual perception.

These dichotomies were derived based on three criteria. First, a resource is considered separate if it uses different neural structures from the other resource under consideration. For instance, in the codes of processing dichotomy, neural systems supporting sentence comprehension (verbal task) have been shown to be distinctive from those used in mental rotation (spatial task). Sentence comprehension generally activates areas in the left superolateral temporal cortex, whereas mental rotation mainly activates areas in the parietal regions (Just et al., 2000).

The second criterion is efficient time sharing. If two tasks are equal in difficulty, they should be able to be performed concurrently better with separate resources than if they used the same resource. Though, this does not imply a complete lack of decrement in performance. For example, time-sharing efficiency is improved between tactile and visual/auditory modalities as compared to tactile/tactile time-sharing. Tactile resources are a recent addition to MRT, and their time sharing abilities are directly supported by a study in which participants performed dual tasks as tactile-tactile, tactile-visual and tactile-audio (Scerra & Brill, 2012). Performance was worst on tactile-tactile dual tasks, providing evidence that tactile resources can time share better with other modalities.

The third criterion is less theoretical and more applied: the difference in resources should have a tangible impact on design implications (see Sarter, 2007, for review). For instance, Brickman, Hettinger and Haas (2000) proposed a new cockpit design for pilots to help moderate the workload they experienced from the current cluttered display. They utilized visual, auditory and tactile options to present pilots with information in ways that aided concurrent processing, as each of these options relies on a different resource. This allowed pilots to allocate previously used resources to other tasks, which may help increase safety. Changes like those in the cockpit have also been seen in car displays. Many cars now have a visual display for navigation, music choices, and other pertinent items. However, this display competes for the visual resource, which is always being used to keep the car in the lane. When these displays are equipped with an audio tool that can speak the information, such as naming available songs out loud, time sharing is improved and therefore the decrement to driving performance is lessened (Jeon et al, 2015). All of these studies provide evidence for the different resources under the MRM model. One of the main reasons the MRM has been so widely accepted is its applicability in such a wide spread of environments and tasks.

Critiques and Acceptance of Multiple Resource Model

One critique of MRM is its lack of architecture - that the MRM does not actually define what a resource is, it just predicts the outcomes of using different modalities or codes (Sanders, 1997). The MRM does define a resource as having separate neural components, which provides a certain physiological level of evidence. Arguably, this is not very different from defining resource capacity as based on the ability to introduce a second task, as it does not define the concept in a hard and fast way (i.e. "a resource is a specific pattern of neural firings"). It may be that cognitive "resources" are somewhat of a metaphor, similar to attention as a "spotlight" (see Fernandez-Duque & Johnson, 2002, for a review of attention metaphors). In more recent years, some neuroscience studies have suggested that resources can be operationally defined based on neural oxygen consumption or activation of brain areas (Just et al., 2001). Together, this evidence suggests that this critique is not as relevant as it may have been when it was first introduced.

Another main critique is the lack of decisiveness in where resources stop being divided (Sanders, 1997; Hancock et al., 2007). Already, vision has been divided into two categories, focal and ambient, and the tactile resource has been added to the modalities. At what point does it become too complicated to be useful? While the human mind is complex and therefore models of the mind are also likely to be complex, it is important that the MRM be beneficial to the design of technologies and dual task scenarios, which can be difficult if it becomes overly complicated. This is not expected to be a problem though, as overflow of the model is not likely, and the criteria needed for two entities to be considered separate resources are strict. Additionally, growth of the model is not a problem in and of itself, as long as the applications of its predictions are still clear.

The MRM has been widely accepted, especially in the Human Factors world of psychology and in the design of multimodal displays, for a few reasons. First, single resource theories of attention (e.g. Kahneman, 1973; Sanders, 1997), do not account for time sharing in the same way that the MRM does. While a single resource suggests that performance is limited by capacity or efficiency, which can vary on other dimensions such as arousal, it does not account for the differences in time sharing across modalities or codes when the tasks are equally difficult. The inability of these single resource theories to provide an explanation for those differences has rendered them less useful in applications. Conversely, the MRM provides direct applications to design of dual task technologies or products (see Sarter, 2007, for review). For example, displays involving visual and auditory modalities have helped anesthesiologists monitor a patient while conducting another task (Crawford et al., 2002) and multi-modal proximity warning devices in cars have been shown to improve response time to stopped vehicles (Kramer et al., 2007). Although the existence of theories for continued basic research is important, the natural next steps to cognitive resource identification are applications specifically for improving human performance. The smooth transition from the MRM into applications provides an incentive for designers and researchers to use the model.

The wide acceptance of the MRM should inherently support more research on the topic. By conducting more research, a deeper understanding of and more applications for the MRM can be developed. This can also bolster the theory, reveal falsifying evidence, and improve the design of technologies – all of which can help progress science. Therefore, the current research aims to build upon the MRM and examine its application to frames of reference.

Updates to the MRM

In 2002, the MRM was updated to include a nested dichotomy within the visual modality of processing (Wickens, 2002). Named *visual channels*, this differentiates the resources of focal and ambient vision. Focal vision is primarily used for object recognition in a small, direct field of view, whereas ambient vision involves the entire visual field and is used for perception of movement and orientation. This explains why people are able to keep their car in the center of the lane using their peripheral vision while glancing in the rearview mirror with their focal vision. The dichotomy was presented in one form by Previc (1998) in a model of how we view the 3-D world around us. He asserted that the focal realm is a small area in front of the person and predominantly activates the ventral cortical visual pathways of the brain, whereas the ambient realm covers about 180 degrees of the front visual field and predominantly activates the dorsal cortical visual pathways of the brain. This supports the first of the requirements (different neural structures) for separate resources.

The second requirement, time sharing, has support from a handful of studies (i.e. Lenneman & Backs, 2018; Tsang & Chan, 2018). Specifically, Allen et al (1969) found that performance was worse on dual tracking tasks when peripheral vision could not be used, which suggests that focal and peripheral vision can be time shared.

The third requirement, implications for designers, currently has a large focus in improving design of automation in cars. One way to do this is to use ambient light for navigation by placing lights on the steering wheel that indicate the direction of an upcoming turn, rather than requiring focal vision to focus on a screen with directions. The design applications of ambient light were investigated in a 2016 study. It was found that ambient light resulted in the lowest frequency and duration of glances, and was rated as most acceptable and least cognitively demanding by participants (Matviienko et al., 2016). While there are certainly other applications, it is already clear that the dichotomy of focal and ambient vision does define separate resources under the MRM. The addition of the visual channels can be used as a recent precedent for new resource dichotomies.

A Parallel Dichotomy. The addition of ambient and focal visual channels may have a parallel in frames of reference. It has been suggested that humans use two frames of reference in everyday life – egocentric and allocentric (Klatzky, 1997). An egocentric frame of reference is when locations are represented with respect to the perspective of the observer – for instance, recognizing that your friend is sitting to the right of you. Egocentric frames of reference are often used in driving for carrying out objectives such as determining how far away a turn is or how close you are to the car in front of you. Conversely, using an allocentric frame of reference (also referred to as exocentric, geocentric or world-reference view), processes locations in relation to an external framework. This is often used when providing cardinal directions, such as "head north," or in situations such as air traffic controllers locating planes on the radar screen, where the entire relevant airspace is represented on the screen in a fixed orientation and the planes are shown as small icons in their relative positions.

While it is clear these frames of reference encode information differently, it is not clear if they use the same or separate resources within a multiple resources framework. They do meet two of the three criteria for being considered separate resources – different neural components and design implications, which are detailed below – but the time-sharing component has not yet been studied. It seems the two frames of reference are interconnected, but to what depth is currently ambiguous. Understanding the separation of the two frames of reference would be beneficial for applications such as navigation design, as well as contributing to the MRM and providing more insight into the cognitive mechanisms involved.

Criteria for Separate Resources

Neuroscience. Research on the neural correlates of egocentric and allocentric frames of reference have some general consensus, but also a lot of uncertainty surrounding them. Overall, the literature seems to point towards a frontoparietal network of activation for egocentric tasks and hippocampal activation for allocentric tasks. These conclusions are not unanimously agreed upon and there is contradicting literature; however, most studies have found different neural correlates when comparing the two frames of reference.

Egocentric Frame of Reference. Galati and colleagues (2000) were some of the first to investigate the neural correlates of frames of reference through fMRI. Participants in their study decided if a vertical line that intersected a horizontal line was to the left or right of a body-based (egocentric) midpoint or a screen-based (allocentric) midpoint. They found activation in the frontoparietal network with extensive activation in the right hemisphere on the egocentric trials. In a similar study, Ruotolo and colleagues (2019) found the same results, with most activation in the frontal and parietal regions of the brain. These results have been supported in a number of other studies (i.e., Zaehle et al., 2006; Gramman et al., 2006), including a brain lesion study showing that patients with lesions in the right parietal lobe exhibited spatial neglect and/or deficits in representing the location of objects and people in relation to themselves (Vogeley & Fink, 2003). Together, these studies provide strong evidence to support the claim of frontoparietal network activation in egocentric tasks.

