Resource Allocation Using Touch And Audition

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RESOURCE ALLOCATION USING TOUCH AND AUDITION

by

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ABSTRACT

When people multi-task with inputs that demand attention, processing, and encoding, sensory interference is possible at almost any level. Multiple Resource Theory (MRT) suggests that such interference may be avoided by drawing from separate pools of resources available when using different sensory channels, memory processes, and even different response modes. Thus, there should be advantages in dividing tasks among different sensory channels to tap independent pools of attentional resources. For example, people are better with two tasks using the eye and ear, than when using two auditory or two visual inputs.

The majority of the research on MRT involves visual to auditory comparisons, i.e., the prime distance senses. The unstated implication is that the theory can be easily applied to other sensory systems, such as touch, but this is untested. This overlooks the fact that each sensory system has different characteristics that can influence how information processing is allocated in a multiple-task environment. For example, vision requires a directed gaze that is not required for sound or touch. Testing MRT with touch, not only eliminates competing theories, but helps establish its robustness across the senses.

Three experiments compared the senses of touch and hearing to determine if the characteristics of those sensory modalities alter the allocation of processing resources. Specifically, it was hypothesized that differences in sensory characteristics would affect performance on a simple targeting task. All three experiments used auditory shadowing as the dual task load.

In the first and third experiments a target was placed to the left or right of the

participant and the targeting cue (either tactile, auditory, or combined) used to locate the target originated from the side on which the target was located. The only difference between experiments 1 and 3 was that in experiment 1 the auditory targeting cue was delivered by headphones, while in experiment 3 it was delivered by speakers.

Experiment 2 was more difficult both in auditory perception and in processing. In this study the targeting cues came from in front of or behind the participant. Cues coming from in front of the participant meant the target was to the left, and conversely if the cue came from behind it meant that the target was to the right.

The results of experiments 1 and 3 showed that when the signals originated from the sides, there was no difference in performance between the auditory and tactile targeting cues, whether by proximal or distal stimulation. However, in experiment 2, the participants were significantly slower to locate the target when using the auditory targeting cue than when using the tactile targeting cue, with nearly twice the losses when dual-tasking. No significant differences were found on performance of the shadowing task across the three experiments.

The overall findings support the hypothesis that the characteristics of the sensory system itself influence the allocation of processing resources. For example, the differences in experiment 2 are likely due to front-back reversal, a common problem found with auditory stimuli located in front of or behind, but not with tactile stimuli.

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CHAPTER 1: INTRODUCTION

The earliest models of information processing were bottleneck or filter models (Matlin, 2005). These models emerged to address the question of how people select among multiple sources of information. In this approach, multiple sources of data flow into the human information processing system and some information is fully considered while the rest is ignored. Attention is the process which determines what information is to be considered and what information is to be neglected. Thus, information entering the system encounters a "bottleneck" as the information overwhelms the mind's limited capacity to attend to and process all of the information. However, this so-called unattended or ignored information still has an impact on subject's ability to attend to information and at least some processing for meaning and relevance occurs even at the earliest stages of information processing (Gopher & Donchin, 1986; Matlin, 2005; Proctor & Van Zandt, 1994a).

Research on these early models provided evidence that "higher level" cognitive processes must access memory and meaning, and thereby influence attention and the selection of information. These complications along with the difficulty of pinpointing the locus of a single bottleneck led some researchers to take a different approach and develop resource models. These models conceptualize attention as a finite pool of resources and propose that sometimes attention is distributed, in varying degrees, to several tasks rather than simply choosing a single task or message. Thus, attentional limitations arise from a limited capacity of resources for mental activity and when resource demand exceeds the supply performance suffers (Fracker & Wickens, 1989; Gopher & Donchin, 1986; Kahneman, 1973; Moray, 1967; Proctor & Van Zandt, 1994a).

The first of these models were single resource models (Gopher & Donchin, 1986; Kahneman, 1973). These models propose that there is a single pool of resources with a finite capacity and that the individual has the freedom to allocate, or distribute, varying degrees of effort, or intensities, to material passing through the channel. Allocating more resources to one task must always result in fewer resources, and poorer performance, for other tasks (Proctor & Van Zandt, 1994a). The allocation of resources thus exists along a continuum from tasks which demand no resources (automated tasks) to tasks that demand the full allocation of resources to obtain maximum performance (resource limited) (Wickens, 2002).

An alternative view is the multiple resource theory. Multiple-resource models propose that there are several distinct subsystems each with their own limited pool of resources (Navon & Gopher, 1979). These models were developed because the amount of performance decrement for multiple tasks often depends on the stimulus modalities and the responses required for each task (Fracker & Wickens, 1989; Proctor & Van Zandt, 1994a; Sanders & McCormack, 1993). Thus, the research showed that the decrements in performance were due to differences in the qualitative demands for information processing structures not the quantitative resource demand (Wickens, 2002).

Wicken's Multiple Resource Theory (MRT) is based on the idea that multiple resources exist and in some cases are separate from on another. A resource can be defined as an underlying commodity that is both limited in availability and allocatable, that enables performance of a task (Smith & Buchholz, 1991; Wickens, 1984; Wickens, 2002). The theory has both practical and theoretical implications. The practical implications stem from the predictions that the theory makes concerning the human operator's ability to perform in high workload multi-task environments. The theoretical implications stem from the ability of the theory to predict dual task interference levels between concurrently performed tasks, to be consistent with the neurophysiological mechanisms underlying task performance, and to account for variability in task interference that cannot easily be explained by simpler models of human information processing (Wickens, 2002).

Multiple resource theory proposes that there are four important categorical and dichotomous dimensions that account for decrements in multiple task performance. Each dimension has two discrete levels. Assuming that all other things are equal, two tasks that demand both one level of a given dimension will interfere with each other more than two tasks that demand separate levels on the dimension. The four dimensions are (1) processing stages, (2) perceptual modalities, (3) visual channels, (4) processing codes (Wickens, 2002).

There are three stage of processing. The first is perceptual encoding which represents the initial processing effort. This stage includes preliminary encoding such as preattentive processing and feature discrimination. The second stage is defined as central processing and includes elaborative tasks like decision making, memory operations, and translatory operations. The third stage is response processing for making manual or vocal responses. Research indicates that perceptual encoding and central processing tasks use common resources while response processing uses separate resources (Smith & Buchholz, 1991; Wickens; 2002; Wickens & Holland, 2002).

The input modalities are either auditory or visual and rely on separate resources at the perceptual encoding stage. It is apparent that sometimes attention is divided between the eye and the ear better than between two auditory channels or two visual channels. The advantage of cross-modal (auditory-visual) over intra-modal (all auditory or all visual) time sharing may not be the result of separate perceptual resources within the brain, but rather the result of the peripheral factors that place the two intra-modal conditions at a disadvantage. The degree to which peripheral rather than central factors are responsible for the examples of better cross-modal time-sharing remains uncertain and, when peripheral factors are carefully controlled, cross-modal displays do not always produce between time-sharing (Wickens & Liu, 1988). In the real world, however, these simple peripheral factors can create enough interference that off-loading some information from one channel to another is necessary to reduce the interference (Wickens, 2002).

In addition, to the differentiation between auditory and visual modalities of processing, there is good evidence that two aspects of visual processing, focal and ambient vision appear to define separate resources in the sense of supporting efficient time-sharing. This is due to qualitatively different brain structures, and is associated with qualitatively different types of information processing. Focal vision, which is nearly always foveal, is required for fine detail and pattern recognition, while ambient vision is mostly peripheral and is used for sensing orientation and motion. It is suggested that each type of vision has its own resources and that two tasks which use different aspects of vision are time-shared better than two tasks that use the same aspect of vision (Wickens, 2002).

The processing codes are either spatial or verbal. This separation of spatial and verbal resources seems to account for the relatively high degree of efficiency with which manual and vocal responses can be time-shared, assuming that manual responses are usually spatial in nature and vocal ones are usually verbal. Past research indicates that the processing of these codes whether functioning in perception, working memory or response, rely on separate resources that may be anatomically related to right and left cerebral hemispheres. Task-hemispheric integrity states that simultaneous tasks are performed best when each is confined to single hemisphere, that is, when the hemisphere responsible for centrally processing the tasks receives direct sensory input and directs the sensory input and the response (Boles & Law, 1998; Wickens, Mountford, & Schreiner, 1981).

According to Stimulus, Central processing, and Response (S-C-R) compatibility in order for optimum performance to be achieved, S-C-R operations should take advantage of hemispheric differences in the type of processing. Specifically, insofar as spatial information is (a) processed to a greater degree by the right hemisphere to a degree greater than the left hemisphere, (b) largely but not exclusively carried visually, and (c) primarily expressed manually, the combination is one that particularly favors the right hemisphere, even though it is really only the spatial central processing operation that is lateralized. Conversely, because verbal information is (a) processed to a greater degree by the left hemisphere, (b) largely though not exclusively carried auditorily, and (c) primarily expressed vocally, this combination particularly favors the left hemisphere. Even though each hemisphere has a preferred linkage, both hemispheres are capable of processing auditory and visual input, and manual if not vocal output (Boles & Law, 1998; Wickens, Vidulich, & Sandry-Garza, 1984).

Thus, according to the MRT and the related principles of task hemispheric integrity and S-C-R compatibility, resources are differentiated both within and between hemispheres. Dividing the labor of dual tasks between hemispheres in an appropriate way is one means, but not the only means, of escaping resource limitations and minimizing interference between tasks (Boles & Law, 1998).

The MRT also describes four important relationships. The first is that the more two tasks depend on separate resources the more they will be time shared efficiently (i.e., without significant cross-task interference). The second is that when two tasks require common resources the performance on the tasks will depend on how resources are allocated to the tasks. Third, the difficulty of a task is increased when additional resources are needed for its performance. If two tasks fully use available common resources, increasing the difficulty of one task will hamper performance on a concurrent task. If two tasks use separate resources, increasing the difficulty of one task will not affect performance on a concurrent task. The fourth is that task priority determines how attentional resources are allocated, and plays the biggest role when tasks are difficult and share resources (Smith & Buchholz, 1991).

Therefore, according to the theory, if two pieces of information are being received by the same sensory system or contain the same type of information (both spatial), then the same pool of attentional resources is accessed. This results in competition between those two signals for available attentional resources and that competition results in impaired processing of the information.

On the other hand, if the inputs tap two independent pools of attentional resources, then it should be easier to divide attention between the two inputs (Wickens, 1980; 1984; Wickens & Holland, 2000). Thus, attention can be better divided between inputs to the eye and the ear than between two auditory or two visual inputs. This is referred to as cross-modal time-sharing and has been supported in a number of situations (Wickens, 1980; Wickens & Holland, 2000). Similar results have been found with research on processing codes for different types of information. Research on multitask studies has indicated that spatial and verbal codes depend on separate resources no matter if the codes are functioning in the same domain such as perception or working memory (Polson & Friedman, 1988). Thus, when MRT is taken into account during the design of systems, the tasks involved have been shown to cause minimal interference with each other resulting in better performance (Wickens & Hollands, 2000).

Nevertheless, even when MRT has been applied, task performance can still be degraded by changes in task difficulty. Such changes can result in greater fatigue, slower response times, and more errors due to the increased workload associated with the changes in difficulty. In terms of MRT, the additional workload of harder tasks requires more attentional resources to process and results in poorer performance. This is a fairly straightforward if somewhat simplified account of a single task. However, in situations involving multiple, simultaneous tasks the explanation of the effects of a change in the level of task difficulty is not as simple to describe. This can be a problem for anyone who may have to deal with such changes at any time.

Since its conception, ample empirical evidence exists to support the tenets to the MRT. Despite this body of research, several limitations of challenges to the theory have been recognized. These include the need to better understand how resource demand is coded for individual tasks within a multiple task situation and the need to better accommodate the distribution of resources between two time-shared tasks. Of particular concern are the phenomena of ‘preemption’ and ‘engagement’. In these phenomena, one task demands or attracts so much attention to itself that any benefits that might otherwise have been realized by its separate resources are eliminated, as full attention is given to that task. Specifically, the task functions similarly to an alarm. Alarms are specifically designed to interrupt whatever task is ongoing in order to redirect the user’s attention to a problem that requires the operator’s attention (Woods, 1995). The alarm thus ‘engages’ all of the operator’s resources. As a consequence, the concurrent task is essentially ‘dropped’ altogether. The monitoring and processing of the concurrent task are thus ‘preempted’ and its resources are redirected to first task, which in the case of an alarm, is the task that the alarm is alerting the operator to. It is therefore important to understand the conditions in which preemption, or other intrinsic characteristics that lead to such pronounced allocation effects, offset the benefits offered resource separation (Wickens, 2002).

A third challenge stems from evidence for many more cognitive and perceptual processes than are included in the model. For example, patterns of ERP recordings in research on spatial cuing suggests that instead of a single attentional mechanism that uses either suppression or facilitation or both of these processes, these results suggest that there are multiple mechanisms of visual-spatial attention that operate in different ways. ERP recordings believed to be generated in the lateral extrastriate cortex exhibit attentional suppression in visual search tasks when the target is defined by a color-form conjunction, but this effect is eliminated when the target is defined simply by its color (Luck et al., 1994).

Thus, there is evidence for more than three stages of processing and certainly there are more than two each of encoding and response modalities. There are also likely to be more than two processing codes, and equally importantly, the verbal and spatial codes may well consist of multiple components. In other word, the MRT seems unduly restrictive in its account of resources (Boles & Law, 1998).

The restrictiveness of the MRT can be further extended to include modalities and the emphasis on visual and auditory processing. Although, the theory has been applied to other sensory modalities (e.g. Sklar & Sarter, 1999), even in the most recent formulation of the model (Wickens, 2002), Wickens does not include a reference to other sensory modalities. This omission is inconsistent with an earlier reformulation (Wickens, 1992) in which Wickens, in an apparent attempt to differentiate between attentional and structural resources, suggested that resources are defined by distinct anatomical structures in the brain.

Physiological and perceptual research has shown that there are differences in the physiological structures responsible for the reception, transmission, and interpretation of sensory input. These differences are the result of the different forms of sensory stimuli that humans are capable of receiving. For example, the stimulus for vision is light, and our visual receptors have evolved to receive and translate light into electrical activity, whereas our hearing has evolved to receive and translate vibration, particularly within the frequency of the human voice. In addition, there are structural differences among our sensory systems that in some cases limit the perception of stimuli. Our eyes, for example, are located in the front of our heads and are space close enough together to grant us binocular vision. This, however, limits the range of vision, and precludes us from seeing things behind us without moving our heads. Our ears, on the other hand, are placed on the sides of our heads which allows us to collect auditory stimuli from any direction. These differences, both physiologically and structurally, suggest that if resources are defined by distinct anatomical structures, then there should be different processing codes for each sensory system. It also supports the idea that there are additional components in the central processing stage needed to explain how stimuli are translated from different systems into spatial and/or verbal codes. To this end, the goal of this study is to show that the characteristics of the sensory systems involved in a multiple task situation play a role in the allocation of resources as seen by changes in performance on the two tasks involved.

The majority of the research on multiple resource theory and the effects of task difficulty on performance has been done using vision and/or audition as the source of perceptual information. This is not surprising. Humans are visual creatures. Vision is the primary sense humans use to explore and interact with the world. As such, it has been studied more and more is known about its limitations than any of the other senses. This can be seen by taking a look at any perception, biological psychology, or cognitive textbook, or by thinking about the most popular forms of entertainment. The only other sense that comes as close in terms of our knowledge is audition. Audition is our primary means of communication. However, even audition pales in comparison to vision in terms of what is known about the sense and how it is used.

Such a heavy concentration on vision and audition has left many questions unanswered concerning our other senses. There is some research on the other senses, primarily our sense of touch, however, the amount pales in comparison to the sheer amount of research available on MRT, vision, and audition. There are several possible reasons for this lack of attention to other senses. One is the amount of knowledge and research available of vision. This also explains why most of the research involving touch includes comparisons with vision. Simply put, we have a better understanding of vision, so it is easier for us to use vision as the primary source of sensory input in our research and as a comparator. Also, since much of the research on vision and audition has produced similar results, it is quite possible that many researchers believe that these results are generalizable to the other senses. The problem with this latter assumption, as mentioned earlier, is that there are fundamental differences between our senses that may affect the allocation of resources, and the coding of the information from those sources.

The Structural Differences between Vision, Audition, and Touch

The structural differences between the three major senses, as mentioned earlier, are due to the stimuli that activates each sense. In addition, these structural differences are also responsible for the limitations of each sense. Evolutionarily speaking, the senses form a continuum from the most primitive to the most highly evolved. Touch is the most primitive of our senses in the sense that it has changed the least during human evolution is both structure and form. The most highly evolved sense is vision as seen by the amount of specialization in the brain. Audition falls in between the two. In the following sections, the structure of each sense is briefly described as well as their development.

Vision

Vision requires light to be reflected off distant objects onto the retina in the back of the eye. The retina contains photoreceptors specialized to convert light energy into neural activity. The rest of the eye acts like a camera, forming crisp, clear images of the world on the retina. Thus, like a quality camera, the eye automatically adjusts to differences in illumination and automatically focuses itself on objects of interest (Bear, Connors, & Paradiso, 2001). The eyes are frontally directed in humans. This results in small monocular visual fields but relatively large areas of binocular overlap, as well as blind areas behind them. In primates, this results in a binocular field of about 142 degrees bordered on each side by monocular fields of about 42 degrees. The remaining 152 degrees is a blind area. In contrast, animals with laterally directed eyes such as the rabbit have large monocular fields of vision and relatively small binocular fields of vision. They also have little or no blind spots. The rabbit, for example, has two monocular fields of view that measure 170.5 degrees on each side of the head, a binocular field in front that measures approximately 10 degrees, a binocular field in the rear that measures approximately 9 degrees, and no blind areas (Schiffman, 2001).