Allocentric Frame of Reference. The hippocampus appears to be the main neural area activated for tasks requiring an allocentric frame of reference. Burgess and colleagues (2002) conducted a review of the literature supporting cognitive map theory, which states that the hippocampus represents locations and contexts of environments. They found an abundance of results that suggest the hippocampus is involved in complex navigation and specifically, the right hippocampus is involved in general allocentric object location and navigation. More recently, Ekstrom, Arnold and Iaria (2014) provided a critical review of the literature surrounding the hippocampus as an allocentric neural correlate. They cited studies of rats with lesions to the hippocampus that were unable to complete the Morris Water Maze task, an allocentric based navigation task regarding an underwater platform and external landmarks. They also referenced studies that found the human hippocampus to be active in allocentric but not egocentric tasks, as well as findings supporting the parahippocampal cortex being involved in navigation. Both reviews also referred to studies that showed impairment in allocentric spatial navigation abilities of people with lesions to the parahippocampal cortex but not the hippocampus, and vice versa, indicating the importance of both areas to allocentric spatial abilities.

Transformations Between Egocentric and Allocentric Frames of Reference. The main brain area found to be activated in transforming spatial information between egocentric and allocentric FoR is the retrosplenial cortex (RSC). Clark and colleagues (2018) found considerable overlap in active neurons in the RSC for coding egocentric and allocentric spatial scenes. They theorize that the RSC is more specialized for allocentric coding, but does play a role in both. It has also been found in rodent brains that the RSC has place cells that guide flexible spatial behavior and, in rodents, is the site for transformations (Wang et al., 2020). Additionally, in both primates and humans, the RSC has been shown to have connective patterns with medial temporal lobe structures, supporting the theory that the RSC plays a crucial role in the translation between frames of reference (Boccia, et al., 2017). While transformations between the frames of reference are not a part of the criteria for being considered separate resources, it does indicate that the two are related and may need to be taken into consideration when determining how they interact in time sharing formats.

Disagreement in the Literature. While there is a general consensus that the neural correlates for each FoR are separate, there is still some disagreement across the literature. Lesion studies have shown that egocentric and allocentric neglect can occur simultaneously, suggesting that some parts of the brain may be responsible for both FoR (Galati et al, 2000). The studied lesions are not always in the same brain area, further complicating attempts to understand the neural correlates. Studies have also found significant overlap in the activation areas between frames of reference, especially in circumstances where egocentric tasks have activated the hippocampus or activated a subset of allocentric activations (Zaehle et al, 2006; Wang et al., 2010). The uncertainty in the literature could be due to methodology differences (see Ekstrom et al., [2014] for a discussion of methodology) and therefore may be difficult to discern through neuroscience studies alone.

It is also possible that rather than the underlying frame of reference, differences in the nature of egocentric and allocentric judgements might cause variations in the neurological correlates. Kosslyn et al. (1989) proposed two distinct forms of spatial relations: categorical (such as up/down/left/right) and coordinate (distance-based). These can occur in both egocentric and allocentric tasks, but if the type of judgment across the frame of reference taps different spatial relations, then different areas of the brain will be activated for reasons other than differences in the frame of reference. For example, judging the distance between two objects might employ coordinate spatial relations in an allocentric frame of reference ("the mouse is six inches from the keyboard"), whereas judging the relative location of an object to yourself might employ categorical spatial relations in an egocentric frame of reference ("the mouse is to my right"). Leaving aside whether differences in spatial relations might rely upon additional separate pools of resources, it is critical not to confound the two dimensions of relations and frame. Thus, properly assessing the influence of frames of reference requires matching the type of spatial relations judgments across conditions.

Additionally, egocentric and allocentric judgements are not completely dichotomous, but fall along more of a continuum. Consider a "tethered" viewpoint, where the display screen shows a view as if a camera was behind and above the person at a 45-degree angle (see Wickens, Vincow & Yeh, 2005 for pictorial representations). While this is technically an allocentric point of view, the user still sees the external world in relation to themselves (i.e. “right” on the screen is to their actual right), which presents an egocentric component. This type of view was not used in the neuroscience literature reviewed here, but it is another example of why the categorization of frames of reference may be complex both in neurological and cognitive science.

In sum, if two tasks using different frames of reference can clearly be effectively time shared, it may suggest that they are different resources and therefore have different neural correlates. If they cannot be time shared, it may be that the overlap and inconsistencies seen in neuroscience studies is due to the nature of frames of reference and not methodological differences. Based on the current literature, it is likely that egocentric and allocentric frames of reference activate different neural structures, suggesting that they do meet the neurological-based criteria for being considered different resources. The behavioral research conducted in this experiment will hopefully provide more insight. If the frames of reference are able to be effectively time shared, this would provide more support for the activation of different neural structures and may point to the differences in tasks and methodologies as a potential reason for the larger discrepancies in neural correlates.

Applications. Another requirement for consideration of multiple resources is applications to design. Applications of frames of reference have been extensively studied in navigation, especially aviation and driving, producing an overall unanimity for the best use of each frame of reference. An egocentric frame of reference is best for navigation tasks that require local guidance (Olmos et al., 2000) and an allocentric frame of reference is best for global spatial or situational awareness (Wickens & Prevett, 1995). Much of the reasoning for these conclusions stems from the inherent benefits and drawbacks of each frame of reference.

Egocentric Viewpoints. A fully egocentric viewpoint is essentially identical to the viewpoint of our eyes (Wickens et al., 2005). Even within this constraint, there are various ways to design egocentric displays. From our actual bodily viewpoint, we can turn our heads to see outside our straightforward line of vision, which some displays mimic through specific degrees of view that can be rotated. Displays can also keep specific degrees of view without rotation, or they can be slightly askew from the straightforward field of view (i.e. as if from the top of the person's head).

An egocentric FoR has three main advantages: (1) It is a natural view so there are no transformations necessary to maintain the user's current viewpoint, which helps keep cognitive workload steady; (2) Targets ahead of the user are viewed with depth perception so their movement is easier to perceive, as is the ability to interact with or avoid them; (3) The location of targets or objects in relation to the user is as they appear in the display (i.e. an object on the left of the screen is to the user's left). These advantages are most beneficial in navigation or tracking tasks (Wickens & Prevett, 1995; Wickens et al., 2005). An egocentric frame of reference also can reduce cognitive workload in navigation tasks because it reduces the mental rotation necessary to determine where a person is or is going (Aretz & Wickens, 1992). When creating navigation aids, track-up maps use the egocentric viewpoint. A track-up map will follow the navigator, turning to face the same direction they do; meaning north will change direction on the display in relation to the user's point of view. Track-up maps have been shown to be useful for target navigation tasks, distance estimation, and overall accuracy and speed in navigation (Wickens et al., 2005; Wen, et al., 2013; Rodes & Gugerty, 2012). They are beneficial for quick and accurate target navigation, whether it be needing to drive to an unfamiliar place or locate a target such as a hurt comrade in a military scenario.

However, egocentric frames of reference also have large drawbacks. Most importantly, they tend to have a “keyhole cost,” which results when dynamic information outside the current field of view is not seen (Wickens, 2003). Even when a display can be rotated, it does not guarantee that the change will be seen or processed (change blindness). Part of the reason a change may go unnoticed is because when panning, the viewpoints must be held in working memory and then integrated, which can create a heavy cognitive workload (Wickens et al., 2005). This may not be performed well when other tasks are using mental resources, which is often the case when navigating. These costs are also seen in track-up maps, as their representation of the environment is unstable and changing so the user often lacks strong situation awareness and doesn’t learn functional knowledge of the environment that could be used if there was no navigation aid available.

Allocentric Viewpoints. An allocentric viewpoint represents targets or locations based on an external framework (Klatzky, 1997). Often, this framework is based around cardinal directions or other targets, such as when one says “the grocery store is north of the home improvement store.” Allocentric viewpoints fall along a continuum. A display may be static, such that the borders of the display do not move and the same area is always represented, or it may be more dynamic, where the area within the display changes based around a specified parameter, such as a radar screen used by air traffic control. An environment also may be represented from an above, “God-like” point of view, or somewhere closer to egocentric, such as behind and slightly above the user, where they can still see the representation of their location.

The biggest benefit from an allocentric frame of reference is support of situation awareness (Wickens et al., 2005; Endsley, 1995). Because an allocentric frame of reference allows most of or the entire environment to be seen at once, keeping slices of it in working memory and combining them to create a mental picture is not necessary. The user is less likely to miss a change in the environment and can scan far larger areas than from an egocentric point of view. On the other hand, allocentric frames of reference are less likely to benefit performance on tasks that require direct navigation, distance estimations or bearing identification (Klatzky, 1997).

North-up maps are inherently allocentric, which makes them also associated with the benefits and drawbacks of an allocentric point of view. A north-up map is stable, with north always at the top of the frame, making it so that locations can easily be seen in relation to each other, but not so easily in relation to the user's current point of view. The stability of these maps encourage spatial awareness and functional navigation information. They are useful when trying to learn a new environment (Taylor et al., 2008). However, these allocentric maps tend to require higher cognitive workload during navigation because of the necessary mental rotation and transformation to align your current view with the map. They also tend to show decreased accuracy in navigation and longer reaction times for responses to location queries in comparison to track-up maps (Williams et al., 1996). This can be an issue if the user needs to arrive somewhere without errors, such as military personnel reaching a safe landing zone.

Time Sharing. In some situations, there is a clear benefit to using a north-up or track-up map, or a different form of an egocentric or allocentric viewpoint. Finding the correct exit on an unfamiliar highway lends itself to a track-up map or egocentric viewpoint to assist in distance estimation and reduce the cognitive workload. Moving to a new city and learning the layout of the town can benefit from an allocentric or north-up map because it allows high interest locations to be mentally mapped out in relation to other locations, which is useful when the starting point of travel changes (i.e. going to store B from store A, rather than from home to store A). However, there are situations in which the consideration of these factors is not so clear-cut, and concurrent access to both points of view would be useful.

Imagine you are a soldier in a warzone with a hurt comrade to rescue, unreliable service for your navigation system, and your life on the line. It's important to get to the victim quickly and accurately, as a wrong turn could put you face to face with an enemy, but it's also important to gain a functional knowledge of the area in case your navigation system loses service. In this case, a north-up, egocentric map would help with accuracy and target location, but a track-up, allocentric map would be most helpful in learning the environment. It can be difficult to combine the two maps in a functional way, but moreover, not much is known about the ability of time-sharing and concurrent processing between the two frames of reference. It is unclear if egocentric and allocentric resources are separate or overlapping, which would help determine timesharing abilities. However, situations in which this parallel processing is necessary do arise, often in military and aviation settings.

In conclusion, determining the allocations of resources could have major implications for the design of navigation systems. Previous research has generated theories surrounding each frame of reference in their applications, advantages and disadvantages, and neurological correlates, all of which indicate support of different resources. However, without understanding the timesharing abilities of frames of reference, their resource dependency distinction cannot be defined under the MRM. In the neuroscience literature, it seems that the retrosplenial cortex is responsible for transforming spatial information between egocentric and allocentric frames of reference, which suggests the two can work together. Explicitly determining time sharing abilities will help define them as being supported by separate or the same resource(s). While this will fill a theoretical gap in the literature, it also has larger implications in applications for use and design.

The current experiments used a dual task paradigm to determine how multitasking performance for various pairs of frames of reference conditions compare to each other and to control tasks. The tasks were drawn from the existing neuroscience literature (Galati et al., 2000; Zaehle et al., 2006). Line judgements were provided in an egocentric (EL) or allocentric (AL) version. The secondary task was audio stimuli, asking about the spatial relationships of shapes in egocentric (EA) or allocentric (AA) terms. Combining these four options provided four trial types for participants, EL-EA, EL-AA, AL-EA, and AL-AA. For a control condition, line judgements were made on color (CL) rather than based on the egocentric or allocentric frame, producing two more categories: CL-EA and CL-AA. Making color judgements is intended to be associated with neither egocentric nor allocentric frames of reference because color discrimination is not a spatial task. This condition is considered to provide a neutral assessment of the overall cognitive demands of the auditory task. Based on current literature, it was hypothesized that:

1. Performance on incongruent (egocentric-allocentric) line-audio tasks will be better compared to congruent (egocentric-egocentric or allocentric-allocentric) line-audio tasks because there will be less resource competition.
2. Performance on dual tasks involving color judgements will be better than those involving the same frame of reference judgements because there is no spatial resource involved in

color judgements, compared to the competition for the spatial resource in the dual frame of reference trials.

3. Performance on dual tasks involving color judgement will be similar in performance to those involving different frame of reference judgements because both types of tasks involve different resources and therefore time sharing will not be worse in one condition than the other.

EXPERIMENT ONE

Methods

Participants. 54 Colorado State University Psychology students participated in the online study for partial course credit. All self-reported not being colorblind. *A priori* power analyses were conducted based on an effect size of 0.2 at alpha .05. The correlation between the secondary tasks was unknown, but based on limited pilot data, the number of correct responses in each category appeared very similar. With a strong correlation of r=.7, the power calculation suggested 42 participants would be necessary; with a correlation between measurements of the secondary task of r=.5, a sample of 66 participants would be necessary. Therefore, a sample size 54 participants was expected to provide enough power to detect a small effect with a medium to high correlation between audio responses, while allowing for some fluctuation in the correlation of the measures.

Task. Participants viewed 11 second videos during which six lines appeared on the screen for 1.5 seconds each. The lines were a medium shade of green, intersected by a short vertical line in differing shades of green (Figure 1). Horizontal lines appeared across the middle of the screen with variability in the x-axis locations, and the vertical lines could intersect the horizontal line at 10 different intervals. Before each video played, participants were told to count the number of times the vertical line appeared in a specific spot or hue. For egocentric tasks, participants counted the number of vertical lines that were to the right or left of the center of their body, regardless of color or location in relation to the horizontal line. For allocentric tasks, participants counted the number of vertical lines that intersected the horizontal line to the right or left of the horizontal line's center, regardless of color or location in respect to their bodies. Importantly, both of these judgments demand the use of categorical spatial relations, varying only the frame of reference. For control tasks, participants counted how many times the vertical line was lighter or darker than the horizontal line, regardless of position.

Figure 1. Examples of the shades of vertical lines and four possible locations of the vertical line.

Concurrent with the line task, a secondary task was implemented in which participants listened to an auditory cue describing the position of three shapes and then answered a question based on the information. Egocentric audio cues described the shapes in relation to the participant's body (i.e. "the circle is to your right"). Allocentric audio cues described the shapes in relation to each other through cardinal directions (i.e. "the circle is north of the square). Together, these tasks created six categories: egocentric congruent, allocentric congruent, egocentric incongruent, allocentric incongruent, control egocentric, and control allocentric. Congruent trials meant the line and audio tasks were the same frame of reference, whereas incongruent trials had different frames of reference for each task.

Procedure. Data was collected online through Qualtrics, therefore participants used a personal device with an ability to press buttons on screen, listen to sounds, and respond with key presses. After consenting, they were asked to put their browser into full screen mode and presented with instructions to center their computer screen with their body, aided by a graphic.

Then, they listened to an audio cue to adjust their volume as needed and saw Figure 1 with explanations of lighter and darker lines with a chance to adjust their computer brightness if needed. They experienced three practice trials where they determined the position and hue of the line as a single task. Participants received instructions detailing the types of audio cues they would hear and practiced with one egocentric and one allocentric cue. Once participants practiced the single tasks, they experienced two practice trials that were exactly like the experimental trials; one was the egocentric incongruent condition, and the other was the control condition with egocentric audio. Correct answers were required before the experimental trials could start. After the experimental trials, participants were debriefed and given course credit.

Experimental Design. The study measured accuracy of line and audio tasks across three types of lines (egocentric, allocentric, color) and two types of audio (egocentric, allocentric; see Table 1). Each trial type was tested ten times and blocked together. The blocks contained five trials of each sub-type (i.e., counting the vertical bar to the right or to the left, or lighter or darker). The blocks and trial sub-types were presented in a random order to each participant. Participants were offered an optional break between blocks. No feedback was provided on responses except on the practice trials.

Table 1. All dual task combinations experienced by participants.

Line	Audio
Egocentric	Allocentric
Egocentric	Egocentric
Allocentric	Allocentric
Allocentric	Egocentric
Color	Egocentric
Color	Allocentric

Results

Average accuracy across all trials, combined for the line and audio tasks, was 65%, suggesting a difficult but not impossible task. Performance was highest on the incongruent trials at 66% accuracy for both line-audio combinations. Accuracy was not much lower on congruent trials at 65% for egocentric and 61% for allocentric.

Importantly, overall accuracy, averaged over the lines and the auditory task, for the congruent tasks was 63%, as compared to 66% for incongruent tasks. This was marginally significant ($t(53) = 1.97$, $p = .05$, $d = 0.21$), but may suggest, consistent with the first hypothesis, that frames of reference are different resources under the MRM. 55% of participants increased their accuracy in the incongruent condition from the congruent condition. On line accuracy alone, 66% of participants increased their accuracy in the incongruent condition, and 88% of participants increased their audio accuracy in the incongruent condition. These patterns indicate that the differences are not driven by a few outliers. Accuracy averages for all trial types are listed in Table 2.

Table 2. Accuracies averaged for line and audio tasks across all combinations of line-audio trials.

Lines	Audio		
	Egocentric	Allocentric	Average
Egocentric	65%	66%	66%
Allocentric	66%	61%	64%
Color	67%	68%	67%
Mean	66%	65%	66%

Audio Accuracy. To better understand the marginal overall significance between trial types, a 2 (line type) by 2 (audio type) repeated measures ANOVA was run on the accuracy of audio trials, as shown in Figure 2 and Table 3. There was a main effect of line type (F(1,53) = 5.59, p = .02, η_p^2 = 0.09), where allocentric line tasks made the audio task harder than the egocentric line tasks did. There was no main effect of audio type (F(1,53) = 0.43, p = .51, η_p^2 = .01). The interaction marginally failed to reach significance (F(1,53) = 3.50, p = .06, η_p^2 = .06), which again may suggest that using different frames of reference improves performance on the audio task.

Table 3. Accuracies for audio tasks for trials across all conditions.