There are two types of photoreceptors in the eye: rods and cones. The structural differences between rods and cones correlate with important functional differences. Rods are specialized for low-light conditions and are thus relatively poor at resolving fine details in daylight. Cones on the other hand are specialized for daytime vision and are thus better for resolving fine details. In addition, there are three types of cones, each containing a different photopigment. The variations among pigments make the different cones sensitive to different wavelengths of light and are thus responsible for the ability to see color. The arrangement of rods and cones varies across the surface of the retina. In the center of the retina is an area called the fovea. The only receptors found in this area are cones. Each cone in this area transmits its signal directly to a ganglion cell located in the next layer of the retina. This structural specialization maximizes visual acuity at the fovea. Outside of the fovea, the ratio of rods to cones increases. In addition, there is a higher ratio of photoreceptors to ganglion cells in the periphery. It is this arrangement that makes the periphery better for detecting faint changes in light levels. However, because of the lack of cones, stimulation of the peripheral retina only produces black and white vision (Bear et al., 2001).

In addition to the differences in the photoreceptors, there are different pathways in the visual system. Wickens (2002) recognized these differences in his MRT as the focal and ambient visual systems. These differences originate with the ganglion cells to which the photoreceptors send their input. P-cells are small cells with a slow, sustained rate of response. They receive their input from the fovea and are important for fine-detailed vision. These cells send their input to the Parvocellular Division of the visual system. This system responds to color and fine details, is highly sensitive to high contrast, and is believed to be responsible for color vision and acuity. This division is the division that Wickens (2002) refers to as focal vision. The second type of ganglion cells are called M-cells. These are large cells and receive their input from the peripheral retina. Their response to stimulation is both rapid and transient and they are involved in our perception of motion. M-cells send their input to the Magnocellular Division of the visual system. This division does not respond to color or fine detail, but is sensitive to low contrast. This system is responsible for motion and depth perception (Bear et al., 2001; Schiffman, 2001). This is the system that Wickens refers to as the ambient visual system (Wickens, 2002).

In terms of development, the visual system is one of the last, if not the last system to develop (Kisilevsky, Stack, & Muir, 1991; Montagu, 1986; Stack, 2001). It is well established that neonates see poorly. Contrast sensitivity and acuity are at least an order of magnitude worse than in adulthood, and color discrimination is also much worse than in adults (Banks & Bennett, 1991). However, vision improves dramatically over the first year. Infants are capable of scanning and fixation, form and pattern perception, and the perception of faces by 6 months of age. By 4 months of age, they can perceive the adult hue categories of blue, green, yellow, and red. Basic perceptual and spatial abilities are gained by 6 to 7 months of age, and acuity has improved dramatically by 12 months of age (Schiffman, 2001). Despite these great changes, exactly when we are able to make full use of vision is still debated. The debate hinges on the argument that the use of vision for perception depends heavily on learning and thus requires more time to fully develop. In addition, human vision is more evolutionarily developed than the other senses as measured by the amount of our brains that is devoted to the processing of visual stimuli (Banks & Bennett, 1991; Bear et al., 2001; Schiffman, 2001).

As Wickens has already suggested, it is likely that the various visual systems have their own pools of processing resources (Wickens, 2002). This suggests that a structural difference in the sensory system itself is responsible for the allocation of resources to different tasks. Further indications from the literature of visual dominance also support the idea that characteristics of a sensory system can influence the allocation of resources. Visual dominance refers to the fact that when conflicting or simultaneous information occurs through different sense, the visual system often determines what we perceive. Posner, Nissen, and Klein (1976) have proposed that visual dominance is related to a relatively poor alerting ability of the visual system. Because stimuli in other modalities can attract attention more readily, perception maintains a bias toward the visual system. Thus, when visual events are occurring simultaneously with auditory events, the auditory modality is generally at a disadvantage (Proctor & Van Zandt, 1994b). In addition to the dominance of vision over audition as demonstrated by means of the McGurk illusion, in which the "heard" syllable is determined by the "seen" syllable when auditory and visual components of speech are set in conflict, a similar dominance of vision over chemosensory information has also been shown (Batic & Gabassi, 1987; Spence, Kettenman, Kobal, & McGlone, 2001). Similarly, vision has been shown to capture or dominate touch when the two modalities are in conflict (Rock & Harris, 1967; Heller, 1983).

Audition

When we cannot see an object, we can often detect its presence, identify its origin, and even receive a message from it just by hearing it. Aside from simply hearing a sound, we are also able to perceive and interpreting its nuances. In addition, because humans can produce a wide variety of sounds as well as hear them, spoken language and it reception via the auditory system have become an extremely important means of communication. Audition in humans has even evolved beyond the strictly utilitarian functions of communication and survival. For example, musicians explore the sensations and emotions evoked by sound (Bear et al, 2001).

Sounds are audible variations in air pressure. Almost anything that can move air molecules can generate a sound. When an object moves toward a patch of air, it compresses the air, increasing the density of the molecules. Conversely, the air is rarified when an object moves away. The frequency of the sound is the number of compressed or rarefied patches of air that pass by our ears each second. One cycle of the sound is the distance between successive compressed patches. The sound frequency, expressed in units called hertz (Hz), is the number of cycles per second. The human auditory system can respond to pressure waves over the range of
20-20,000 Hz (Bear et al., 2001).

Another important property of a sound wave is its intensity, which is the difference in pressure between compressed and rarefied patches of air. Sound intensity determines the loudness we perceive, loud sounds having higher intensity. The human ear is sensitive to an astonishing range of intensities. The intensity of the loudest sound that doesn't damage our ears is about a trillion times greater than the intensity of the faintest sound that can be heard (Bear et al., 2001).

Real world sounds rarely consist of simple periodic sound waves at one frequency and intensity. It is the simultaneous combination of different frequency waves at different intensities that gives different musical instruments and human voices their unique tonal qualities (Bear et al., 2001).

The sensory receptors of the ear are located in the inner ear within a snail like structure called the cochlea. In the central cochlear duct are the specialized sensory structures, nerves, and supporting tissues for transducing vibrations to nerve impulses. Collectively, these form a receptor called the Organ of Corti, which rests on and extends along the length of the basilar membrane which forms the floor of the cochlear duct. The Organ of Corti contains columns of specialized hair cells arranged in two sets, divided by an arch. One column is called the inner hair cells, which number about 3500, and the outer hair cells, which number about 20,000. Each hair cell has up to 100 tiny delicate bristles called stereocilia. The inner set has a single column of hair cells, whereas the outer set has three columns. About 50,000 auditory nerve fibers connect with the inner and outer hair cells. Between 90 and 95% of the nerve fibers make contact with the relatively sparse inner hair cells, and the remaining 5 to 10% link with the more numerous outer hair cells (Bear et al., 2001; Schiffman, 2001).

Given these significant structural-neural differences between the inner and outer hair cells, they likely transmit different types of auditory information. It has been proposed that, based on their greater representation in the distribution of auditory nerves, the inner hair cells encode frequency information, whereas the corresponding outer hair cells amplify the movement of the basilar membrane to sharpen the frequency response of the inner hair cells. Evidence also suggests that the outer hair cells register low-amplitude, weak sounds and are essential for sound detection close to the absolute threshold (Schiffman, 2001).

In order for us to hear a sound, vibrations are captured by the pinna, the fleshy, wrinkled flap that lies on the outside of the head, and directed down the external auditory canal to the eardrum. The eardrum, a thin, translucent membrane separates the outer and middle ear. When vibrations strike the eardrum it vibrates. This vibration is transmitted to three small bones located in the middle ear. The malleus is attached to the eardrum and is connected to the incus, which, in turn, connects to the stapes, which is connected to the membrane of the oval window, which is the entrance to the inner ear. The inner ear is filled with fluid, so the bones of the middle ear must increase the force of the vibration by a factor of 1.3 to ensure efficient transfer of sound vibrations from the air of the outer ear to the fluid of the inner ear (Bear et al., 2001; Schiffman, 2001).

The inner ear is composed of the cochlear, which resembles a snail. Along most of its length it is divided by its central canal, the cochlear duct, into two canals. The upper canal is the vestibular canal and starts at the oval window and connects with the lower canal, the tympanic canal. These two canals connect at the tip or apex of the cochlea by way of a small opening called the round window found at the base of the tympanic canal. The cochlear duct is bounded by two membranes. It is divided from the vestibular canal by the Reissner’s membrane, and it is separated from the tympanic canal by the basilar membrane. When the oval window is moved by the stapes, the vibrations within the cochlea cause the basilar membrane to move. This causes the cilia to push against the tectorial membrane which is attached at only one end to the Reissner’s membrane and extends lengthwise across the cochlear duct. This bends the cilia and triggers the first stage of neural conduction (Bear et al., 2001; Schiffman, 2001).

The physiological processes essential for hearing begin to function in a rudimentary way during the prenatal period. In normal-hearing infants, absolute thresholds as well as sensitivity to fundamental properties of sound such as frequency, intensity, and temporal structure are close to adult thresholds by the age of 6 months. The ability to localize sound sources also improves substantially over the first year (Fernald, 2001). Research on hearing has shown that our sense of audition is much better for receiving temporal information as well as for communications from any direction (Proctor & Van Zandt, 1994b**;** Regan & Spekreijse, 1977; Welch, Dutton-Hurt, & Warren, 1986). Auditory cues can also be used to provide spatial information. In fact, not only is our sense of hearing allow us to locate the location and avoid or approach sound-emitting objects and events, but they also guide the direction of visual attention (Schiffman, 2001). One example, of the use of such cues involves the improvement of fighter-pilot performance, because knowledge of the locations of threats and targets is necessary for survival (Proctor & Van Zandt, 1994b).

Touch

The somesthetic system is the most basic of our sensory systems. Unlike other sensory systems whose receptors are specialized, well-defined, localized sensory structures, like the retina in vision or the cochlea in hearing, its sensory surface covers nearly the entire body and serves many purposes in addition to mediating cutaneous sensations. The skin covers the entire body with the average adult human having about 3,000 square inches of skin area (Schiffman, 2001). It serves as a continuously renewable and flexible shield against many foreign agents and mechanical injury by holding in our bodily fluids, warding off harmful ultraviolet and infrared radiation from the sun, and protects us against the loss of light-sensitive elements. It also regulates and stabilizes body temperature, either cooling the body or limiting heat loss, and the pressure and direction of blood flow. As a sense organ, the skin has specialized nerve endings embedded in it that can be stimulated in a variety of ways to mediate different sensations. These nerve endings inform us of what is next to our body, including thermal information and potentially harmful stimuli.

Neurologists distinguish between two classes of somatic sensation: protopathic and epicritic. Protopathic sensations involve pain and temperature senses and are mediated by receptors with bare nerve endings. Epicritic sensations involve fine aspects of touch and are mediated by encapsulated receptors. These sensations involve fine aspects of touch and are mediated by encapsulated receptors. These sensations include the ability to detect gentle contact of the skin and localize the position that is touched (topognosis), and discern vibrations. It is these epicritic sensations that are the focus of the study (Kandel, Schwartz, & Jesell, 2000).

The receptors that mediate touch are called mechanoreceptors. These receptors are excited by indentation of the skin or by motion across its surface. When an object presses against the hand, the skin conforms to its contours. The depth of indentation depends on the force exerted by the object on the skin as well as its geometry. All mechanoreceptors sense these changes in skin contour but differ morphologically in important ways that affect their physiological function. The receptors of the glaborous, or hairless, skin are Meissner's corpuscles, located in the dermal papillae; Merkel disk receptors located between the dermal papillae; and bare nerve endings. The receptors of hairy skin are hair receptors, Merkel's receptors (with a slightly different organization than those found in glaborous skin), and bare nerve endings. Subcutaneous receptors, beneath both glaborous and hairy skin, include Pacinian corpuscles and Ruffini endings (Kandel et al., 2000).

Meissner’s corpuscle and Merkel disk receptors in the superficial layers resolve fine spatial differences because they transmit information from a restricted area of the skin. Pacinian corpuscles and Ruffini endings in the deep layers resolve only coarse spatial differences. They are poorly suited accurate spatial localization or for resolution of fine spatial detail. These mechanoreceptors located in the deep layers of the skin sense more global properties of objects and detect displacements from a wide area of skin (Kandel et al., 2000).

The ultimate destination of the neural message sent by cutaneous receptors is a region of each hemisphere of the brain is the somatosensory cortex. Here the skin is topographically projected and arranged so that neighboring areas of the skin are represented in neighboring regions of the somatosensory cortex. While some areas of the skin, such as the fingers, lips, and tongue, are represented more heavily in the somatosensory cortex due to the large number of receptors located in those areas, all areas of the skin are represented on the somatosensory cortex. As a result of this mapping, we are easily able to identify the location of the skin that is touched. This ability to localize touch sensations on the stimulated region of the skin is called point localization. Thus, an itch on the back is easily located and accurately scratched. Of course, those areas which are more heavily represented in the somatosensory cortex are associated with more accurate point localization. Nevertheless, in terms of the identification of the gross location of the contact, such as front, back, left or right, this difference in point localization accuracy makes little difference (Schiffman, 2001).

The somesthetic system is also a much more primitive system than either vision or audition in terms of development. It is the earliest system to develop in the human embryo while audition and vision are the last to develop (Kisilevsky et al., 1991; Montagu, 1986; Stack, 2001). Somatosensory receptors are well developed by birth. Pacinian corpuscles, Krause end bulbs, Ruffini cylinders, and Meissner's corpuscles are all present at birth, and information carried by the spinothalamic (heat, cold, pain, general touch) and lemniscal systems (form, contour, position, temporospatial information) are all functional (Weiss & Zelazo, 1991).

Human development also indicates the primacy of touch. For the infant at birth, tactile sensations in the form of pressure sensations, which greatly intensify during birth, provides the clearest experience of reality of any of the sensory impressions flooding in. From then on there are tactual experiences of sucking, which occur in connection with the vital process of taking in food. Even without active touching, tactual impressions constantly occur in the infant, owing to their contact with their clothing, the ground, and the body care received. This contact occurs to such an extent that all other sensory impressions are overshadowed in both scope and intensity (Katz, 1925/1989).

Between birth and 6 months of age, infants' touching appears unmistakenably to gravitate toward the mouth. In addition to its nutritional function, the mouth is the primary instrument used to contact, capture, and explore objects. Oral capture and mouthing of objects appear to drive and organize early exploratory behavior, and mouthing is one of the infant's primary means for discriminating among objects (Rochat & Senders, 1991). Rochat (1983) reported that the potential perceptual/exploratory functioning of the mouth is apparent at birth, and increases in frequency and importance during the first four months of life. Other research indicates that infants as young as 4 months use their sense of touch to thoroughly explore the texture of objects (Morange-Majoux, Cougnot, & Bloch, 1997).

From a physiological point of view, it is reasonable to consider the mouth, like the hands, as a perceptual instrument. The surface in and around the mouth, and the fingers contain the highest concentration of tactile receptors on the body surface. Like the hands, the mouth has a high perceptual potential, combining tactile as well as kinesthetic reception from the mobility of jaws, tongue, and lips (Gibson & Pick, 2000). Somatotopic and motor homunculus representations indicate that fingers and lips have a relatively large cortical projection corresponding to the greater tactilokinesthetic sensitivity of these regions (Rochat & Senders, 1991).

By two months, there is a clear shift in dominance from the feeding to the exploratory system. As soon as the child learns to use its hands, a true passion for touching awakens. An important improvement in the touching tool occurs with the opposition of the thumb. The child relies on the tactual impression, which alone seems to guarantee the reality of the object (Katz, 1925/1989). Because its perceptions have the most compelling character of reality from a perceptual point of view, touch plays a far greater role than the other senses in the development of belief in the reality of the external world. Nothing convinces us as much of the world's existence, as well as the reality of our own body, as contact between the body and its environment. What has been touched is the true reality that leads to perception. Thus, while the eye shows us a broken rod when immersed in water, the hand proves that the rod is whole (Rochat & Senders, 1991).

Due to its characteristics and its early development, it is not surprising that research indicates that touch plays an important role in human development in addition to exploration. Evidence indicates that touch regulates physiological and behavioral responses by aiding in the control of the infant's state of arousal (Lacreuse & Fragaszy, 2000/2003; Montagu, 1986). Touch has also been shown to be an effective stimulus for soothing neonates both alone and when paired with vestibular-proprioceptive stimulation (Lacreuse & Fragaszy, 2000/2003).

Research has also shown that in the neonate, touch can reduce stimulation by acting to maintain the infant's state or it can stimulate the infant. These results illustrate how touch can work to both instigate and maintain communication. It has also been suggested that nonverbal maternal behaviors, including touching, provide a means of modulating the overall level of stimulation to which the infant is exposed, potentially facilitating regulation the infant's own state and level of arousal (Lacreuse & Fragaszy, 2000/2003).

Touch also plays an important role in the socialization of the infant. Physical contact between the parent(s) and infant is believed to play an important role in the infant's developing social and emotional needs. Much of this research is focused on the concept of "bonding." Bonding is considered a unidirectional affectional tie from the parent of the infant, and is believed to form rapidly during the first hours and days following birth (Campbell & Taylor, 1980; Toney, 1983). Physical contact is thought to enhance the effects and development of bonding, which is believed by some to have lasting effects on subsequent development and the parent-child relationship (Stack, 2001).

Further evidence for the primacy of touch comes from the study of touch in the animal kingdom. Tactile perception plays a major role in the investigation of the environment and is universal among animals. As with infants, for many mammals the mouth is the body part most sensitive to touch and the main tool of perceptive exploration. In rodents, for example, the perception of the surroundings relies predominantly on the vibrissae. In primates, the mouth remains rich in tactile receptors and is still largely represented in the motor and sensory cortices, but the differentiation of the anterior limbs into prehensile extremities has resulted in considerable broadening of explorative capabilities, and the manipulation of objects. Touch is essential to the success of the practical actions of the hand, such as tool use. Such advances culminate in the human hand, which has become the main tool of investigation, manipulation and transformation of the world (Lacreuse & Fragaszy, 2000/2003).

For example, in Old World monkeys, such as the Capuchin, the use of the precision grip is most remarkable. It allows them to hold an object between the flexed fingers and the opposed thumb, without participation of the palm. Capuchins, which are among the greatest tool users after the chimpanzees and humans, show finger independence and demonstrate different types of fine grip. They also have the ability to combine actions, objects and surfaces and perform activities that are rarely observed in other monkeys (Lacreuse & Fragaszy, 2000/2003).

Touch is also important for other species in the animal kingdom. In rodents, the vibrissae constitute a very important sense organ of rodents. Like our hands, the whiskers of a rodent are a highly sensitive apparatus for acquiring information about the environment (Staiger et al., 2000). The simplest of these uses is to provide information important for orienting head. More complex uses include the discrimination of surface texture, feature recognition, and object localization (Sachdev et al., 2001).

The properties of touch can also explain the behavior of animals that react to acoustical stimuli without having auditory organs, or that do have auditory organs, but who let their behavior be determined more by mechanical shocks in the surrounding medium rather than by acoustical stimuli. For example, lizards, ants, elephants and many other animals respond in a variety of ways to ground shakes that are not accompanied by any acoustical stimuli. Web-weaving spiders demonstrate a highly-developed vibration sense and can be attracted by a chambered tuning fork. The sense of vibration also plays a prominent role in the lives of ground-dwelling animals that move by creeping. The sense signals the approach of danger or food from a far distance (Katz, 1925/1989).

Further, evidence of the primitive nature of the sense of touch comes from the plant kingdom. Research has shown that some plants display a different level of sensitivity to different intensities of contact. For example, plants such as the mimosa are sensitive to jolts, and react with full force of movements even to a single impulse (Katz, 1925/1989).

Overview of the Study

One way to demonstrate a difference in the allocation of resources in the sensory modalities is to cross-compare two systems using a dual-task paradigm. In the study, audition and touch will be compared using a targeting task and a verbal-shadowing task. The targeting task requires the participants to locate and eliminate a target displayed on a computer screen by moving a set of crosshairs over the target and clicking the right mouse button. The verbal shadowing task requires the participants to repeat back a series of sentences.

The processing of the targeting task requires spatial processing while the verbal-shadowing task requires verbal processing. Since the two tasks require two different processing codes there should be no interference between the tasks at the central processing stage. Also, there should be no interference in response because the targeting task requires a manual response, and the verbal-shadowing task requires a verbal response. Therefore, the only source of interference should be at the sensory processing stage.

For the purpose of this study, the comparison will be made using audition and touch. Vision has been excluded from this study for two reasons. First and foremost are the indications from the literature, of visual dominance (Batic & Gabassi, 1987; Posner, Nissen, & Klein, 1976; Spence, Shore, & Klein, 2001). As mentioned above, research has shown that when visual events occur simultaneously with auditory events, tactile events, and chemosensory events, the other sensory modalities are captured or dominated by vision (Batic & Gabassi, 1987; Heller, 1983; Proctor & Van Zandt, 1994b; Rock & Harris, 1967; Spence et al., 2001).

Research, however, suggests that touch and audition can be decoupled resulting in neither sense dominating the other. In a study of task relevancy, Eimer, van Velzen, and Driver (2002) found that participants directing attention in the audition-relevant condition did not influence tactile ERPs. While reliable attentional modulations of somatosensory ERPs were observed when touch was relevant, no such effects were present in the audition-relevant condition, even though clear cross-modal effects on visual ERPs were present in the same auditory task. This corroborates and extends Eimer and Driver's (2000) proposal that the tactile modality may be unique, in that touch alone can be "decoupled" from an influence of which side is cued for another modality.

The second reason for not using vision in this study is due to a structural difference between vision, audition, and touch. The visual receptors are the eyes, and as mentioned above, in humans they are located on the head, facing forward. This results in a limitation of the field of vision. Therefore, unlike a rabbit, whose eyes are positioned on the sides of the head, we cannot see behind us without moving our heads (Schiffman, 2001). Both audition and touch, on the other hand, are omni-directional. Since our ears are on the sides of our heads, we can receive auditory stimuli from in front or behind us. Likewise, since the receptors for touch are found in our skin, and our skin covers our entire body, we can perceive touch stimuli from any direction.

Participants completed the targeting task using either an auditory cue or a tactile cue to locate the target. Since the targets could not been seen, the cues were continuously given until the participant placed the crosshairs on the target at which time the cue stopped. This was the subject's cue to "shoot" the target. The targets were located either to the left or right of the center starting point. In experiment 1, if the target was to the left, the signal originated on the left, whereas the signal originated on the right if the target was to the right. Participants in experiment 1 received the auditory cue over headphones, while the tactile cue was delivered by tactors placed on the sides.

According to one possible interpretation of MRT, because both the auditory targeting cue and the verbal-shadowing task use the same sense, there should be greater interference in this condition, than when the targeting cue is delivered tactorily. If this is the case, then performance on the targeting and shadowing tasks should be worse in the dual-task auditory condition, where both the targeting cue and the shadowing stimuli are delivered auditorily, than in the dual-task tactile condition when the targeting cue is tactile. However, a second interpretation suggests that there should be no difference because the two tasks do not use the same central processing codes or the same response codes. Also, because the target locations are either to the left or to the right, which is the easiest localization task auditorily and very straightforward in terms of touch, there should be little or no difference between the performance of the dual-task auditory and the dual-task tactile conditions. In the first experiment, it is hypothesized that there will be no difference between the tactile and auditory cues in any of the conditions.

In experiment 2, the same two tasks were used, however, the direction of origin was changed. Since the purpose of this study was to determine if structural differences in our sensory systems can affect the allocation of resources, the second experiment took advantage of a structural limitation of audition to alter the targeting task. Because of the location of our ears, the localization of sounds that originate from in front or from behind us is the hardest auditory localization task.

Sound localization depends on stimulation of the two ears or binaural cues. The auditory system uses the physical differences in stimulation that arise because the two ears are separated in space to locate the sound's point of origin. The first of these cues is the interaural time difference, which is the time differences produced when a sound reaches one ear before it reaches the other. The second binaural cue is interaural intensity difference, which refers to the difference in intensity of a sound reaching each ear. A sound that lies at different distances from each ear not only strikes the nearer ear first, but it also delivers a slightly more intense sound to that ear. The final binaural cue is phase difference. Under certain conditions, especially for low frequency sounds, localization may be aided by detecting a difference in the phase between the sounds reaching the two ears. Sounds which have wavelengths longer than the diameter of head are defracted around the head, which means that the waveform of the sound reaching one ear may be in a different part of its cycle than the waveform of the sound arriving at the other ear, and, in some cases, this difference may provide a cue fro sound localization. Therefore, if a sound originates from our left, we hear it in our left ear before we hear it in our right (interaural time difference), appears to louder in our left ear than our right (interaural intensity difference), and may have a different waveform. It is for this reason that the localization of a sound to the left or to the right is the easiest localization task (Bear et al., 2001; Schiffman, 2001).

However, the situation changes dramatically when the sound originates from in front or from behind a person. As the location of the sound source moves more to our front or more behind us, the interaural time difference, the interaural intensity difference, and the phase difference all become smaller until the disappear totally for sound that originate from directly in front of us or directly behind us. When this happens, it is not uncommon for people to experience front-back reversal. In front-back reversal, the person determines that the sound originates from in front of them when it actually originated behind them, and vice versa (Bear et al., 2001; Schiffman, 2001). Front-back reversal is a well-documented phenomenon that appears in many auditory studies (Proctor & Van Zandt, 1994b).

In experiment 2, the origins of the targeting cues were placed directly in front of and directly behind the participants. If the cue originated from in front of the participants, then the participant was instructed that the target was to their left, while if the cue originated from behind the subject, then the participant was instructed that the target was to their right. Because there is no tactile front-back reversal it was expected that the participants would perform worse in the dual-task auditory condition than in the dual-task tactile condition. The auditory front-back reversal requires the participants to have to allocate more sensory processing resources in the dual-task auditory condition to locate the target than they have to in the dual-task tactile condition resulting in poorer performance on the targeting.

In regards to the shadowing task, according to MRT the participants' performance should be worse when using the auditory targeting cues because the two tasks are using the same sensory systems. However, research indicates that people can learn to do two complicated activities simultaneously without having an affect on each other (Spelke, Hirst, & Neisser, 1976). Since the shadowing task procedure is the same across all targeting conditions it is expected that following this amount of training that no significant difference will be found between the participants' performance on the shadowing task across conditions.

Overall, the results of the experiments combined should demonstrate that changes made in a task which are due to structural differences in the sensory modality influence the allocation of resources in the sensory processing stage of information processing. In other words, performance cannot be simply predicted in a multiple task scenario based simply on spreading the tasks across different modalities, but instead, the natures of the modalities themselves must be taken into account as well.

Hypotheses

The hypotheses for the overall study are shown in Table 1.

Table 1: *Study Hypotheses.*

Hypothesis 1	Characteristics of the sensory system influence the allocation of resources such that when changes in the requirements of a task emphasize the strengths of the sensory system task performance will not be affected, but when the changes emphasize limitations of the sensory system, task will performance will be negatively affected.
Hypothesis 2	As long as the changes in one task of the dual-task paradigm do not influence the allocation of resources concerning the second task, there will be no differences in performance on the secondary task when the requirements of the first task change.
Hypothesis 3	Alterations in the requirements of any task that appear to make the task more difficult, such as the addition of another task or alterations within the requirements of a task will result in operators judging the difficulty of the task to have increased.

CHAPTER 2: EXPERIMENT 1

Hypotheses

The specific hypotheses for experiment 1 are shown in Table 2.

Table 2: *Hypotheses for Experiment 1.*

Hypothesis 1: Targeting Hypothesis	When using the auditory cue, performance will be no worse on the targeting task in either the baseline or dual-task condition than when using the tactile cue.
Hypothesis 2: Combination of Cues Hypothesis	The combination of the auditory and tactile targeting cues will result in better performance on the targeting task than either the auditory or tactile cues alone.
Hypothesis 3: Shadowing Hypothesis	The addition of the targeting task will have no effect on performance on the shadowing task regardless of the modality of the targeting cue or the combination of cues.
Hypothesis 4: NASA-TLX Hypothesis	No difference will be found between the subjective workload ratings for the different modalities (auditory or tactile) of the targeting cue on the targeting task.

Methods

Participants

Thirty students from the University of Central Florida acted as participants in this study. They ranged in age from 18 to 26 years of age, with the median age being 19. Participants received either extra credit in psychology classes or were paid twelve dollars for participating in this experiment. All participants reported normal hearing and none reported having nerve damage that would interfere with detecting the tactile cue.

Layout

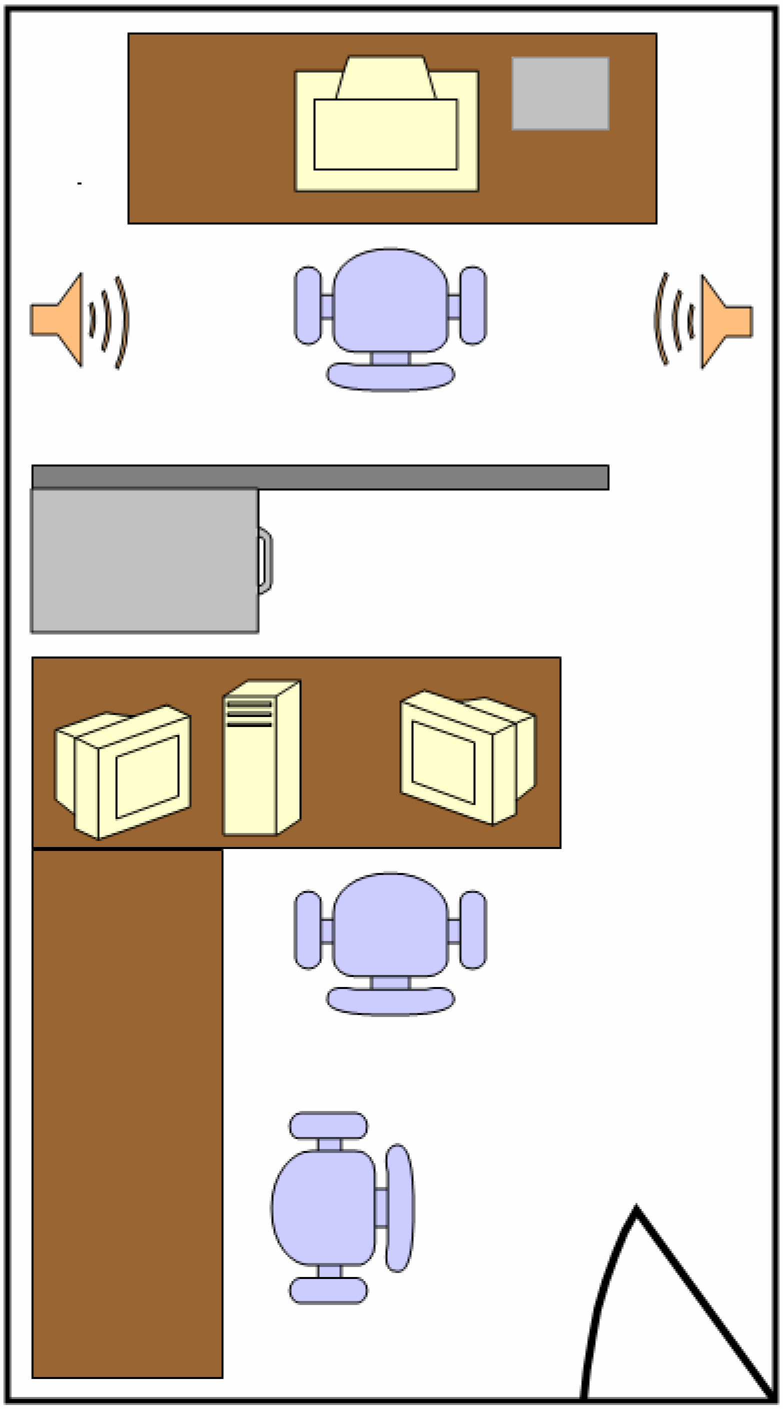


Figure 1: Laboratory Layout

As seen in Figure 1, the laboratory was divided into two areas. Located in the experimental area, were the experiment computer, monitor, mouse, and headphones. The experiment computer was connected to a splitter box which was connected to two monitors: the one in the experimental area and a second monitor located in the control area. This allowed the researcher to monitor the progress of the participant without entering the experimental area. A second computer located in the control area provided the input signal for the tactors and recorded the shadowing stimuli.

Equipment

All stimuli in this experiment were delivered using a TRG8 computer with an X86 GenuineIntel~1600 processor running Windows 2000 Professional. The graphical stimulus was delivered on a 19" color monitor located in the experimental area. This computer was also connected via a splitter box to a 15" color monitor in the control area. The auditory targeting cue and stimulus were delivered through a set of Sennheiser HD 280 pro headphones. The tactile targeting cue was delivered through two custom built tactors, which were powered by a custom built tactor box. The tactile signal was generated by a second computer that was identical to the first, and which was connected to a 15" color monitor.

Stimulus Materials

Auditory Stimuli

The auditory cue was composed of six tones, three under 1,500 Hz (440 Hz, 800 Hz, & 1,000 Hz) and three between 4,000 and 11,500 Hz (4,000 Hz, 7,000 Hz, and 11,000 Hz). The high frequency ensures the use of interaural intensity differences and the low frequencies ensure the use of interaural temporal differences in localization. The combination of frequencies also helps prevent the signal from being completed blocked by a voice at the same frequency. The stimuli was recorded in a wave file and played back by Microsoft Sound Recorder.

The shadowing stimuli consisted of 80 sentences that ranged from 15 to 20 words in length. The sentences were designed to prevent the participants from using past knowledge as an aid in reproducing the sentences during the shadowing trials. Five of the sentences were used as practice, 15 were used to create the baseline, and 60 sentences were used in the dual task portion of the experiment. These 60 sentences were broken down into two groups of 30 sentences. The practice and baseline sentences were presented with a 5-second interval between each sentence. The dual task sentences were broken down into three blocks of 10 sentences separated by a 15-second interval. Within each block the sentences were separated from each other by a 5-second interval. The sentences were recorded in wave files and played back by Microsoft Sound Recorder.

The shadowing stimulus was recorded using SoundForge version 4.5.

Tactile Stimulus

The tactile stimulus was a repetitive vibration presented at 740 Hz. The stimulation was played back by Microsoft Sound Recorder.

Target Stimulus

The shooting range used in the study was adapted from the target range of the video game, Ghost Recon. Targets were programmed to appear at random. The time between the offset of one trial and the onset of the next ranged from 2 to 9 seconds. The targets appeared randomly in any one of four positions around the building. The experimental program recorded the initial response time, the initial direction in which the mouse was moved, the number of clicks required to "hit" the target, and the response time from target onset to target offset.

Measures

The NASA-TLX (Hart & Staveland, 1988) index was used to evaluate the subjective workload of each of the baseline and dual-task conditions. This index consists of six scales on which the individual rate the workload from low to high. The scales evaluate mental demand, physical demand, temporal demand, performance, effort, and frustration level. An overall measure of workload is obtained by assigning a weight to each scale according to its importance for the specific task and then calculating the mean of the weighted values of each scale. Mental demand can be described as how much mental and perceptual activity was required to complete the task. Physical demand can be described as how much physical activity did the task require to complete. Temporal demand describes how much time pressure the person feels due to the rate or pace at which the tasks or task elements occur. Performance describes how successful the individual thinks he or she was in accomplishing the goals of the task set by the experimenter and how satisfied the person is with his or her performance in accomplishing these goals. Effort describes how hard the individual had to work to accomplish a specific level of performance. Finally, frustration level describes how insecure, discouraged, irritated, stressed, and annoyed versus secure, gratified, content, relaxed, and complacent the individual felt during the task (Proctor & Van Zandt, 1994a).