Lines	Audio		
	Egocentric	Allocentric	Average
Egocentric	69%	75%	72%
Allocentric	66%	63%	65%
Average	68%	69%	68%

Planned comparisons looking first at the egocentric audio task indicated there was a marginal difference between congruent trials (69%) and incongruent trials (66%; t(53) =-1.81, p = .07, d = 0.22), suggesting that performance of the egocentric audio task may be superior when coupled with the egocentric line task than when the egocentric audio task was combined with the allocentric line task. For the allocentric audio task, there was a sizable difference between congruent trials (63%) and incongruent trials (75%; t(53) = -2.82, p = .006, d = 0.48), suggesting that pairing the allocentric audio task with the egocentric line task was better than pairing it with the allocentric line task. All results stand when the alpha level is adjusted through a Bonferroni correction to .025 for the multiple comparisons. While the latter of these comparisons supports the hypothesis that tasks using different frames of reference can be time shared better than tasks using the same frame of reference, the first comparison does not support that hypothesis.

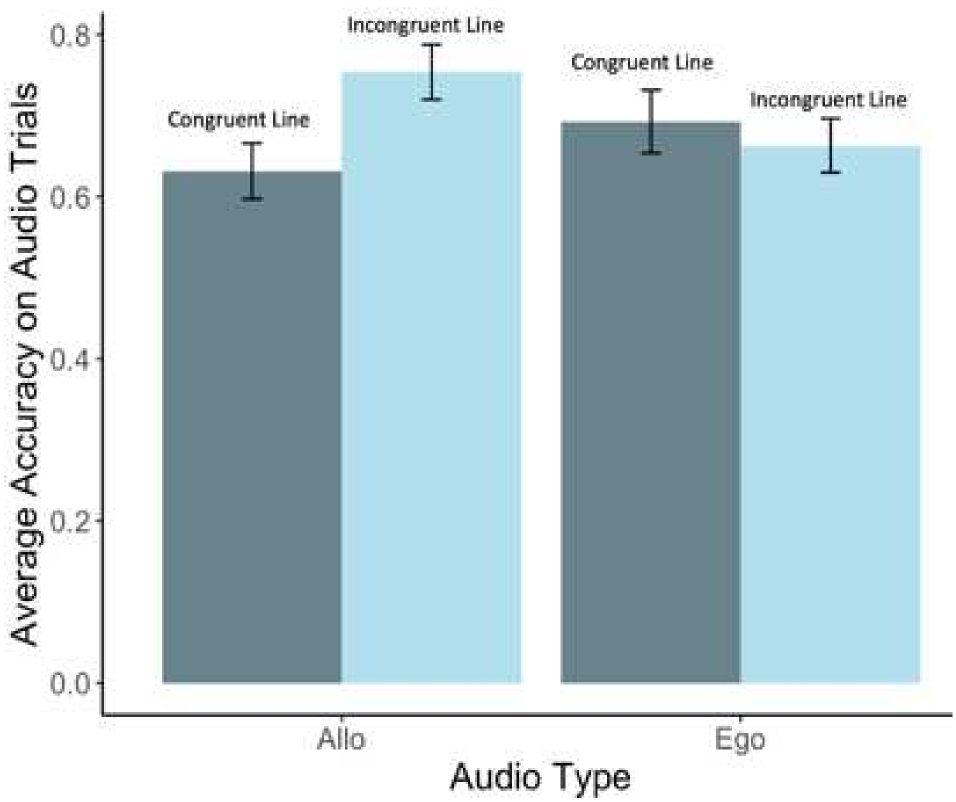

Figure 2. Accuracy on audio questions based on line-audio combinations. Error bars represent one standard error.

Line Accuracy. A 2 (line type) by 2 (audio type) repeated measures ANOVA was run on the accuracy of line trials as shown in Figure 3 and Table 4. There was no main effect of line type (F(1,53) = 2.95 *p* = .09, $\eta_p^2 = 0.04$). There was a main effect of audio type (F(1,53) = 7.67, *p* = .007, $\eta^2 = 0.12$), where allocentric audio made the line task more difficult than egocentric audio. The interaction was not significant (F(1,53) = 1.05, *p* = .30, $\eta_p^2 = .04$).

Table 4. Average accuracies for line tasks across all trial types.

Lines	Audio		
	Egocentric	Allocentric	Average
Egocentric	61%	57%	59%
Allocentric	66%	59%	63%
Average	64%	58%	61%

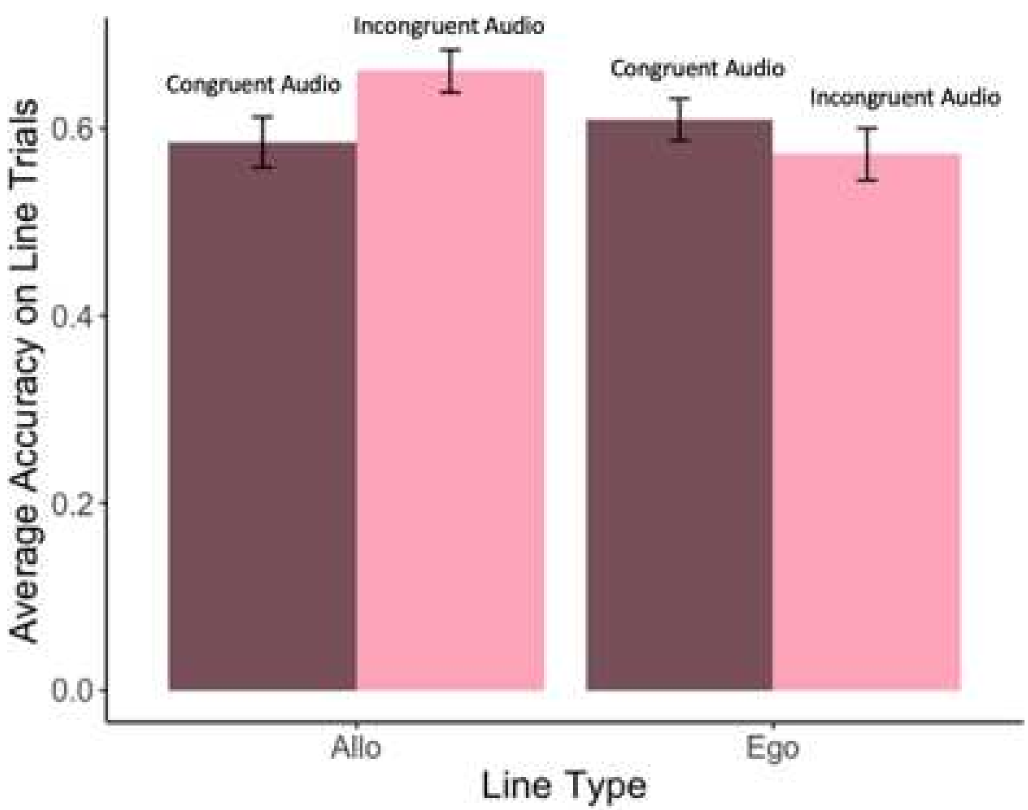

Figure 3. Accuracy on line questions based on line-audio combinations. Error bars represent one standard error.

Planned comparisons showed no difference on the egocentric line task between congruent audio trials (61%) and incongruent audio trials (57%; $t(53) = -1.31$, $p = .19$, $d = 0.19$) but there was a difference for the allocentric line task between congruent trials (59%) and incongruent trials (66%; $t(53) = -2.76$, $p = .007$, $d = 0.41$). This indicates that the allocentric line task was performed better when combined with the egocentric audio task than with the allocentric audio task. The results of the planned comparisons stand when a Bonferroni correction is applied and a new alpha level of .025 is used. As in the above audio accuracy results, the line task performance offers some support for the hypothesis that using difference frames of reference improves performance.

Cost and Benefit Comparisons. The control condition was then used for comparisons to determine the costs and benefits of congruent and incongruent frames of reference. For all comparisons, the application of a Bonferroni correction and new alpha level of .0125 does not change the statistical significance of the findings. For egocentric audio tasks, there was no difference between the control condition (62%) and incongruent condition (66%; $t(53) = -0.95$, $p = .34$, $d = 0.16$); and no difference between the control condition and the congruent condition (69%; $t(53) = -1.49$, $p = .13$, $d = 0.24$). These findings are consistent with those above in showing that the line task paired with the egocentric audio task does not influence performance.

For allocentric audio tasks, there was not a significant difference between the control (62%) and congruent condition (63%; $t(53) = -0.23$, $p = .81$, $d = 0.04$), but there was a significant difference between the control and incongruent condition (75%; $t(53) = -3.58$, $p < .001$, $d = 0.61$). Enhanced performance in the incongruent condition compared to the control condition suggests that there is a benefit in using two different frames of reference. It also indicates that the differences are not due to a cost of trying to use the same frame of reference resource for two tasks, nor from some type of interference with the task properties, because the combination of allocentric audio with allocentric line task is no worse than the combination of allocentric audio with the control line task.

Discussion

Experiment 1 examined three main hypotheses. First, it was hypothesized that performance on incongruent tasks would be better than on congruent tasks, which was marginally supported. Based on the theory that separate resources better support time sharing as compared to the same resource, the higher accuracy and improved performance by 55% of participants on incongruent tasks suggests that these two frames of reference may be different resources. However, using the 55% as an effect size under the percent correct classifications (Grice et al., 2020), and a p-value of .05, there is only slight evidence in favor of the two frames of reference. Additionally, only the interaction of line and audio frame of reference on audio accuracy was near significance, while the interaction on line accuracy was not. Thus, it is difficult to draw concrete conclusions, and this is further examined in Experiment 2.