Design

A baseline was established for the shadowing condition and three targeting cues: Auditory only, Tactile only, and Tactile/Auditory combined. In the dual task portion of the study, the shadowing was combined with each of the targeting cues to form three dual-task conditions: Dual-Task: Auditory Targeting Cue Only, Dual-Task: Tactile Targeting Cue Only, and Dual-Task: Auditory/Tactile Cues Combined. Four measures were recorded for each targeting cue in both the baseline and dual task portions of the study: Initial Response Time (the time, measured in milliseconds, between the appearance of the beginning of a trial and the participant's first motion), Accuracy (the number of shots (clicks of the mouse) needed to knock down the target), Initial Movement (the direction of the first movement made during a trial), and Response Time (the total amount of time, measured in milliseconds, that it took the subject to knock down the target).

Procedure

Prior to arrival the participant was randomly assigned to an order set. The order set consisted of one of four baseline orders, one of six dual-task orders, and one of two sentence orders. The baseline orders insured that each baseline task appeared in each of the four presentation positions. The dual-task orders were made so that all possible combinations of the three dual-task conditions would be equally represented. A total of 48 possible order sets were possible. This was done to account for any possible effects of the order of presentation.

Upon arrival, the participants were asked to read and sign a consent form and to then fill out a demographic questionnaire. The information collected from the questionnaire included age, gender, height, weight, whether or not the participants needed glasses or hearing aids, whether or not the participants had any nerve damage that would affect their ability to sense tactile stimuli, how often they played video games, and their past experience with firearms.

Upon the completion of the consent form and questionnaire, the participant was escorted into the experiment area where a research assistant placed the tactile belt around the participant's midsection. The participant's girth was measured using a cloth tape measure. This number was then divided by two to obtain the half-way point of the participant’s girth. The first tactor was placed on one side at point zero, and the second was placed on the opposite side at the half-way point.

Once the tactor belt was in place, the participant was seated in front of the experimental computer. The participant was then told that they would be asked to complete two tasks, first separately and then simultaneously, during the experiment. The targeting task was then explained and then the participant was instructed to click on “Start” to preview the targeting task. After four trials, the experimenter stopped the session by pressing Escape on the experimental keyboard that was located in the control area of the lab. The experimenter then turned on both the auditory and tactile targeting cues.

Then the experimenter then told the subject that before the first condition was presented that a cross modal matching task had to be performed to establish that the participant was perceiving the tactile and auditory targeting cues to be the same intensity. The experimenter then set the tactile signal to its normal setting and the volume on the headphones was turned down to zero. When the experimenter pressed Start, the participant felt the left tactor vibrate. Then the experimenter started turning the volume up on the headphones. The participant was instructed to stop the experimenter when he or she perceived the loudness of the auditory cue to match the intensity of the tactile cue. Participants were told that this is a purely subjective task and there is no right or wrong answer. The procedure was repeated twice, once with the left and once with the right. Then the experimenter told the participant that the procedure would be repeated two more times for a total of four trials. The difference was that for the last two trials, the volume was initially set high and then turned down until the subject said stop. Otherwise, the procedure was the same. Following each trial, the researcher recorded the volume setting and turned the volume down again. When all four cross modal trials were finished the results were averaged and the auditory volume was set at this average value for the duration of the study.

After the cross-modal matching task was completed, the baseline portion of the experiment was begun. Participants were told that the targeting task was identical to the example trials they had done at the first of the experiment except that from then on the target would not be visible. Instead, the only way to locate the target would be with the tactile cue, the auditory cue, or the combination of the two. The participants were then told that when he or she pressed Start the mouse pointer would disappear. When the targeting cue started, the pointer would reappear as a set of crosshairs. Participants were told that if the cue came from the left, it meant move left. If the cue came from the right, it meant move right. When the crosshairs were on the target, the cue stopped and the participants were to click the left mouse button and that would end the trial, and reset everything for the next trial. If the cue jumped from one side to the other, it meant that the participant had passed over the target and the participant had to go in the opposite direction. Participants were instructed to wear the headphones during each condition to maintain consistency throughout the study.

Once the participant indicated that he or she understood the procedure, the participant was instructed to click on start whenever they were ready to begin. For each targeting cue, the participants were given 10 practice trials, followed by 25 baseline trials. The practice trials were discarded. Following each baseline, the file was saved on the experimental computer.

For the shadowing baseline, participants were told that they would be completing a shadowing task in which they would be presented with a series of sentences. They were instructed to repeat the sentences exactly as they heard them. The participants were then given 5 practice sentences to familiarize themselves with the pacing and length of the sentences, and the speaker's voice. When the practice was over, the experimenter set up the baseline which was made up of 15 sentences. When the participant was ready he or she pressed Start, and the experimenter started the recorder to record the baseline. Following the completion of the baseline, the experimenter saved the file to the control computer's hard drive.

Following each baseline, the participant was given the NASA TLX and asked to complete it for the task they had just completed.

When the participant had finished all of the baselines, the dual-task portion of the study was explained. During this phase, the participant completed both the targeting task and the shadowing task at the same time. The only difference was that the shadowing portion was composed of 30 sentences as described above. Because of the limited number of sentences, the first and last targeting conditions used the same set of sentences, while the second targeting condition used the other set. This order of sentence grouping was rotated every participant. For example, participant 1 received set 1 first, then set 2, then set 1 again, while participant 2 received set 2 first, then set 1, then set 2 again. Participant 3 received the same order as participant 1.

Following each dual-task condition the participant was asked to complete the NASA-TLX for the task they had just completed.

Following the last dual-task combination, the participant was debriefed and released.

Results

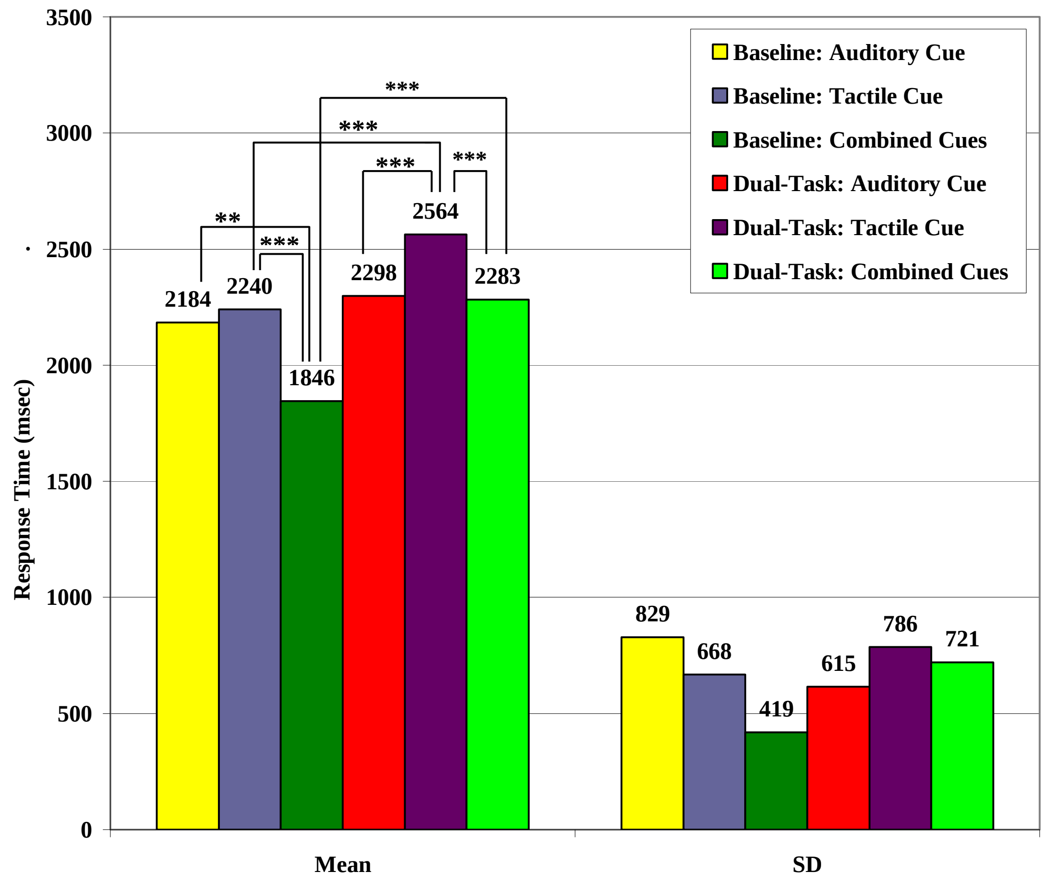
The alpha level was set to .05 to distinguish significant effects.

Targeting Data Analysis

The data was analyzed using SPSS 11.0. A repeated measures procedure was used to compare the six experimental conditions (Baseline: Auditory Targeting Cue Only, Baseline: Tactile Targeting Cue Only, Baseline: Tactile/Auditory Targeting Cues Combined, Dual Task: Auditory Cue Only, Dual-Task: Tactile Targeting Cue Only, Dual-Task: Tactile/Auditory Targeting Cues Combined) for response time, initial response time, direction of initial movement, and accuracy.

Response Time

The mean response time (RT) and standard deviation for each condition is shown in Figure 2 and given in Table 3 which is located in Appendix A.



**, The mean difference is significant at $\alpha = .01$.
***, The mean difference is significant at $\alpha = .001$.

Figure 2: Mean Response Times and Standard Deviations, and Results of Pairwise Comparisons Response Times for Experiment 1.

The test of within-subjects effects found a significant difference between the six experimental conditions, Wilks' $\Lambda = .226$, $F(5, 25) = 17.172$, $p = .000$, multivariate $\eta^2 = .774$.

Nine specific post hoc comparisons were made using Fisher's Least Significant Difference (LSD) technique. The results are shown in Figure 2 and given in Table 4 which is located in Appendix A.

According to these results, on average, the participants were faster in the baseline conditions when using only the auditory targeting cue than they were when they used only the tactile targeting cue, however, this difference was not significant. However, in the baseline conditions, the mean response time for the auditory targeting cue and the tactile targeting cue were significantly slower than the mean response time for the auditory/tactile cues combined. This indicates that the combination of targeting cues resulted in improved performance over either of the other targeting cues alone.

Although, there was no significant difference between the mean response times for the auditory targeting cue alone and the tactile targeting cue alone, there was a significant difference in the mean response times of the auditory and tactile targeting cues when the shadowing condition was added. In the dual-task conditions, when the participants used the auditory cue they were, on average, significantly faster than when they were using the only the tactile cue. In addition, when the participants were using the combined auditory/tactile cues in the dual-task condition, they were significantly faster, on average, than they were when using the tactile cue alone. This indicates that when the cues were combined the participants were significantly faster than they were when using the tactile cue alone, and they were also faster than when the used the auditory cue alone although this difference was not significant.

Finally, the mean response times for the tactile targeting cue and for the auditory/tactile cues combined were significantly slower in the dual-task condition than they were the mean response times from the baseline conditions. In both cases the subjects were, on average, significantly faster in the baseline condition than they were when the shadowing task was added. No significant difference was found between the mean response times in the baseline and in the dual-task conditions for the auditory cue.

<u>Initial Response Time</u>

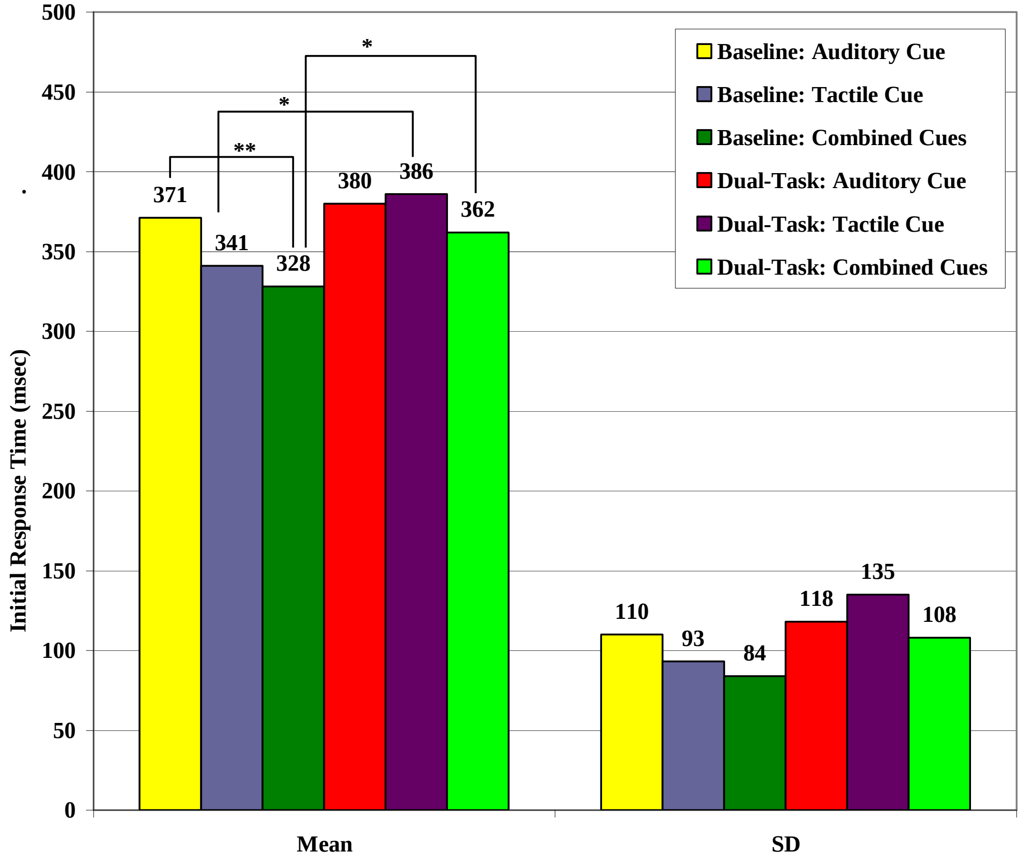
Initial Response time is the time in milliseconds between the onset of the targeting cue and the participant's first movement. The mean initial response times and standard deviations are shown in Figure 3 and are given in Table 5 which is located in Appendix A.

The test of within-subjects effects found a significant difference between the six experimental conditions, Wilks' $\Lambda = .527$, $F(5, 25) = 4.491$, $p = .005$, multivariate $\eta^2 = .473$.

Nine specific pairwise comparisons were made using Fisher's Least Significant Difference (LSD) technique. The results are shown Figure 3 and given in Table 6 which is located in Appendix A.

According to these results, when participants were only performing the targeting task, there was no significant difference in the participants' initial response times between the auditory cue and tactile cue, or between the tactile and combined auditory/tactile cues. However, when the participants used the auditory cues in the targeting task they were significantly slower to react to the onset of the targeting cue than when they were using the auditory/tactile cues combined.

In the dual-task conditions there was no significant difference between any of the targeting cues.



*, The mean difference is significant at α = .05.
**, The mean difference is significant at α = .01.

Figure 3: Mean Initial Response Times and Standard Deviations, and Results of Pairwise Comparisons for Initial Response Times for Experiment 1.

In the comparison of the baseline conditions and dual-task conditions, there was no difference in the participants' initial response time when they used the auditory cue. However, when they used the tactile cue or the combined cues the participants were significantly faster in the baseline conditions than they were in the dual-task conditions.

Direction of Initial Movement

The direction that participants initially moved following the onset of the targeting cues was recorded and scored as follows: 0 = wrong direction, 1 = correct direction.

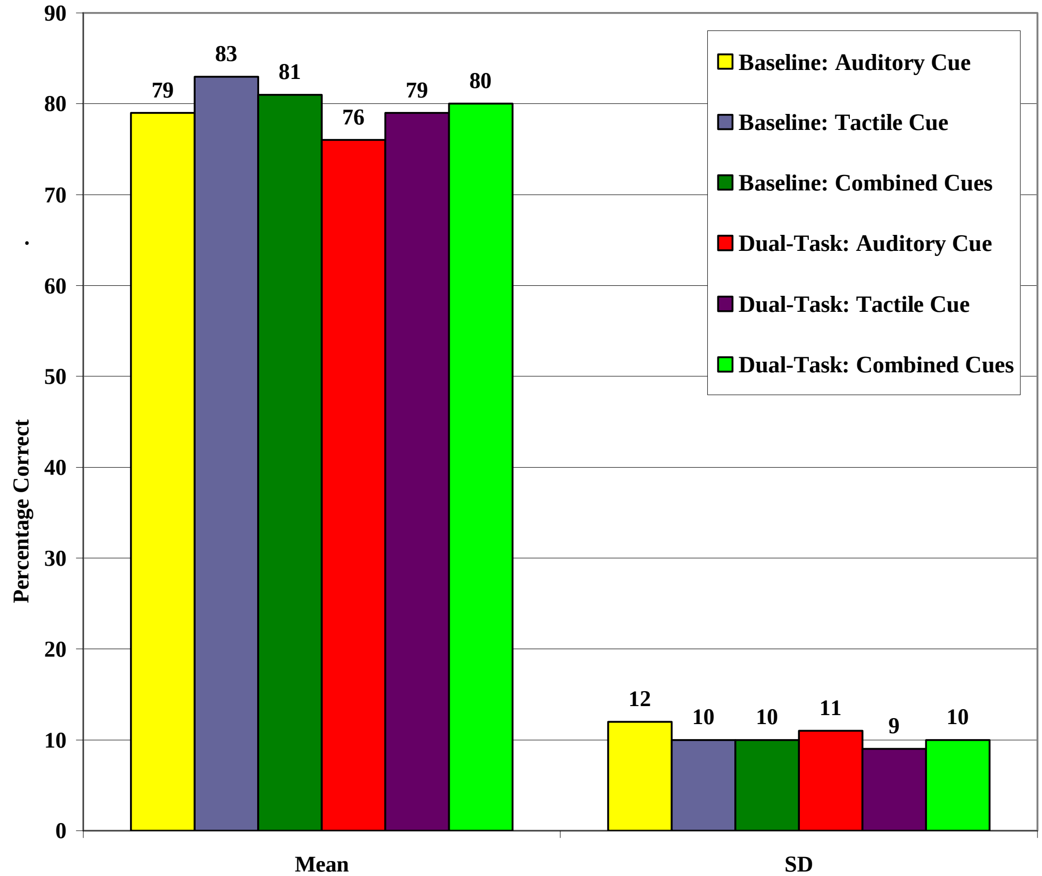


Figure 4: Mean Accuracy & Standard Deviations of Direction of Initial Movement for Experiment 1.