The second hypothesis, that performance on the control trials would be better than those involving the same frame of reference, was disconfirmed. Overall accuracy in the control condition was only 2% more accurate than the congruent trials, which has no statistical or practical significance. For audio performance, the control condition was no different than any of the congruent conditions. This is somewhat surprising, given the findings supporting different frames of reference. Discriminating the color of a visually presented line demands verbal resources (as seen in the Stroop task), rather than spatial resources. This means that fewer of the same resources are employed for a frame of reference and color dual task scenario than would be the case for the congruent FoR task. Performance here, compared to that of the congruent trials was expected to be better because drawing from different resources better supports time sharing.

The marginal significance of the first hypothesis and very small effect size coupled with this finding may suggest that all FoR judgments tap one resource. It is important to note that the difficulty of the color task in comparison to the FoR tasks may not have been the same, which could also be a factor in these results.

The final hypothesis, that performance on control trials would be similar to the incongruent trials, was confirmed for overall accuracy. This may support the first hypothesis, as the similarity in performance may suggest that both types of trials use separate resources. However, accuracy on the control tasks was significantly worse than the egocentric incongruent condition, which does not support this hypothesis. Coupling these findings with the results that control and congruent trials are not significantly different complicates the conclusions that can be drawn about resource use. It seems that generally, different frames of reference are better under dual task conditions, but importantly, these results do not systematically align with any prediction the MRM would have made, which will be returned to in the General Discussion.

EXPERIMENT TWO

In Experiment 1, the difference in performance on congruent and incongruent trials was only marginally significant, with only a significant interaction for audio accuracy. One reason the difference in performance was low could be that the cognitive resources involved were not at maximum use. Although overall accuracy was not particularly high, the tasks were difficult and near perfect performance was not expected. When cognitive resources are not at their maximum load, it is likely that people are better able to multitask, regardless of resource congruency (e.g., Collet et al., 2010). The current study aimed to increase the difficulty of each trial by increasing the cognitive load on participants to amplify the interactions seen in Experiment 1. The number of lines was increased and the time they were viewed was shortened. It was hypothesized that the overall accuracy would be lower here than in Experiment 1 due to the increase in difficulty and resource use. Additionally, performance on the control trials was again expected to be better than congruent trials and similar to incongruent trials. Lastly, it was expected that performance would be significantly worse on congruent trials than incongruent.

Methods

Experiment 2 was the same as Experiment 1 except for the following:

1. 50 undergraduates participated for partial credit.
2. Each video now contained 11 lines rather than 6, making the lines visible for half a second each (rather than 1.5 seconds each). The first six lines were the same as those in Experiment 1, the last five were new. The audio task remained the same.

Results

Validating the intent to increase task demands, average accuracy across all trials was 58%, which is significantly lower than in Experiment 1 ($t(103) = 2.88$, $p < .005$, $d = 0.56$). Performance was highest on the allocentric congruent and allocentric-line incongruent trials at 59%, but was not much lower on the egocentric congruent trials at 57%. Accuracy was lowest on the egocentric-line incongruent trials at 48%.

Importantly, accuracy for the congruent tasks was 56%, as compared to 52% for incongruent tasks. This is a significant difference ($t(49) = 2.89$, $p = .005$, $d = 0.29$), however, this does not support the hypothesis that egocentric and allocentric frames of reference are different resources because the improved performance was on congruent tasks, rather than incongruent. Of people whose score differed between the two conditions, 66% had lower scores in the incongruent versus the congruent condition, suggesting these results are not simply due to a few participants with large differences across conditions.

Table 5. Overall accuracies of all audio-line frame of reference task combinations.

Lines	Audio		
	Egocentric	Allocentric	Average
Egocentric	58%	48%	53%
Allocentric	60%	61%	61%
Color	64%	62%	63%
Mean	61%	57%	59%

Audio Accuracy. A 2 (line type) by 2 (audio type) repeated measures ANOVA was conducted on audio accuracy as shown in Figure 4. There was a main effect of line type (F(1,49)

= 13.49, $p < .001$, $\eta_p^2 = .21$), where egocentric lines made the audio task harder than allocentric lines. There was no main effect of audio ($F(1,49) = 0.40$, $p = .53$, $\eta_p^2 = .01$), but there was a significant interaction ($F(1,49) = 4.78$, $p = .03$, $\eta_p^2 = 0.08$), likely driven by the low accuracy (57%) on the incongruent condition for the allocentric audio task.

Table 6. Accuracy of audio tasks across all conditions

Lines	Audio		
	Egocentric	Allocentric	Average
Egocentric	64%	57%	61%
Allocentric	65%	69%	67%
Average	65%	63%	64%

In follow up planned comparisons, for the egocentric audio task there was no significant difference between congruent (64%) and incongruent (65%) conditions ($t(49) = -0.33$, $p = .74$, $d = 0.05$). For the allocentric audio task, there was a significant difference between the congruent condition (69%) and the incongruent condition (57%; $t(49) = 4.05$, $p < .001$, $d = 0.65$), with this large effect showing better performance when allocentric audio was coupled with the allocentric line task than when combined with the egocentric line task. This is again not predicted by the MRM because the congruent conditions that should tap more of the same resource pool had significantly higher accuracy.

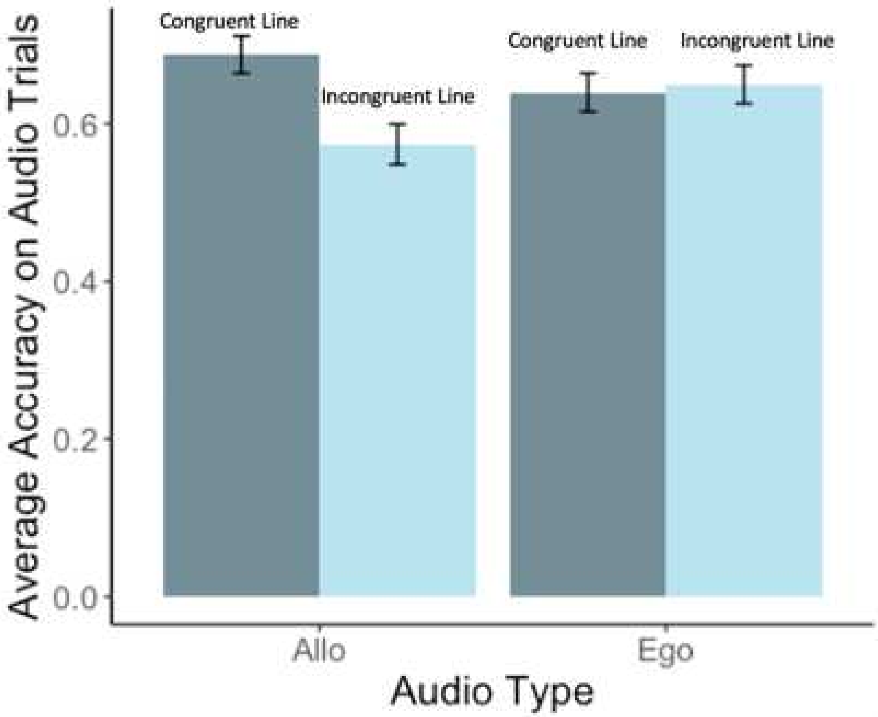

Figure 4. Accuracy of audio questions by line-audio combination. Error bars represent one standard error.

Line Accuracy. A 2 (line type) by 2 (audio type) repeated measures ANOVA was then conducted on line accuracy. There was a main effect of line (F(1,49) = 4.60, p = .03, η_p^2 = .08), where egocentric lines were harder than allocentric. There was also a main effect of audio (F(1,49) = 6.46, p = .01, η_p^2 = .11), where the line task was harder when the audio task was allocentric rather than egocentric. There was a marginally significant interaction (F(1,49) = 3.32, p = .07, η_p^2 = .06) that likely reflects the very low accuracy (39%) in the egocentric line incongruent condition.

Planned comparisons showed a significant difference in the egocentric congruent trials (52%) compared to the incongruent trials (39%; t(49) = -3.10, p = .003, d = 0.43). Although the difference is large, the improvement is on the congruent trials, which is inconsistent with the predictions from the MRM. There was not a difference between allocentric congruent (52%) and incongruent trials (54%; t(49) = -0.52, p = .60, d = 0.07). For all comparisons, the application of a Bonferroni correction and new alpha level of .0125 does not change the statistical significance of the findings.

Table 7. Accuracies of line tasks across conditions.