A mean was calculated for each experimental condition with 1.00 being a perfect score. The lower the score, the more often the participants moved in the wrong direction during that experimental condition. The mean direction of initial movements for each targeting condition and their standard deviations are shown in Figure 4 and given in Table 7 located in Appendix A.

The test of within-subjects effects found no significant difference between the six experimental conditions, Wilks' $\Lambda = .709$, $F(5, 25) = 2.135$, $p = .093$, multivariate $\eta^2 = .291$.

Accuracy

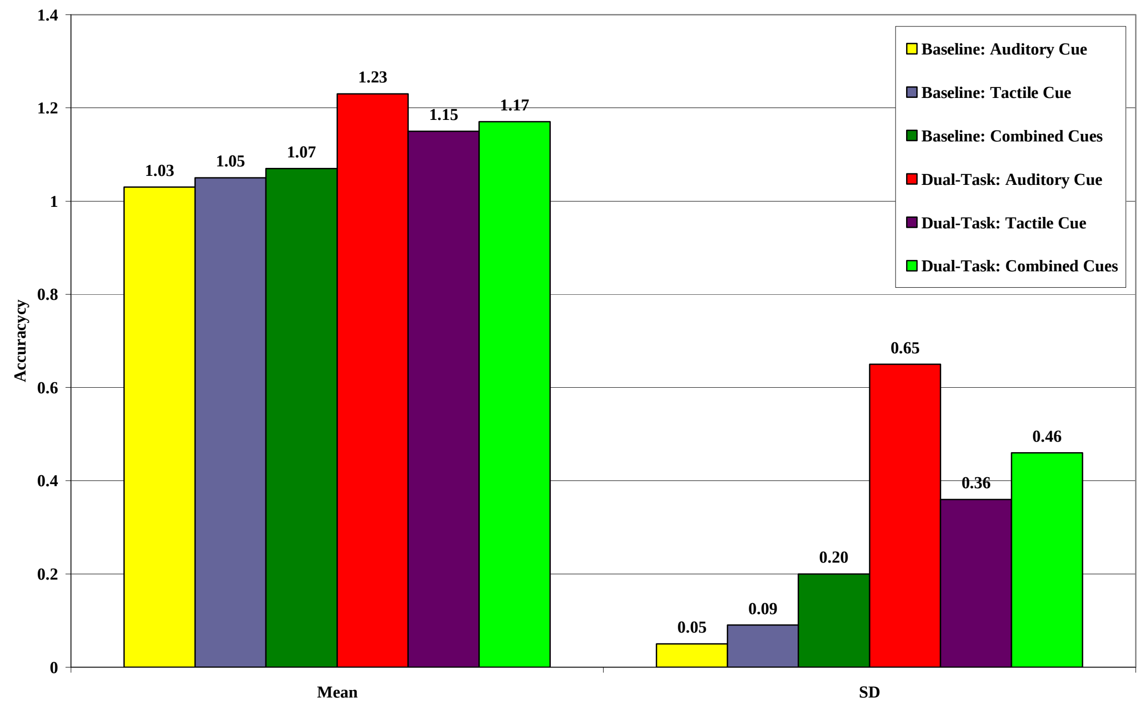


Figure 5: Accuracy Means and Standard Deviations for Experiment 1.

The accuracy of the participants in each experimental condition was recorded and scored as the number of clicks on the left mouse button required to end a trial. A score of 1.00 equals one click (shot) and was considered perfect. The higher the number, the more shots required, and the lower the accuracy. The mean accuracy for each condition and their standard deviations are shown in Figure 5 and is given in Table 8 which is located in Appendix A.

The test of within-subjects effects failed to find a significant difference between the six experimental conditions, Wilks' $\Lambda = .829$, $F(5, 25) = 1.031$, $p = .421$, multivariate $\eta^2 = .171$.

Shadowing Analysis

Scoring

To analyze the shadowing data, the sentences for the baseline and dual-task conditions were first transcribed, and the number of words for each sentence was determined. To score the participants' shadowing performance, each participant's taped shadowing task was replayed and a slash mark was made through any word which was mispronounced, or not said. No specific methodology for completing the shadowing task was given to the participants, but the participants all chose to use the same strategy to complete the task. The methodology used was to begin repeating the sentences as soon as they heard the speaker start. Because this methodology leads naturally to pauses and breaks in the shadowing, pauses and breaks were not scored.

Once a score for a sentence was determined, the ratio correct was calculated by dividing the number of words correctly repeated by the number of words in the sentence. These ratios were then averaged to produce an average number of correct words repeated for the task.

Each participant had four shadowing scores: Baseline Shadowing, Shadowing for the Dual-Task Auditory Targeting Cue only, Shadowing for the Dual-Task Tactile

Targeting Cue only, and Shadowing for the Dual-Task Auditory/Tactile Targeting Cues combined.

Analysis

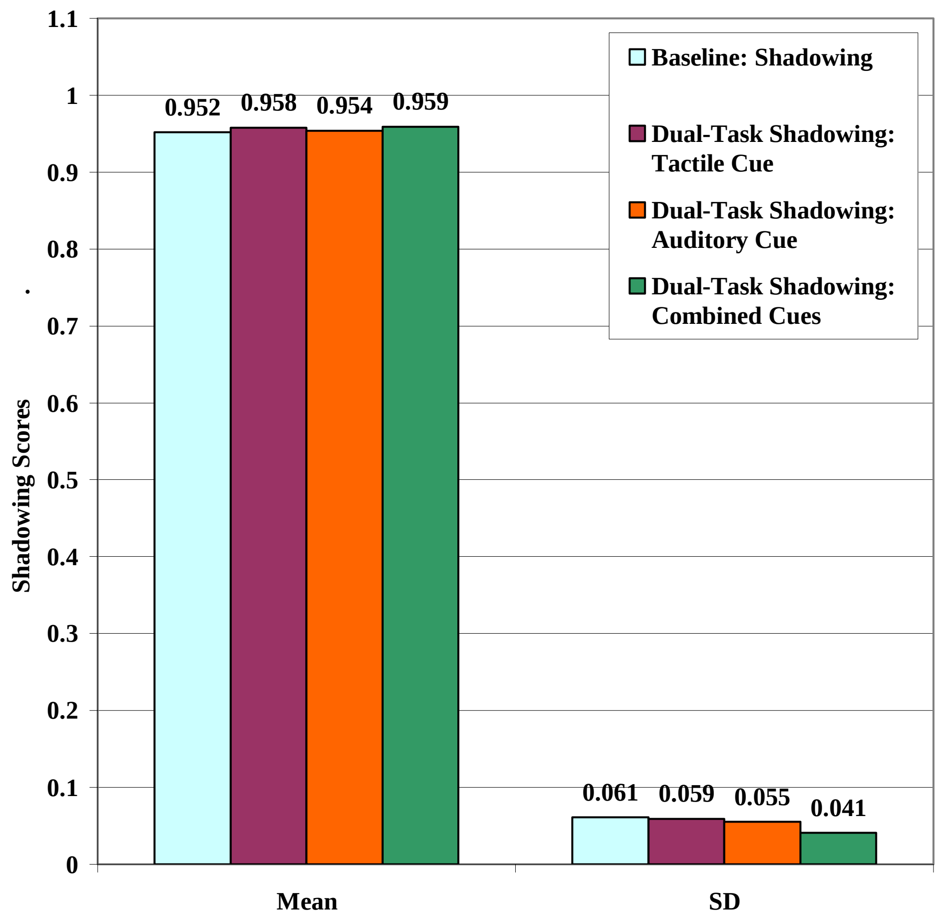


Figure 6: Means and Standard Deviations for Shadowing Conditions for Experiment 1.

A repeated measures procedure was used to compare shadowing performance in terms of accuracy (the ratio of works correctly repeated to the total number of words) for the shadowing baseline and the three dual-task conditions. The mean shadowing score and the standard deviation for each of the three dual-task conditions (Auditory cue only, Tactile cue only, and Tactile/Auditory cues combined) and the baseline shadowing condition are shown in Figure 6 and given in Table 9 located in Appendix A.

The test of within-subjects effects failed to find a significant difference between the four shadowing conditions, Wilks' $\Lambda = .962$, $F(3, 27) = .356$, $p = .785$, multivariate $\eta^2 = .038$.

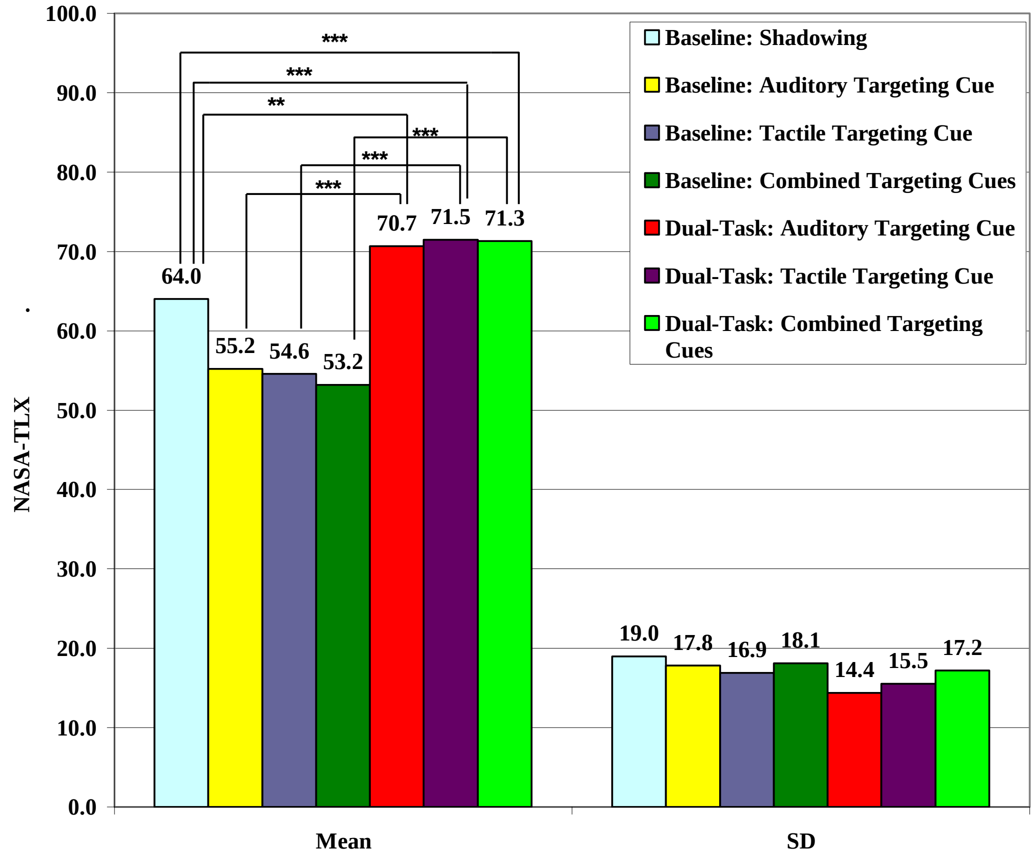
NASA-TLX Analysis

A repeated measures procedure was used to compare the scores of the NASA-TLX workload measure for all baseline and dual-task conditions. The means and standard deviations for the seven NASA-TLX administrations are shown in Figure 7 and given in Table 10 (see Appendix A).

The analysis found a significant difference in the participants' subjective interpretation of the workload of the different conditions in the experiment, Wilks' $\Lambda = .351$, $F(6, 24) = 7.713$, $p = .000$, multivariate $\eta^2 = .649$.

The mean NASA-TLX scores for each condition were compared using Fisher's Least Significant Difference (LSD) technique. The results of these comparisons are shown in Figure 7 and given in Table 11 (see Appendix A).

According to the results of the post hoc analysis, there was no difference in the mean perceived workload associated with the different targeting cues in the baseline portion of the experiment, nor was there a difference in the mean perceived workload associated with the different targeting cues in the dual-task portion of the experiment. A significant difference was found when the mean perceived workload associated for each targeting cue in the baseline was compared with the mean perceived workload for the same cue in the dual-task portion. On average, participants perceived the targeting task to be more difficult when the shadowing task was added for all targeting cue conditions.



**, The mean difference is significant at $\alpha = .01$.
***, The mean difference is significant at $\alpha = .001$.

Figure 7: NASA-TLX Means and Standard Deviations, and Results of Pairwise Comparisons for the NASA-TLX for Experiment 1.

Finally, on average, participants also perceived the difficulty of the shadowing task to increase when combined with the targeting task for all of the targeting cues.

Discussion

Overall, the results support the hypothesis that there would be no difference between the tactile and auditory cues in any of the conditions. This supports the idea that in order for MRT to be used to predict the allocation of resources in multiple task situations the characteristics of the sensory modalities involved must be take into account. A simple explanation of MRT would predict that the addition of the shadowing task would result in the shadowing and targeting tasks competing for resources because both are auditory tasks and this would result in poorer performance on both tasks. In this scenario, the targeting task using the tactile cue and the auditory shadowing task are depending on different modalities there is no competition for resources and performance should not be impaired in any way. Overall, the results do not support this prediction (Smith & Buchholz, 1991; Wickens & Holland, 2002; Wickens, 2002).

In addition, the tasks used in this study were designed to eliminate resource competition at any other stage in the model. First, since the two tasks rely on different processing codes, spatial for the targeting task and verbal for the shadowing task, there is no interference at the central processing stage. Second, the response modes for each task are different so there is no competition at this level either.

Whether the targeting cue being used was tactile or auditory did not significantly affect the time it took the participants to respond following the onset of the targeting cue in either the baseline condition or dual-task conditions. There was also no significant difference between the cues in terms of how long it took the subjects to locate the target in the baseline condition. Surprisingly, the participants seemed to locate the target faster in the dual-task condition when using the auditory cue than when using the tactile cue. The difference in cues, however, did not affect the direction of the initial movement in either condition.

These results provide support for an early stage of sensory processing in which the allocation of resources depends on the characteristics of the sensory system involved and how these interact with the task. The task of locating an object to our left or right is the simplest directional decision we make when using our hearing because all of the interaural cues are maximumally effective in this situation (Bear et al., 2001; Schiffman, 2001). The task is also rather simple from the perspective of touch. Thus, it isn't surprising that no difference was found between audition and touch in performing the targeting task.

The fact that when the participants used the auditory cue they located the target faster in the dual-task condition than they did when using the tactile cue is also not really that surprising. The MRT can not explain this finding, but the finding can be explained if the natures of the sensory modalities involved are taken into account. Our sense of hearing has evolved to serve two purposes, one to alert us to the approach of things we cannot see, and two, to allow us to communicate (Schiffman, 2001). The first of these tasks was necessary for survival early on in human history and develops early in our development (Clarkson & Clifton, 1991; Schiffman, 2001). The second also develops early in life. Thus, the auditory targeting and shadowing task are not a new experience and ones with which we have had lots of practice. In fact, daily we perform multiple auditory tasks. Because of this we are more practiced at splitting our attention in this way than splitting it between a tactile and an auditory task. As a result, the difference in response times can be attributed to our familiarity with the tasks.

The results of the comparisons of the two targeting cues alone with the combination of cues also suggest that familiarity with the use of auditory localization cueing and shadowing tasks may account for some of the results. When the combined cues were compared with the auditory cues no difference was found in the initial response time to the onset of the cues. Furthermore, no difference was found between the two after the shadowing task was added. These findings are explainable by our familiarity with using our sense of hearing to perform both of these tasks at the same time. In a sense, the participants found little difference between the uses of the two types of cues. This is further supported by the fact that the participants considered the shadowing task to require more work when combined with the targeting task no matter which targeting cue was used. This indicates that no matter which cue was used, the participants felt that the addition of the second task did make the situation more challenging.

The fact that the types of cues differed when the participants were performing the targeting tasks alone can be explained by an additive effect of the tactile and auditory cues. Specifically, one cue alerts the participant and the second cue confirms the direction. In a single cue scenario, if confirmation is needed, it must be supplied by the next cue in the sequence.

The additive explanation is supported by the results with the tactile cue alone when compared with the combined cues. For these two types of cues the participants were slower both to respond to the targeting cues and to locate the target than when using only the tactile cues. This suggests once again that one cue serves to alert the participants to the task while the second confirms this information provided by the first. This explanation is consistent with what we know about auditory alerts. Research has shown that auditory signals attract attention more readily than visual signals and suggest that they can be used to alert operators to other sources of information including alerts in other modalities (Proctor & Van Zandt, 1994b).

Research on spatial cuing has found a similar result when using attention-directing cues in a targeting task. The results of these studies suggest that the attention-directing cues may lead to a reallocation of resources, resulting in enhanced sensory processing for stimuli presented at the cued location (Luck, Hillyard, Mouloua, & Hawkins, 1996). In these situations, the attentional cuing may govern the order, or schedule, by which information is read out of an early processing stage where representations are subject to rapid decay and masking. This produces higher quality representations for information at cued (relative to uncued) locations at a later processing stage where detection occurs, thereby enhancing measured sensitivity (Hawkins et al., 1990). In the present study, the first cue received can be interpreted as acting as a cue for the location of the target for the second signal which results in the focusing of attention in that direction. A number of studies have shown that the effects of attention are greater when the task requires the integration of multiple features (Briand & Klein, 1987; Cheal & Lyon, 19992; Prinzmetal, Presti, & Posner, 1986; Treisman, 1985).

As predicted, no difference was found between the baseline conditions and the dual-task conditions for the shadowing task. Since there were no potential source of competition for resources at any stage except at the level of sensory input, and since the tasks involved are familiar, there is no reason that there should have been a difference except for the additional work required to complete both tasks. The familiarity of the shadowing task is a result of the fact that this is a task that humans regularly engage in throughout life and have thus been trained to so well that performance on such tasks is fairly consistent. This familiarity thus resulted in no significant difference being found in the different shadowing conditions (Spelke et al., 1976). This result showed up in the participants' rating of the workload in that they rated all of the dual-tasks situations to require more work than the baseline for the same cue.