Lines	Audio		
	Egocentric	Allocentric	Average
Egocentric	52%	39%	46%
Allocentric	54%	52%	53%
Average	53%	46%	49%

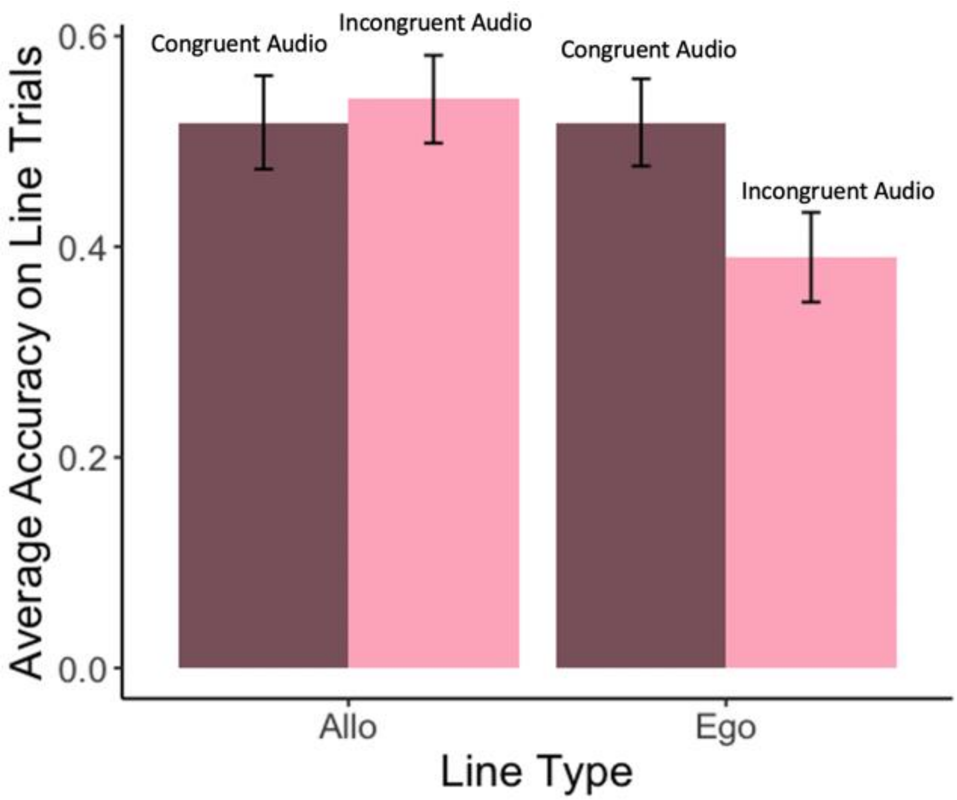

Figure 5. Accuracy of line tasks by line-audio combination. Error bars represent one standard error.

Cost and Benefit Comparisons. Control trials were used for comparisons to determine the costs and benefits of the same and different resource use. Once again, Bonferroni corrections were not applied as statistical significance would not be impacted by a lower alpha. There was a significant difference in audio accuracy for allocentric congruent trials (68%) and allocentric control trials (60%; $t(49) = -3.46$, $p = .001$, $d = 0.44$). However, the control allocentric trials were not significantly more accurate than the incongruent trials (65%; $t(49) = 0.95$, $p = .34$, $d = 0.16$), which was true for 70% of participants. This suggests there is a benefit to sticking with the same frame of reference. For egocentric audio trials, there were no differences between control (69%) and incongruent (65%; $t(49) = 1.49$, $p = .14$, $d = 0.24$) or control and congruent (64%; $t(49) = 1.60$, $p = .11$, $d = 0.30$), suggesting that secondary task combination for egocentric tasks does not matter. This could potentially support the MRM, but may not reach significance due to a lack of power.

Comparing Experiments 1 and 2. Accuracy in Experiment 2 was lower than Experiment 1 ($t(103) = 2.88$, $p < .005$, $d = 0.56$), as expected. The main difference between the two experiments was the trends in performance between congruent and incongruent trials. Experiment 1 showed slight support for improved performance on incongruent trials overall and for audio accuracy, but Experiment 2 showed stronger support for improved performance on congruent trials. For line tasks, however, Experiment 1 indicated incongruency is better for allocentric tasks, but Experiment 2 indicated congruency is better for allocentric tasks. Looking only at audio tasks, both experiments suggested that the pairing of a secondary task with an egocentric frame of reference does not matter. For allocentric audio tasks, Experiment 1 suggested incongruency is better but not because of a cost in congruency, whereas Experiment 2 suggested that congruency is better because there is an actual benefit. These are very contradictory results that arise from the changes in difficulty across experiments. This is discussed further in the General Discussion.

Discussion

Experiment 2 was intended to increase the load on cognitive resources to further test the interference between FoR. The decrease in overall accuracy suggested that cognitive resources were stressed more and confirmed the first hypothesis that performance would be worse than in Experiment 1. Performance was no different for overall accuracy in the control conditions than in either congruent or incongruent conditions, which disconfirms the second hypothesis. This was also true for egocentric audio accuracy. However, when looking at allocentric audio trials, the control condition was significantly worse than the congruent condition, which may suggest there is a benefit to using the same resource in a dual task environment when load is high.

Most notably, there was better performance under congruent conditions compared to incongruent conditions, which disconfirmed the second part of the second hypothesis and is not predicted under the Multiple Resource Model. The reason for these results is not immediately clear, although it may be a result of task switching costs or shared processing routines, rather than resource interference. Previous research has shown that when two tasks are governed by the same rules, concurrent processing can be better supported (e.g. Duncan, 1979; Fracker & Wickens, 1989; Rogers & Monsell, 1995). That is likely the case here, however, there is no obvious basis to predict this change in the outcomes would occur in Experiment 2 compared to Experiment 1, where identical tasks were presented at a slower rate. There are a few pieces of evidence that support the similarity based cooperation account: Similar performance in the control and incongruent conditions indicates that the change of rules between tasks makes it more difficult than when using the same rules (as seen in the congruent conditions) and it is not simply different resources being used in the control condition as the congruent condition; a slight (but not significant) improvement in the congruent condition over the control condition again indicates it may be that the rule similarity improves performance; and significantly better performance in the allocentric congruent condition than the allocentric control condition all support task similarity as an explanation for these results.

GENERAL DISCUSSION

The current experiments were designed to test cognitive resource interference between egocentric and allocentric frames of reference. Stimuli from neuroscience frame of reference research were adjusted and used to create a dual-task paradigm to assess capabilities of egocentric and allocentric time sharing. Experiment 1 assessed time sharing capabilities under a lower cognitive load, and Experiment 2 aimed to increase the resource use associated with both tasks to further assess time sharing abilities.

Very little replicated across experiments. The primary effect that did replicate was that the frame of reference for the line task, when paired with an egocentric audio task, did not change performance on either task. This is an interesting effect because it does not align with any prediction of the Multiple Resource Model (MRM) or the hypotheses. This could be because egocentric audio tasks were easier than allocentric audio tasks, as the former trended towards higher accuracy than the latter. The egocentric audio tasks may have been easy enough to not warrant heavy dual task interference.

Multiple Resource Model Framework

Frames of reference already appear to meet two of the three criteria necessary to be considered separate resources (neural correlates and applications to design). It was hypothesized that they would meet the time-sharing criteria and thus be considered separate resources. Experiment 1 suggested this might be true with marginally higher accuracy on trials involving an egocentric-allocentric combination (incongruent) as compared to those using the same frame of reference (congruent), but Experiment 2 suggested the opposite. 60% of participants in Experiment 2 had improved performance on the congruent trials compared to the incongruent trials, which provides evidence that the difference was not due to any outliers but instead was a consistent pattern. This was not only unexpected, but also directly contradicts any prediction of the MRM. If the frames of reference were the same resource, results would have shown no major difference in performance between incongruent and congruent trials. Yet, the results indicating improved performance on the congruent trials under higher workload were much stronger than those indicating separate resources.

The marginal support in Experiment 1 for improved performance on incongruent tasks may be a result of the lower difficulty of the trials. Lines appeared on the screen for a second and a half, which provided an ample amount of time for participants to recognize the line, make a decision, and refocus their attention to the audio cue. The lower level of difficulty may have allowed participants to time share the two tasks without any major decrement to performance, regardless of frame of reference use or task type. However, when the lines were present for only half a second in Experiment 2, the difficulty and cognitive resource use were increased. While it was hypothesized that this would amplify the interaction of line and audio task type, instead, it created unpredicted results.

One possibility for the unexpected improvement in performance is that under higher workload, frames of reference are subject to similarity based cooperation. Although it has been shown that task similarity can induce confusion between tasks or elements due to an increase in interference - for instance, attempting to count while someone else is also counting out loud, sometimes task similarity can be beneficial. When the rules that govern two tasks are similar, it can improve concurrent processing (Fracker & Wickens, 1989). Specifically, when considering the fast pace of Experiment 2, the need to switch between the mental rules of "is this line to my left/right?" and "is the shape to the north/south/ east/west?" is much more difficult than considering all shapes and lines in the same way. For this reason, it may be that the results of Experiment 2 are explained by the shared processing routines hypothesis, which states that more similar rules between two tasks increases the ability of them to be performed simultaneously, and such similarity dominates when more rapid switching is required (Duncan, 1979).

In a slightly more recent study, Rogers and Monsell (1995) found that when one target and one "irrelevant" (supposed to be ignored) visual stimulus were shown together, response time was faster on congruent trials where the irrelevant stimulus would have produced the same response as the target than on incongruent trials. Although response time was not measured in the current research, faster responses in counting the target lines could have allowed easier switching between the audio and line tasks, and therefore improved performance. Post-hoc, this explanation is not surprising, but questions remain surrounding the classification of resource dependency for frames of reference. The contrast between Experiments 1 and 2 perhaps implies some trade-off occurring between resources and similarity-based cooperation where increased difficulty results in tipping the balance from a congruent resource competition cost to a congruent cooperative processing benefit.