In summary, the results of the analyses cannot be easily explained by a simple explanation based on MRT. The results, however, can be explained fairly easily by considering the structure of the two sensory modalities used in the study. The ease of the tasks from the perspective of the sensory systems involved, as well as the natural familiarity with using these cues for similar tasks can account for all of the results. Nevertheless, in can be argued that the simplicity and even the familiarity of the tasks can account for the findings whether or not one takes the characteristics of the sensory modality into account or not. To account for this possibility experiment 2 alters the task to make it more difficult and less familiar.

CHAPTER 3: EXPERIMENT 2

Introduction

As stated earlier, the second experiment takes advantage of a structural limitation of audition to alter to targeting task. Due to the location of our ears, the localization of sounds that originate from in front or from behind us is the hardest auditory localization task. Incorporating this into the experiment will increase the difficulty of both tasks.

Hypotheses

It is hypothesized that this increase in difficulty will have a greater affect on task performance with the auditory cues than on task performance with the tactile cues. The specific hypotheses for experiment 2 are shown in Table 12.

Table 12: *Hypotheses for Experiment 2*

Hypothesis 1: Targeting Hypothesis	When using the tactile cue, performance will be better on the targeting task in the dual-task conditions than when using the auditory cue.
Hypothesis 2: Combination of Cues Hypothesis	The use of the combination of the auditory and tactile cues will result in better performance on the targeting task than when the targeting task is performed using only the auditory cue, but no difference in performance on the targeting task will be found between the conditions using the combination of cues and only the tactile cues.
Hypothesis 3: Shadowing Hypothesis	The addition of the targeting task will have no effect on performance on the shadowing task regardless of the modality of the targeting cue or the combination of cues.
Hypothesis 4: NASA-TLX	Subjective workload will be rated as being higher when the auditory cue alone is used on the targeting task than when either the combined

Hypothesis	cues or only the tactile cue is used, but no difference will be found between the subjective workload ratings for the combined cues and the tactile cue alone.

Methods

Participants

Thirty students from the University of Central Florida acted as participants in this study. The participants ranged in age from 18 to 23 years of age, with the median age being 21. Participants received either extra credit in psychology classes or were paid twelve dollars for participating in this experiment. All participants reported normal hearing and none reported having nerve damage that would interfere with detecting the tactile cue.

Layout

The lab layout was the same as for Experiment 1 (see Figure 1), with one exception. In this study, all the auditory stimuli came from speakers. One speaker was placed in front of the subject, and the other was placed behind the subject. The speakers were placed at a height of approximately 57 inches above the floor, and were located approximately 47 inches from the center of the room.

Equipment

All the equipment in this experiment was the same at in Experiment 1 with the exception of the speakers which were standard computer speakers.

Stimulus Materials

All the stimuli used in this experiment were the same as that used in Experiment 1.

Design

The design was the same as that used in Experiment 1 except that all of the cues, tactile and auditory, came from either in front of or from behind the participant.

Procedure

The procedure for experiment 2 was the same as for experiment 1 with the following exceptions. First, before the tactile belt was placed on the participant, the participant's girth was measured using a cloth tape measure just as it was in Experiment 1. This number was then divided by two to obtain the half-way point of the participant's girth. However, in Experiment 2, the first tactor was placed on the front of the participant just above the belly button (point zero), and second was placed on the back at the half-way point.

Second, the participants were told that during the targeting task, the cue would either come from in front or from behind them. If the cue came from in front, then the target was to the left of the crosshairs, and the subject was to move to the left. If the cue came from behind, then the target was to the right of the crosshairs, and the subject was to move to the right.

Results

The alpha level was set to .05 to distinguish significant effects.

Targeting Data Analysis

The data was analyzed using SPSS 11.0. A repeated measures procedure was used to compare the six experimental conditions (Baseline Auditory, Baseline Tactile, Baseline Tactile/Auditory combined, Dual Task Auditory, Dual Task Tactile, Dual Task Tactile/Auditory combined) for response time, initial response time, initial movement, and accuracy.

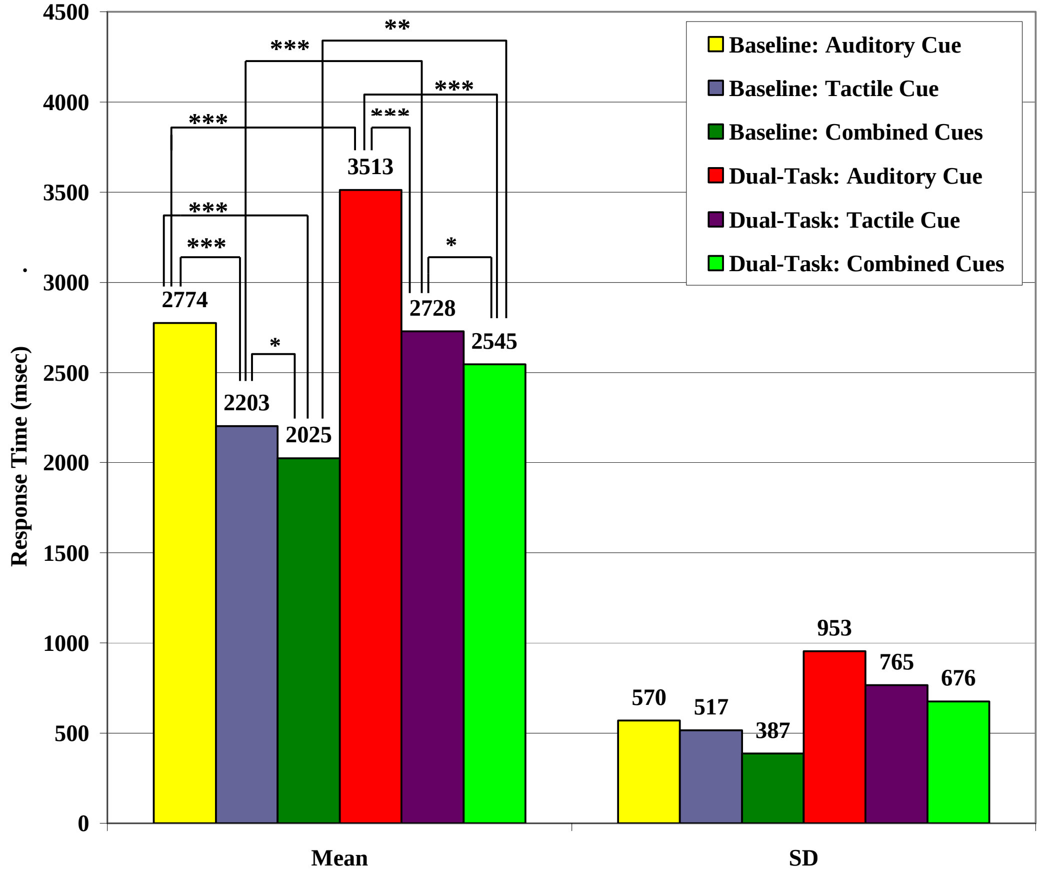
Response Time

The mean response time (RT) and standard deviation for each condition is shown in Figure 8 and given in Table 13 which is located in Appendix B.

The test of within-subjects effects found a significant difference between the six experimental conditions, Wilks' $\Lambda = .168$, $F(5, 25) = 25.705$, $p = .000$, multivariate $\eta^2 = .832$.

Nine specific post hoc comparisons were made using Fisher's Least Significant Difference (LSD) technique. The results are shown in Figure 8 and given in Table 14 (see Appendix B).

According to these results, in the baseline conditions the participants were significantly slower to locate the target when using only the auditory targeting cue than they were when they used either the tactile targeting cue or both the auditory and tactile cues together. The participants also located the target faster when they used the auditory and tactile targeting cues together than they were when using only the tactile targeting cue.



*, The mean difference is significant at α = .05.
***, The mean difference is significant at α = .001.

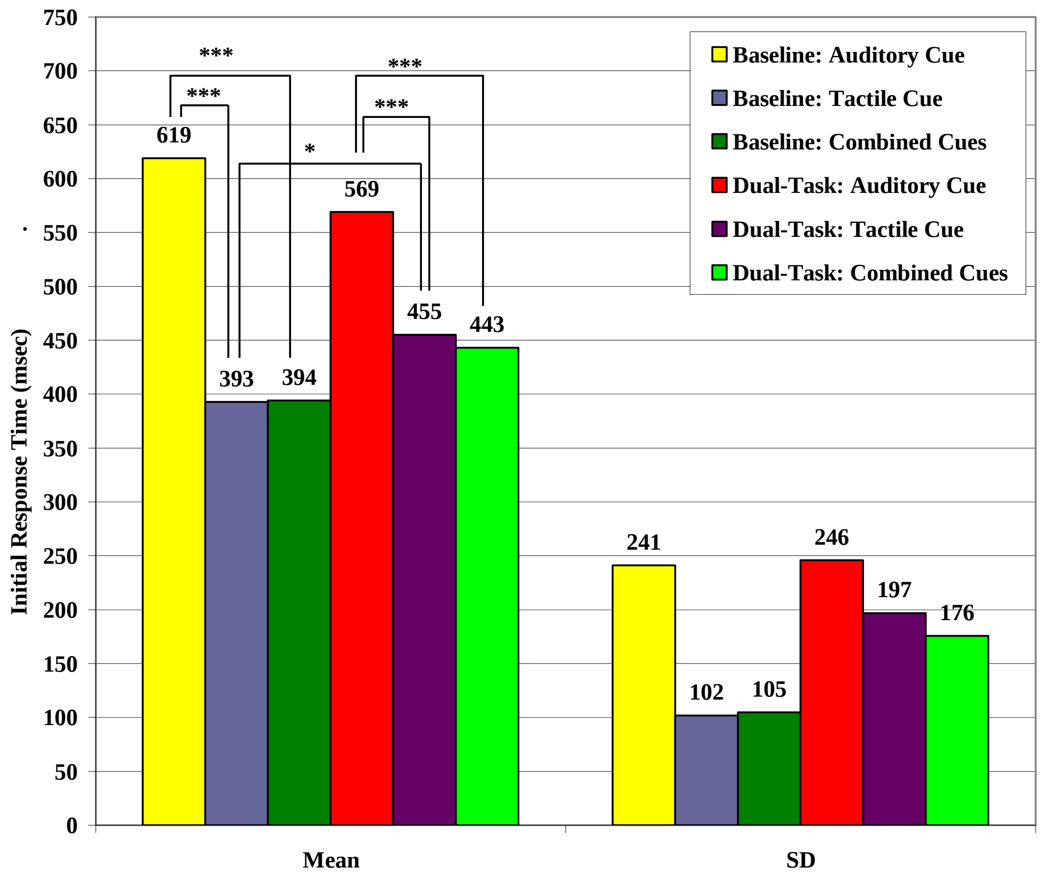
Figure 8: Mean Response Times and Standard Deviations, and Results of Pairwise Comparisons Response Times for Experiment 2.

The results also showed that the participants were significantly faster in locating the target when the shadowing task was added in the dual-task phase when they used the tactile targeting cue alone and when they used both the auditory and tactile cues together than they were when they used only the auditory targeting cue. As with the baselines, participants were significantly slower when only the tactile targeting cue was used and when they used the combination of auditory and tactile targeting cues.

Finally, the addition of the shadowing task resulted in significantly slower response times for all three sets of targeting cues.

Initial Response Time

As was stated in Experiment 1, Initial Response time is the time in milliseconds between the onset of the targeting cue and the participant's first movement.



*, The mean difference is significant at α = .05.
***, The mean difference is significant at α = .001.

Figure 9: Mean Initial Response Times and Standard Deviations, and Results of Pairwise Comparisons for Initial Response Times for Experiment 2.

The mean initial response times and standard deviations are shown in Figure 9 and given in Table 15 (see Appendix B).

The test of within-subjects effects found a significant difference between the six experimental conditions, Wilks' $\Lambda = .297$, $F(5, 25) = 11.847$, $p = .000$, multivariate $\eta^2 = .703$.

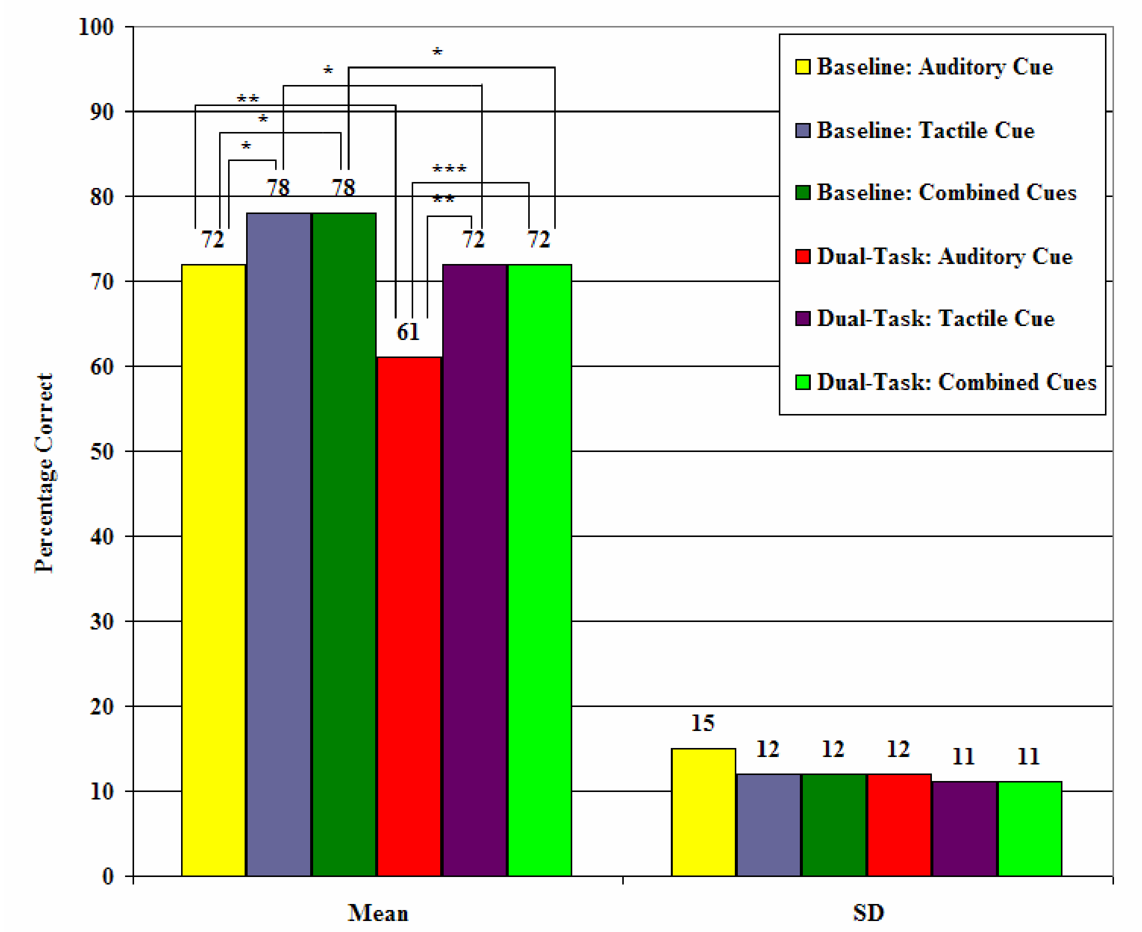
Nine specific pairwise comparisons were made using Fisher's Least Significant Difference (LSD) technique. The results are shown in Figure 9 and given in Table 16 (see Appendix B).

According to the results of the post hoc analysis, when participants were using only the auditory targeting cue, they were, on average, significantly slower to respond to the onset of the targeting cue than they were when the targeting cue was the tactile cue or the auditory/tactile cues combined. This was the finding both for the targeting task alone and for the dual-task condition. The only significant difference found between a baseline condition and its related dual-task condition was for the tactile cue alone. Participants were significantly slower when the shadowing task was added to the targeting task.

Direction of Initial Movement

The direction that participants initially moved following the onset of the targeting cue was recorded and scored as follows: 0 = wrong direction, 1 = correct direction. A mean was calculated for each experimental condition with 1.00 being a perfect score. The lower the score, the more often the participants moved in the wrong direction during that experimental condition. The mean direction of initial movements for each targeting condition and their standard deviations are shown in Figure 10 and given in Table 17 (see Appendix B).

The test of within-subjects effects found no significant difference between the six experimental conditions, Wilks' $\Lambda = .384$, $F(5, 25) = 8.340$, $p = .000$, multivariate $\eta^2 = .616$.



*, The mean difference is significant at α = .05.
**, The mean difference is significant at α = .01.
***, The mean difference is significant at α = .001.

Figure 10: Mean Accuracy and Standard Deviations of Direction of Initial Movement, and Results of Pairwise Comparisons for Initial Direction of Movement for Experiment 2.