Based on the shared processing routines hypothesis, better performance would be expected on the egocentric congruent trials as compared to the allocentric congruent trials. The allocentric line task required judgements of right and left of an external space, and the audio cues required a judgement of north/south/east/west, which are two different rules. In contrast, the egocentric line and audio tasks required considering the position of shapes and lines respectively in relation to your right or left, which creates more similarity in the rules of these tasks as compared to the allocentric tasks, and hence should lend itself to better dual task performance. However, this was not the case, as performance was marginally better in the allocentric congruent condition than the egocentric congruent condition. Importantly, though, even if the results did fully align with the shared processing routines hypothesis, they still do not provide an answer to how frames of reference are classified under the MRM. Although making spatial judgements must use spatial cognitive resources in some capacity, the current results do not suggest that the different frames of reference themselves could be classified as depending upon the same or different resources within the spatial resource of the MRM.

Whether frames of reference use different resources or not, there is a missing piece of the MRM. One of the reasons it has been so widely accepted and is so useful in many applied situations is due to its ability to predict the outcome of dual task scenarios. However, in this case, it did not predict the outcomes and cannot on its own account for them post-hoc. It does not appear that frames of reference should be considered a new set of resources and added into the model in spite of the support from neuro-physiological evidence, but rather, the question remains as to why the MRM cannot be successfully applied in this paradigm under high workload.

Another consideration surrounding the conflicting results is that frames of reference are not dichotomous and may not be able to be divided into resource groups. Egocentric and allocentric frames of reference fall along a continuum, which may explain part of why there is not a clear answer to the neural correlates or resource use of frames of reference. The current research attempted to investigate frames of reference in pure forms, or at the most extreme ends of the continuum, but it is difficult to say with absolute certainty that these tasks only depended on one frame of reference or the other. Even if the current tasks were able to use purely egocentric and allocentric frames of reference, the inherent overlap between the two may make categorizing them into two different cognitive resources practically impossible. While this should suggest that they are the same resource, the improvement of performance in congruent conditions do not support this conclusion either. While the MRM cannot currently account for frames of reference, it should not ignore them. The lack of clarity of explanation for the results from both the MRM and the shared processing routines hypothesis suggest that something is different about frames of reference that cannot be explained by current models.

Speculative Potential Explanations of the Current Findings

It was hypothesized that performance on tasks involving color judgements would be better than the congruent conditions, and similar in performance to the incongruent conditions. However, overall performance in the control conditions was no different than in either the congruent or incongruent conditions except in the allocentric incongruent condition of Experiment 1. This was surprising because color judgements, a non-spatial task, should have used different resources than frame of reference judgements. Under the MRM, spatial resources are clearly needed to make frame of reference judgements. The other processing code is verbal, also considered categorical or symbolic (Wickens, 2002; see Figure 6), which these color judgements and auditory cues could fall under, thereby causing some interference. However, the exact mapping of the color judgements is not clear. If we look outside of the MRM, Baddeley's (1992) working memory model may provide some guidance. It defines visuospatial working memory as one grouping, which could encompass both frame of reference and color judgements. This may explain the similar performance, but still does not clarify where color judgments would map to in the MRM.

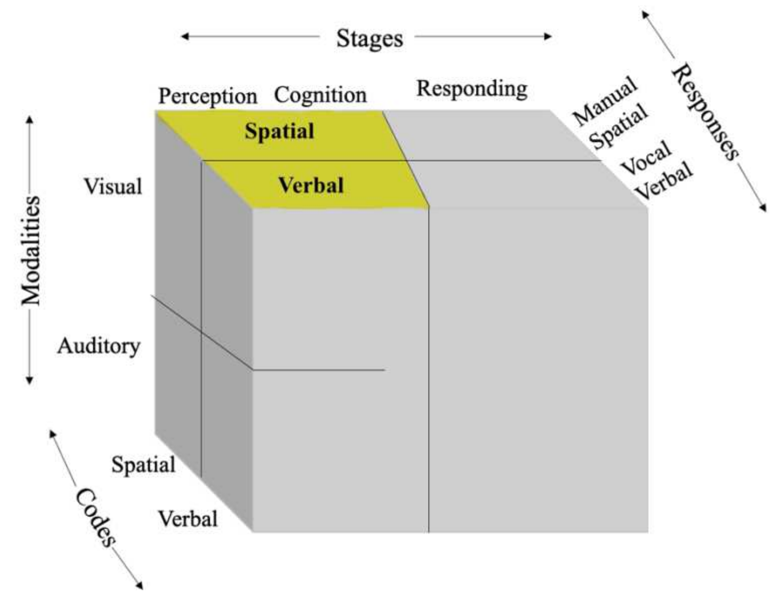

Figure 6. The Multiple Resource Model (adapted from Wickens, 2002). Bolded and highlighted are the codes of processing assumed to be relevant to the current experiments.

Comparisons between control and experimental trials in Experiment 1 indicated that incongruent resources for allocentric audio tasks improved performance because there was a cost of using the same resource, but the same comparison in Experiment 2 suggested that there is an actual benefit of using the same resource for allocentric audio performance. The main effects of line and audio type on accuracy in Experiment 1 suggest that allocentric congruent conditions would be the most difficult, which may be why there was a cost of congruent performance, whereas that was not true in Experiment 2. In Experiment 2, main effects indicated that allocentric audio was more difficult than egocentric, but there was no difference in line type. The benefit of the same frame of reference, even with a more difficult task, indicates that this time-sharing benefit of congruent frames of reference is strong enough to outweigh the difficulty difference.

Another potential explanation could be that the current experiments are actually measuring working memory. Participants must hold the location of shapes, the rule for counting lines, the mental count of lines, and the final answer to the audio cue in their mind at once. There is clearly working memory involved, however, the audio cues require visual working memory and the line task requires verbal working memory. If the current paradigm was testing working memory, accuracy would likely have been similar across all conditions because they all used spatial and verbal working memory. This was not the case, but even if the difference in results is due to spatial working memory interference, it still does not align with the MRM. Spatial cognition is a specified resource in the model and frames of reference would likely be considered breaking the resource into smaller components, much like the dichotomy of focal and ambient vision. Therefore, frames of reference would still be expected to follow the predictions of the MRM and show improved incongruent (for different resources) or similar congruent-incongruent (for same resource) performance.

Conclusions

Considering frames of reference in the framework of the MRM indicates that some part of the MRM is missing or needs to be updated to account for the current findings. It does not seem that frames of reference fit in the model as either one or separate resources. Critically, the findings here illustrate that the current form of the MRM cannot account for the relative efficiency of all multitasking situations. Improved performance on congruent tasks in Experiment 2 might be explained by an alternative account, such as a shared processing routines hypothesis, although the contrast in outcomes between Experiments 1 and 2 are less obvious from such explanations. More research is needed to determine which situations fall into that category and the similarities between them before updating the model or creating a new theory.

Although the current research suggests that the MRM may be missing a component, this is not to say that the MRM is useless, nor incorrect. In its current form, the MRM has been widely accepted and is useful in many situations. It has strongly contributed to human factors research, improved human performance, and has stood up to many tests of its current resource pools. Nonetheless, understanding its limitations is important for its real-world application. The current research is only a starting point of exploring the interactions of task switching, multitasking, cognitive resources, and frames of reference.

Implications

Improved performance in high workload congruent conditions has a multitude of implications for theory and applied settings. These results support the benefits of task similarity in a setting that has not yet been explored. While research has explored the benefits of each frame of reference independently, the direct, controlled comparison of the two provides a base for future applied research with a theoretical background. Specifically, one of the main uses for both frames of reference is in navigation. Navigation aids are often used in high workload situations, as the environment is unfamiliar. Based on the results of Experiment 2, where using the same frame of reference improved performance, it is recommended that if navigation aids provide two sources of directions, they should be in the same frame of reference to enhance comprehension and usability. This is especially useful in situations such as combining tactile and visual navigation cues. Tactile cues are inherently egocentric, so providing tactile cues and a visual track-up map could improve performance, which has been shown to be true in at least one study (Elliot et al., 2010).

Each frame of reference has benefits and drawbacks that are generally resolved by the other frame of reference. One way to improve the use of frames of reference in navigation scenarios would be to combine the two in a navigation aid, however, it seems that this may only be beneficial in low workload scenarios. Although redundant navigation information does not address the drawbacks of the specific frames of reference, it may be helpful in reducing errors and increasing comprehension of the task at hand.

Limitations

The current study was conducted with basic stimuli and tasks without a real-world counterpart. While this creates a controlled environment to examine underlying cognitive mechanisms, other variables and factors from real world navigation settings can impact performance and should be investigated. Importantly, the current research did not include single task difficulty measures for either tasks so the impacts of the difficulty of each task cannot be directly investigated. Future work must include these measures.

Additionally, both experiments were conducted entirely online and had a high number of participants who began the study but did not finish. This self-selection bias likely reduced the number of participants who performed badly on the task. However, in consideration of the strong correlation between congruent and incongruent trial performance, this likely only inflated the accuracy of the trials and not the trends between trial types. While the research would benefit from in-person replication, it is likely that the general results would stand.

REFERENCES

Allen, R.W., Clement, W.F., & Jex, H.R. (1969). Research on display scanning, sampling, and reconstruction using separate main and secondary tracking tasks. *Tech Report,* 170(2).

Aretz, A. J., & Wickens, C. D. (1992). The mental rotation of map displays. *Human performance*, *5*(4), 303-328.

Baddeley, A. (1992). Working memory. *Science*, *255*(5044), 556-559.

Boccia, M., Sulpizio, V., Nemmi, F., Guariglia, C., & Galati, G. (2017). Direct and indirect parieto-medial temporal pathways for spatial navigation in humans: evidence from resting-state functional connectivity. *Brain Structure and Function*, *222*(4), 1945-1957.

Brickman, B. J., Hettinger, L. J. & Haas, M. W., (2000). Multisensory interface design for complex task domains: Replacing information overload with meaning in tactile crew stations. *The International Journal of Aviation Psychology, 10(3),* 273-290.

Burgess, N., Maguire, E. A., & O'Keefe, J. (2002). The human hippocampus and spatial and episodic memory. *Neuron*, *35*(4), 625-641.

Clark, B. J., Simmons, C. M., Berkowitz, L. E., & Wilber, A. A. (2018). The retrosplenial-parietal network and reference frame coordination for spatial navigation. *Behavioral neuroscience*, *132*(5), 416.

Collet, C., Guillot, A., & Petit, C. (2010). Phoning while driving I: a review of epidemiological, psychological, behavioural and physiological

Crawford, J., Watson, M., Burmeister, O., & Sanderson, P. (2002, November). Multimodal displays for anaesthesia sonification: timesharing, workload, and expertise. In Proceedings of the joint ESA/CHISIG Conference on Human Factors (HF 2002). Melbourne, Australia. CD-ROM.

Duncan, J. (1979). Divided attention: The whole is more than the sum of its parts. *Journal of Experimental Psychology: Human Perception and Performance*, *5*(2), 216.

Ekstrom, A. D., Arnold, A. E., & Iaria, G. (2014). A critical review of the allocentric spatial representation and its neural underpinnings: toward a network-based perspective. *Frontiers in human neuroscience*, *8*, 803.

Elliott, L. R., van Erp, J., Redden, E. S., & Duistermaat, M. (2010). Field-based validation of a tactile navigation device. *IEEE Transactions on Haptics*, *3*(2), 78-87.

Endsley, M. R. (1995). Toward a theory of situation awareness in dynamic systems. Human factors, 37(1), 32-64.

Fernandez-Duque, D., & Johnson, M. L. (1999). Attention metaphors: How metaphors guide the cognitive psychology of attention. *Cognitive science*, *23*(1), 83-116.

Fracker, M. L., & Wickens, C. D. (1989). Resources, confusions, and compatibility in dual-axis tracking: Displays, controls, and dynamics. *Journal of Experimental Psychology: Human Perception and Performance*, *15*(1), 80.

Galati, G., Lobel, E., Vallar, G., Berthoz, A., Pizzamiglio, L., & Le Bihan, D. (2000). The neural basis of egocentric and allocentric coding of space in humans: a functional magnetic resonance study. *Experimental brain research*, *133*(2), 156-164.

Gramann, K., Müller, H. J., Schönebeck, B., & Debus, G. (2006). The neural basis of ego-and allocentric reference frames in spatial navigation: Evidence from spatio-temporal coupled current density reconstruction. *Brain research*, *1118*(1), 116-129.

Grice, J. W., Medellin, E., Jones, I., Horvath, S., McDaniel, H., O'lansen, C., & Baker, M. (2020). Persons as effect sizes. *Advances in Methods and Practices in Psychological Science*, *3*(4), 443-455.

Hancock, P. A., Oron-Gilad, T., & Szalma, J. L. (2007). Elaborations of the multiple-resource theory of attention. *Attention: From theory to practice*, 45-56.

Jeon, M., Gable, T. M., Davison, B. K., Nees, M. A., Wilson, J., & Walker, B. N. (2015). Menu navigation with in-vehicle technologies: Auditory menu cues improve dual task performance, preference and workload. *International Journal of Human-Computer Interaction, 31(1),* 1-16.

Just, M. A., Carpenter, P. A., Keller, T. A., Emery, L., Zajac, H., & Thulborn, K. R. (2001). Interdependence of nonoverlapping cortical systems in dual cognitive tasks. *Neuroimage, 14,* 417-426.

Kahneman, D. (1973). *Attention and effort*. Englewood Cliffts, NJ: Prentice Hall.

Kantowitz, B. H. & Knight, J. L., (1976). Testing tapping timesharing: I. Auditory secondary task, *Acta Psychologica*, 40, 343-362.

Klatzky, R. L. (1997). Allocentric and egocentric spatial representations: Definitions, distinctions, and interconnections. *Spatial cognition*, 1-17.

Kosslyn, S. M., Koenig, O., Barrett, A., Cave, C. B., Tang, J., & Gabrieli, J. D. (1989). Evidence for two types of spatial representations: hemispheric specialization for categorical and coordinate relations. *Journal of experimental psychology: human perception and performance*, *15*(4), 723.

Kramer, A. F., Cassavaugh, N., Horrey, W. J., Becic, E., & Mayhugh, J. L. (2007). Influence of age and proximity warning devices on collision avoidance in simulated driving. *Human Factors*, *49*(5), 935-949.

Lenneman, J. K., & Backs, R. W. (2018). A psychophysiological and driving performance evaluation of focal and ambient visual processing demands in simulated driving. *Transportation research part F: traffic psychology and behaviour*, *57*, 84-96.

Matviienko, A., Löcken, A., El Ali, A., Heuten, W., & Boll, S. (2016). NaviLight: Investigating ambient light displays for turn-by-turn navigation in cars. *Proceedings of the 18th International Conference on Human-Computer Interaction with Mobile Devices and Services*. 283-294.

Navon, D., & Gopher, D. (1979). On the economy of the human-processing system. *Psychological review*, *86*(3), 214.

Olmos, O., Wickens, C. D., & Chudy, A. (2000). Tactical displays for combat awareness: An examination of dimensionality and frame of reference concepts and the application of cognitive engineering. *The International Journal of Aviation Psychology*, *10*(3), 247-271.

Previc, F. H. (1998). The neuropsychology of 3-D space. *Psychological bulletin*, *124*(2), 123.

Rodes, W., & Gugerty, L. (2012). Effects of electronic map displays and individual differences in ability on navigation performance. *Human factors*, *54*(4), 589-599.

Rogers, R. D., & Monsell, S. (1995). Costs of a predictible switch between simple cognitive tasks. *Journal of experimental psychology: General*, *124*(2), 207.

Ruotolo, F., Ruggiero, G., Raemaekers, M., Iachini, T., van der Ham, I. J. M., Fracasso, A., & Postma, A. (2019). Neural correlates of egocentric and allocentric frames of reference combined with metric and non-metric spatial relations. *Neuroscience*, *409*, 235-252.

Sanders, A. F. (1997). A summary of resource theories from a behavioral perspective. *Biological Psychology*, *45*(1-3), 5-18.

Sarter, N. B. (2007). Multiple-resource theory as a basis for multimodal interface design: Success stories, qualifications, and research needs. *Attention: From theory to practice*, 187-195.

Scerra, V. E., & Brill, J. C. (2012). Effect of task modality on dual-task performance, response time, and ratings of operator workload. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* (Vol. 56, No. 1, pp. 1456-1460). Sage CA: Los Angeles, CA: Sage Publications.

Taylor, H. A., Brunyé, T. T., & Taylor, S. T. (2008). Spatial mental representation: implications for navigation system design. *Reviews of Human Factors and Ergonomics*, *4*(1), 1-40.

Tsang, S. N., & Chan, A. H. (2018). Tracking and discrete dual task performance for different visual spatial stimulus-response mappings with focal and ambient vision. *Applied ergonomics*, *67*, 39-49.

Vogeley, K., & Fink, G. R. (2003). Neural correlates of the first-person-perspective. *Trends in cognitive sciences*, *7*(1), 38-42.

Wang, C., Chen, X., & Knierim, J. J. (2010). Egocentric and allocentric representations of space in the rodent brain. *Current Opinion in Neurobiology*, *60*, 12-20.

Wen, W., Ishikawa, T., & Sato, T. (2013). Individual differences in the encoding processes of egocentric and allocentric survey knowledge. *Cognitive science*, *37*(1), 176-192.

Wickens, C. D. (1980). The structure of attentional resources. *Attention and performance VIII*, *8*, 239-257.

Wickens, C. D., & Prevett, T. T. (1995). Exploring the dimensions of egocentricity in aircraft navigation displays. *Journal of Experimental Psychology: Applied*, *1*(2), 110.

Wickens, C. D. (2002). Multiple resources and performance prediction. *Theoretical Issues in Ergonomics Science, 3(2),* 159-177.

Wickens, C., D. (2003). Aviation Display. In T. P., & M.,Vidulich, (Ed.), *Principles and practices of aviation psychology.* Mahwah, NJ: Lawrence Erlbaum Associates.

Wickens, C. D., Vincow, M., & Yeh, M. (2005). Design Applications of Visual Spatial Thinking: The Importance of Frame of Reference. In P. Shah (Ed.) & A. Miyake, *The Cambridge Handbook of Visuospatial Thinking*. 383–425.

Williams, H. P., Hutchinson, S., & Wickens, C. D. (1996). A comparison of methods for promoting geographic knowledge in simulated aircraft navigation. *Human factors*, *38*(1), 50-64.

Zaehle, T., Jordan, K., Wüstenberg, T., Baudewig, J., Dechent, P., & Mast, F. W. (2007). The neural basis of the egocentric and allocentric spatial frame of reference. *Brain research*, *1137*, 92-103.