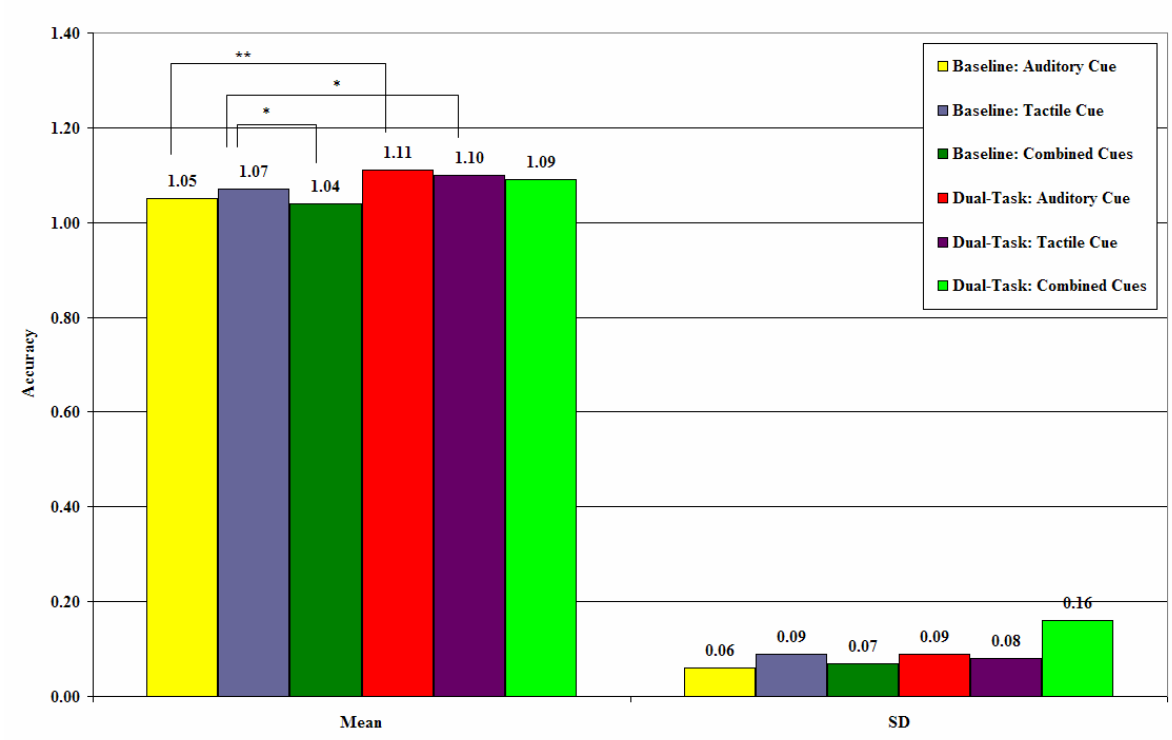
Nine specific pairwise comparisons were made using Fisher's Least Significant Difference (LSD) technique. The results are shown in Figure 10 and given in Table 18 (see Appendix B).

According to the post hoc analysis, when only the targeting task was being performed, the direction of the participants' initial movement was, on average, in the actual direction of the target when using the tactile cue alone or the combined auditory/tactile cues, but not when using the auditory alone. Likewise, when the shadowing task was added in the dual-task condition, the participants' initially moved in the wrong direction significantly more often when using the auditory cue than when they used either the tactile cue or the auditory and tactile cues combined. Participants also moved in the wrong direction initially more often when the shadowing task was added to the targeting task no matter which targeting cue was used to locate the target.

Accuracy

The accuracy of the participants in each experimental condition was recorded and scored as the number of clicks on the left mouse button required to end a trial. A score of 1.00 equals one click (shot) and was considered perfect. The higher the number, the more shots required, and the lower the accuracy. The mean accuracy for each condition and their standard deviations are shown in Figure 11 and given in Table 19 (see Appendix B).

The test of within-subjects effects failed to find a significant difference between the six experimental conditions, Wilks' $\Lambda = .551$, $F(5, 25) = 4.236$, $p = .006$, multivariate $\eta^2 = .449$.



*, The mean difference is significant at $\alpha = .05$.
***, The mean difference is significant at $\alpha = .001$.

Figure 11: Accuracy Means and Standard Deviations, and Results of Pairwise Comparisons for Accuracy for Experiment 2.

Nine specific pairwise comparisons were made using Fisher's Least Significant Difference (LSD) technique. The results are shown in Figure 11 and given in Table 20 (see Appendix B).

According to the post hoc analysis, there was no difference in accuracy between the tactile and auditory cues in the baseline condition or in the dual-task condition. There was also no difference in accuracy when the subjects used the auditory cue alone or the auditory and tactile cues combined in either the baseline of dual-task conditions. However, participants were significantly more accurate when using the combined cues than when using the tactile cue alone in the baseline condition, but this difference did not carry over to the dual-task condition.

Finally, a significant difference in accuracy was found between baseline and dual-task conditions while using the auditory targeting cue alone and when using the tactile cue alone, but not for the combined cues. The results showed that participants were, on average, more accurate when they were performing the targeting task alone than they were when the shadowing task was added in the dual-task condition.

Shadowing Analysis

Scoring

The shadowing task was scored in the same manner as it was scored in Experiment 1.

Analysis

A repeated measures procedure was used to compare the shadowing performance, in terms of accuracy (the ratio of works correctly repeated to the total number of words), for the shadowing baseline and the three dual-task conditions. The mean shadowing score and the standard deviation for each of the three dual-task conditions (Auditory cue only, Tactile cue only, and Tactile/Auditory cues combined) and the baseline shadowing condition are shown in Figure 12 and given in Table 21 (see Appendix B).

The test of within-subjects effects failed to find a significant difference between the four shadowing conditions, Wilks' $\Lambda = .781$, $F(3, 27) = 2.708$, $p = .063$, multivariate $\eta^2 = .219$.

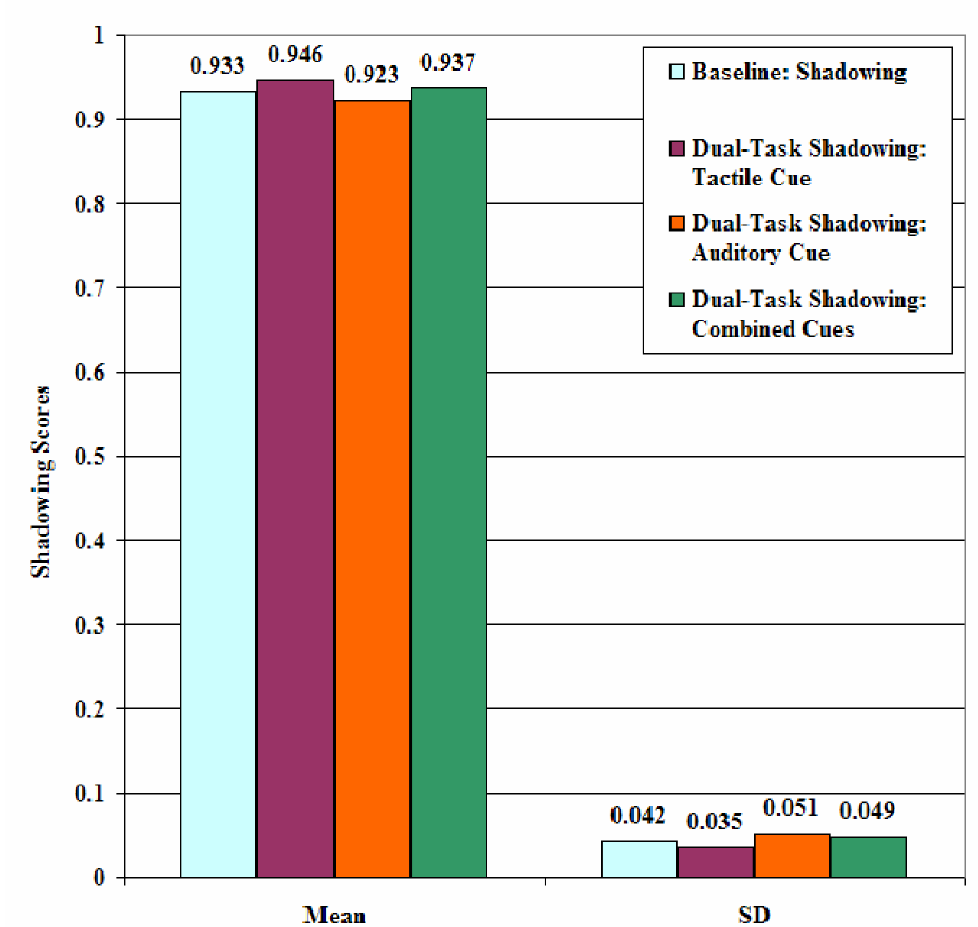


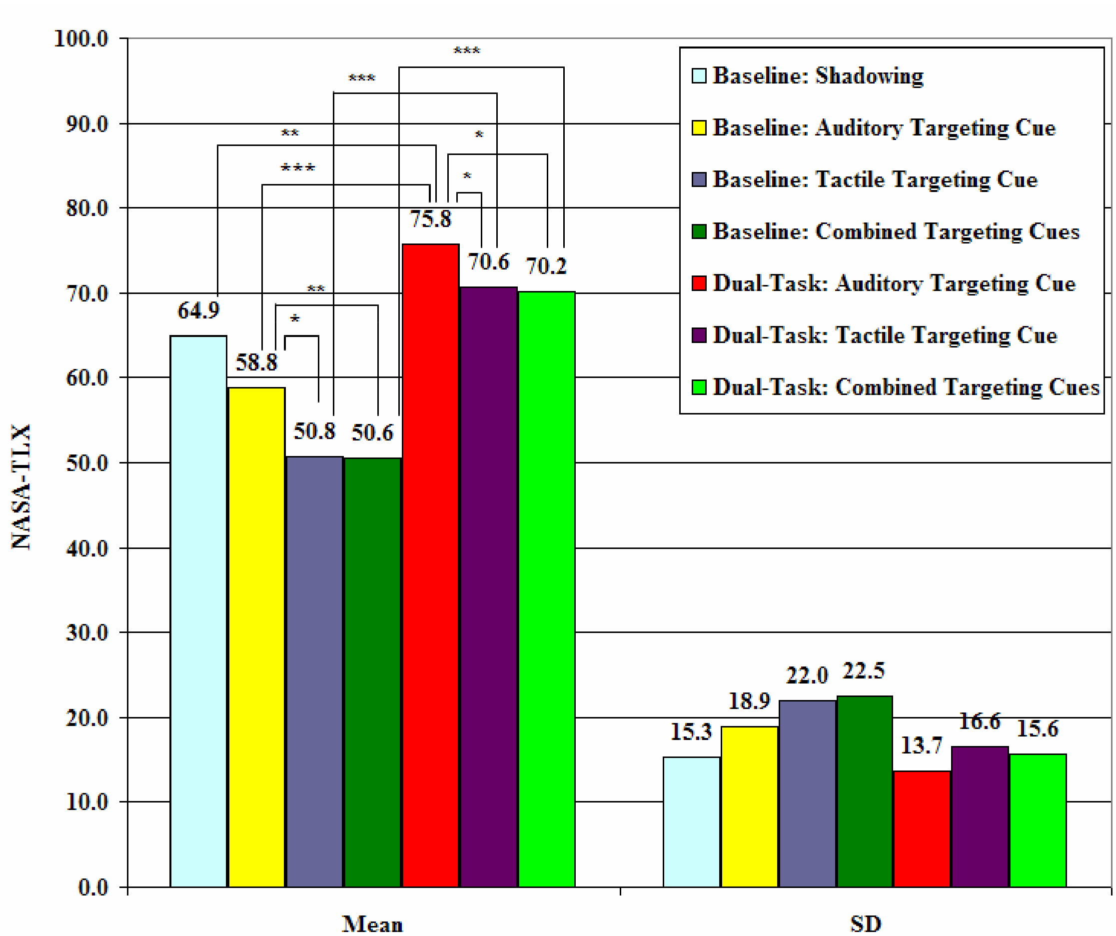
Figure 12: Means and Standard Deviations for Shadowing Conditions for Experiment 2.

NASA-TLX Analysis

A repeated measures procedure was used to compare the scores of the NASA-TLX workload measure for all baseline and dual-task conditions. The means and standard deviations for the seven NASA-TLX administrations are shown in Figure 13 and given in Table 22 (see Appendix B).

The analysis found a significant difference in the participants' subjective interpretation of the workload of the different conditions in the experiment, Wilks' $\Lambda = .345$, $F(6, 24) = 8.241$, $p = .000$, multivariate $\eta^2 = .655$.

The mean NASA-TLX scores for each condition were compared using Fisher's Least Significant Difference (LSD) technique. The results of these comparisons are shown in Figure 13 and given in Table 23 (see Appendix B).



*, The mean difference is significant at α = .05.
**, The mean difference is significant at α = .01.
***, The mean difference is significant at α = .001.

Figure 13: NASA-TLX Means and Standard Deviations, and Results of Pairwise Comparisons for the NASA-TLX for Experiment 2.

According to the results of the post hoc analysis, when performing only the targeting task, the participants perceived the task to be more difficult when using the auditory cue than when using either the tactile cue or the two cues combined. The results were the same when the shadowing task was added in the dual-task condition.

When comparing baseline conditions with dual-task conditions, the participants believed that the workload increased significantly with the addition of the shadowing task no matter which targeting cue they were using. However, they only perceived a significant increase in the workload associated with the shadowing task when the targeting task was added when the participants were using the auditory cue.

Discussion

The results of experiment 2 support the hypothesis that the additional complexity of the targeting task would result in poorer performance when using the auditory cues than when using the tactile cues. This fits with the position that the characteristics of the sensory modalities in use must be taken into account when trying to predict the allocation of resources in multiple task situations. While these results could have been predicted using MRT (Wickens & Holland, 2002), when the results of experiment 1 are also considered, MRT cannot explain why there is a difference in the outcomes of the two studies. On the other hand, the results of both studies can be simply explained by considering the characteristics of the sense of audition and the sense of touch. Simply put, in this study, requiring the participants to decide which direction the targeting cue came from before deciding in which direction the target in was harder when using the auditory targeting cue because of the problem humans have with front-back reversal. When a sound originates from directly in front of us or from directly behind us, the interaural cues are to both ears are the same. In such a situation, it is common for humans to misidentify the location of the sound source (Bear et al., 2001; Schiffman, 2001). There is no front-back reversal with the sense of touch.

The fact that the participants were slower to respond to the auditory cue than the tactile cue in all conditions, and the fact that they took longer to find the target when using the auditory cue can be explained as a result of front-back reversal. The participants were unable to easily locate the direction the cue came from and so took longer to make decisions. However, when using the tactile cue, the participants could easily determine where the targeting cue was coming from so the only decision they had to make was the direction of the target. This is further supported by the fact that participants' initial move was in the wrong direction more often when using the auditory cue than when they used the tactile cue, or the two cues combined. It is also supported by the findings of the NASA-TLX, which shows that participants found that using the auditory cue in the targeting task made the task more challenging than when either of the other cues.

Further support comes from the comparisons the baseline and dual-task conditions for each cue. In these comparisons, although the addition of the shadowing task resulted in slower response times for both the auditory and tactile cues, the difference was greater for the auditory cue than for the tactile cue. This can be attributed to an additional slowing for the decision making process when using the auditory targeting cue due to Front-Back Reversal.

The same pattern, however, was not seen in the initial response to the onset of the targeting cues. For the initial response times, no difference was found when the participants used the auditory cue, but they were significantly faster to respond to the tactile cue in the baseline condition than they were when the shadowing task was added. This could be due to characteristics of the auditory system. Research has shown that auditory cues have been shown to be effective as emergency warning signals alerting individuals to important information (Proctor & Van Zandt, 1994b). Here, the auditory cue was equally effective in alerting the participants to the onset of the cue in both conditions. This explanation is further supported by the fact that no difference was found when between the baseline and dual-task conditions when using the combined targeting cues.

In the analysis comparing the auditory and tactile cues alone to the combined cues, the participants were significantly slower to respond to the onset of the targeting cues and slower to find the target when they were using the auditory cue than they were when using either the tactile cue alone or the two cues combined. The participants were also more likely to move in the wrong direction in the dual-task when using the auditory cues only. However, no difference was found between the tactile cue alone and the combined targeting cues. Since the tactile cue is resistant to front-back reversal, the participants could easily determine from which direction the cue originated. When using the combined cues, the tactile cue thus prevented or cancelled out the front back reversal associated with the auditory cue.

In terms of the measure of accuracy, in the baseline condition, using the tactile cue led to significantly poorer accuracy than when using the combined cues. The same pattern was seen for the comparison of the auditory and combined cues, but this difference was not significant. The best explanation for this is that when the cues were combined it created an additive effect. In this case, one cue acts to alert the participants to the other cue and confirm the information provided. This is supported by the finding of a significant difference between the baselines and dual-tasks for all cues except the combined auditory and targeting cues.

Performance on the shadowing task was not affected by the addition of the targeting task. Once again, this result can be explained by the fact that there was no potential source of competition for resources at any stage except at the level of sensory input. In addition, the tasks involved are familiar and although the front back decision is more complicated, it does not affect the execution of the shadowing task, only the targeting task. Therefore, the familiarity of the shadowing task resulted in no significant difference being found in the different shadowing conditions just as it did in experiment 1. However, the participants determined that the shadowing task required more work when paired with the targeting task, but only when using the auditory cue. Participants considered the shadowing task to be less challenging when paired with the tactile cue or the auditory and tactile cues combined. This is most likely due to the additional workload brought on by the front-back reversal associated with the auditory system.

In summary, the results of experiment 2 can be explained with either the simple MRT explanation or by the characteristics of the sensory modalities being used. MRT would explain the decrement in performance when using the auditory cue as being a result of competition for resources. However, if this is the case, then the performance on the shadowing task should also have been affected. The fact that performance on the shadowing task was not affected by the addition of the dual-task suggests, along with the targeting results, suggest that the characteristics of the sensory modality were responsible for the results. In this case, performance on the shadowing task was not affected because the task requirements had not changed, and it is a simple auditory task which humans are familiar with and have had lot of practice doing. Thus, the results support that argument that the characteristics of the sensory systems being used affect the allocation of information processing resources and should be taken into account before predictions of multiple task performance are made in design.

This experiment did, however, identify a potential problem with the methodology in experiment 1 that could account for the results. This experiment differed in two ways from experiment 1. The first was the alteration in the location of the source of the targeting cues. The second was the method by which the targeting cues were delivered. In this study, the auditory cue was delivered using speakers whereas in the first experiment the cues were delivered using headphones. This difference in presentation methods could have resulted in the lack of difference in performance between the auditory and tactile cues in experiment 1. To eliminate this as a source of confusion, a third experiment was conducted using speakers to deliver the auditory cue.

CHAPTER 4: EXPERIMENT 3

Introduction

In experiment 1, headphones were used to deliver the auditory cue as well as the sentences for the shadowing task. One reason that no differences were found between the auditory and tactile cue could have been due to the headphones eliminating one structural difference between the two senses. Because touch relates to stimulation at the body surface rather than from external space it is considered to be a proximal sense, whereas the stimulation for audition originates away from the body which causes it to be classified as a distal sense (Eimer et al., 2002). By using headphones, we make audition a proximal sense as well.

In experiment 2, however, speakers were used to deliver all auditory cues. This put audition back in its natural setting by making it a distal sense again. To eliminate the possibility that this difference in the two experiments could account for the differences in performance with auditory and tactile cue, experiment 1 was repeated using speakers placed to the left and to the right of the participant to deliver the auditory cue.

Hypotheses

It was predicted that there would no difference between the pattern of results of experiments 1 and 3, indicating that the differences found between experiments 1 and 2 was not due to the differences in methodology, but instead was due to the nature of the sensory systems involved. The specific hypotheses for experiment 3 are shown in Table 24.

Table 24: *Hypotheses for Experiment 3*

Hypothesis 1: Targeting Hypothesis	Despite the use to speakers, when using the auditory cue, performance will be no worse on the targeting task in either the baseline or dual-task condition than when using the tactile cue.
Hypothesis 2: Combination of Cues Hypothesis	Despite the use of speakers, the combination of the auditory and tactile targeting cues will result in better performance on the targeting task than either the auditory or tactile cues alone.
Hypothesis 3: Shadowing Hypothesis	Despite the use of speakers, the addition of the targeting task will have no effect on performance on the shadowing task regardless of the modality of the targeting cue or the combination of cues.
Hypothesis 4: NASA-TLX Hypothesis	Despite the use of speakers, no difference will be found between the subjective workload ratings for the different modalities (auditory or tactile) of the targeting cue on the targeting task.

Methods

Participants

Thirty students from the University of Central Florida acted as participants in this study. The participants ranged in age from 18 to 27 years of age, with the median age being 21. Participants received either extra credit in psychology classes or were paid twelve dollars for participating in this experiment. All participants reported normal hearing and none reported having nerve damage that would interfere with detecting the tactile cue.

Layout

The lab layout was the same as for Experiment 2 (see Figure 1) with one exception. In this study, the speakers were placed to the sides of the participant at a height of approximately 57 inches above the floor, and were located approximately 47 inches from the center of the room.

Equipment

All the equipment in this experiment was the same at in Experiment 2.

Stimulus Materials

All the stimuli used in this experiment were the same as that used in Experiments 1 and 2.

Measures

The same measure of subjective workload (NASA-TLX) was used in this study as was used in experiment 1 & 2.

Design

The design was the same as that used in Experiment 1 except that all of the cues, tactile and auditory.

Procedure

The procedure for experiment 3 was the same as for experiment 1.

Results

The alpha level was set to .05 to distinguish significant effects.

Targeting Data Analysis

The data was analyzed using SPSS 11.0. A repeated measures procedure was used to compare the six experimental conditions (Baseline: Auditory Targeting Cue Only, Baseline: Tactile Targeting Cue Only, Baseline: Tactile/Auditory Targeting Cues Combined, Dual Task: Auditory Cue Only, Dual-Task: Tactile Targeting Cue Only, Dual-Task: Tactile/Auditory Targeting Cues Combined) for response time, initial response time, initial movement, and accuracy.

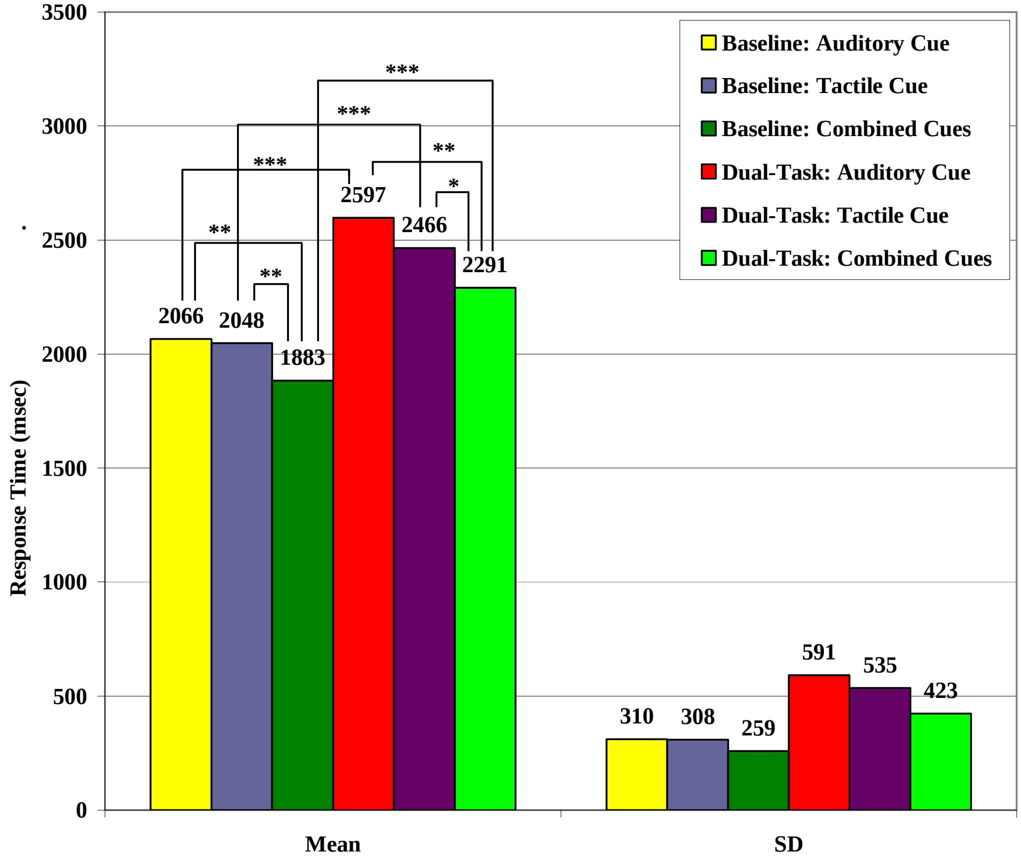
Response Time

The mean response time (RT) and standard deviation for each condition is shown in Figure 14 and given in Table 25 located in Appendix C.

The test of within-subjects effects found a significant difference between the six experimental conditions, Wilks' $\Lambda = .227$, $F(5, 25) = 13.659$, $p = .000$, multivariate $\eta^2 = .773$.

Nine specific post hoc comparisons were made using Fisher's Least Significant Difference (LSD) technique. The results are shown in Figure 14 and given in Table 26 (see Appendix C).

According to these results, on average, the participants were slower in the Baseline conditions when using only the auditory targeting cue than they were when they used only the tactile targeting cue, however, this difference was not significant. However, in the baseline conditions, the mean response time for the auditory targeting cue and the tactile targeting cue were significantly slower than the mean response time for the auditory/tactile cues combined. This indicates that the combination of targeting cues resulted in improved performance over either set of targeting cues alone.



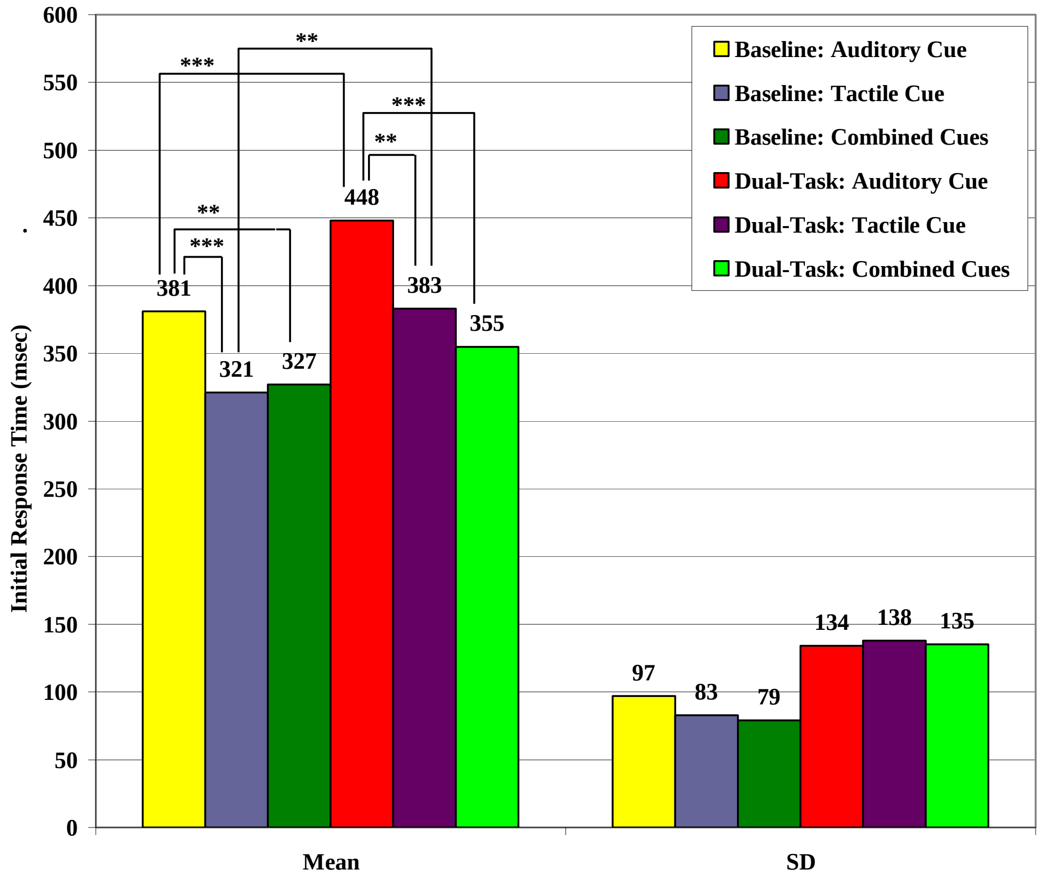
*, The mean difference is significant at α = .05.
**, The mean difference is significant at α = .01.
***, The mean difference is significant at α = .001.

Figure 14: Mean Response Times and Standard Deviation, and Results of Pairwise Comparisons Response Times for Experiment 3.

In the dual-task conditions, although the participants were, on average, slower when they used the auditory cue than when they were using the only the tactile cue, this difference was not significant. In addition, when the participants were using the combined auditory/tactile cues in the dual-task condition, they were significantly faster, on average, than they were when using either the auditory cue alone or the tactile cue alone. This indicates that when the cues were combined the participants were significantly faster than they were when using either cue alone.

Finally, the mean response times for the all of the targeting cues were significantly slower in the dual-task condition than they were in the baseline conditions. This indicates that the addition of the shadowing task significantly slowed the response times of the participants for all of the targeting cues.

<u>Initial Response Time</u>



***, The mean difference is significant at $\alpha = .01$.

Figure 15: Mean Initial Response Times and Standard Deviations Results of Pairwise Comparisons for Initial Response Times for Experiment 3.

Initial Response time is the time in milliseconds between the onset of the targeting cue and the participant's first movement. The mean initial response times and standard deviations are shown in Figure 15 and given in Table 27 (see Appendix C).

The test of within-subjects effects found a significant difference between the six experimental conditions, Wilks' $\Lambda = .197$, $F(5, 25) = 17.139$, $p = .000$, multivariate $\eta^2 = .803$.

Nine specific pairwise comparisons were made using Fisher's Least Significant Difference (LSD) technique. The results are shown in Figure 15 and given in Table 28 (see Appendix C).

According to these results, when using the auditory targeting cue, the participants were, on average, significantly slower to respond to the onset of the targeting cue than they were when using either the tactile cue or the auditory and tactile cues combined. This finding was true for both the baseline and dual-task conditions. No significant difference was found in the participants' initial response time between the tactile cue and the auditory/tactile cues combined in either the baseline or dual-task condition.

The analysis also show that the initial response times were, on average, significantly slower in the dual-task condition when they were also doing both the targeting and shadowing tasks, than when they were only doing the targeting task in the baseline condition for both the auditory and tactile cues. This finding, however, did not hold for the two sets of cues when they were combined.

Direction of Initial Movement

The direction that participants initially moved following the onset of the targeting cue was recorded and scored as follows: 0 = wrong direction, 1 = correct direction. A mean was calculated for each experimental condition with 1.00 being a perfect score.

The lower the score, the more often the participants moved in the wrong direction during that experimental condition.   The mean direction of initial movements for each targeting condition and their standard deviations are shown in Figure 16 and given in Table 29 (see Appendix C).

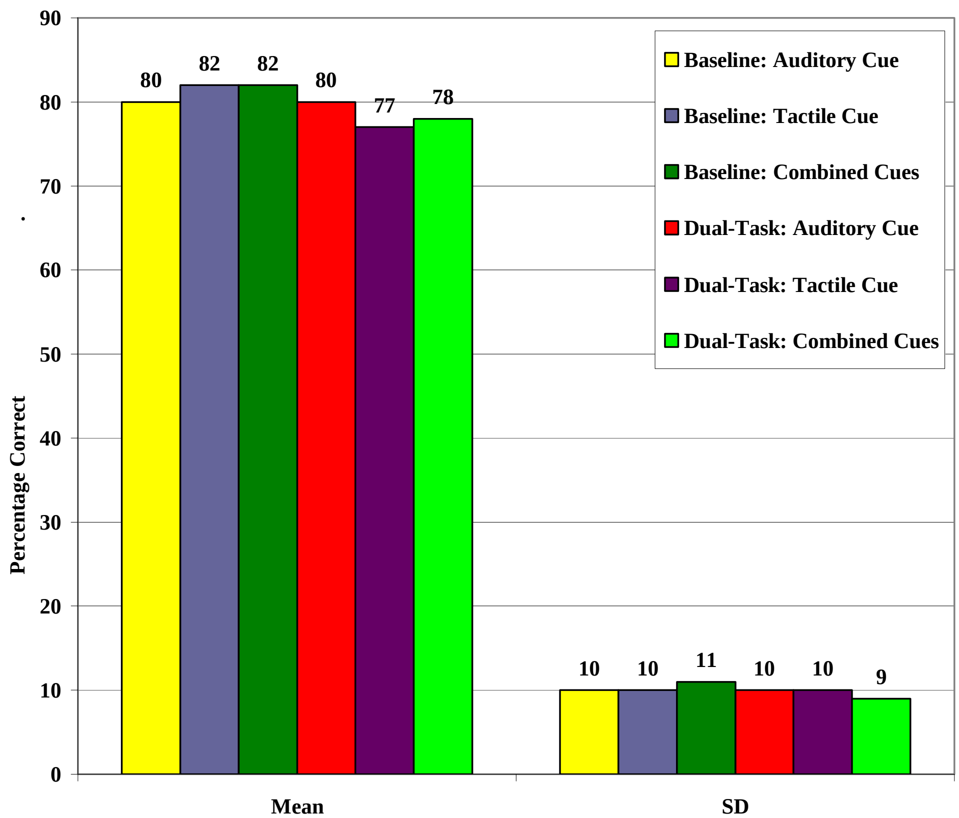


Figure 16: Mean Accuracy & Standard Deviations of Direction of Initial Movement for Experiment 3.

The test of within-subjects effects found no significant difference between the six experimental conditions, Wilks' $\Lambda = .745$, $F(5, 25) = 1.441$, $p = .251$, multivariate $\eta^2 = .255$.

Accuracy

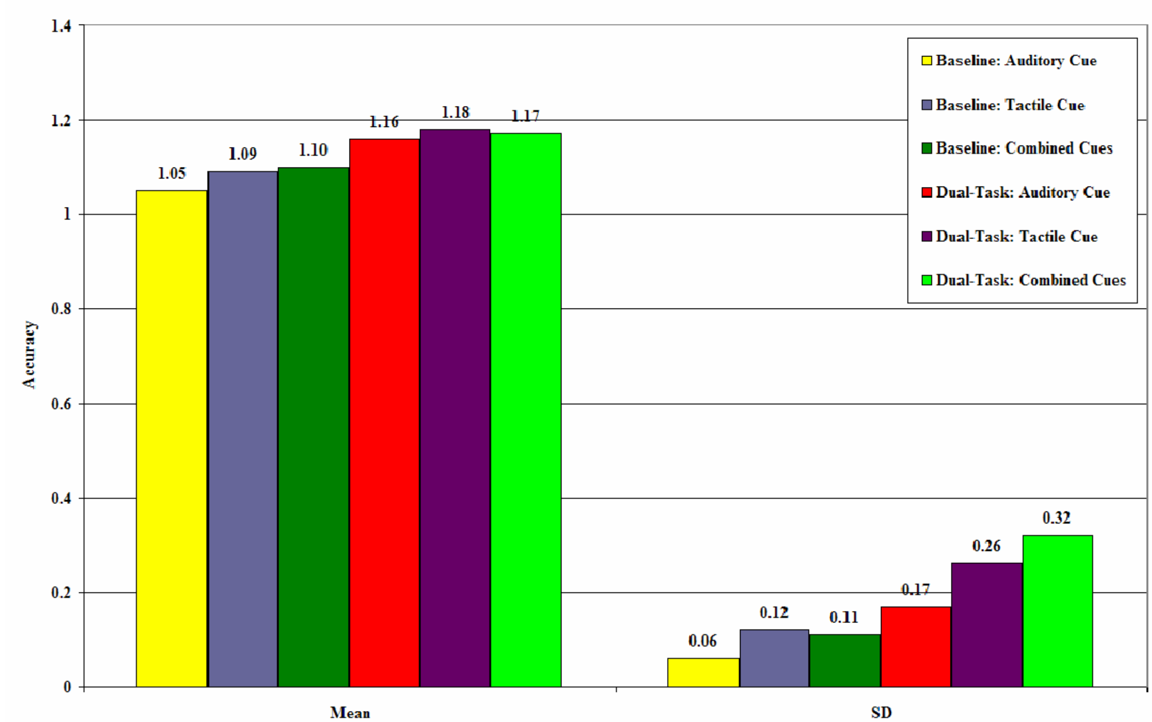


Figure 17: Accuracy Means and Standard Deviations for Experiment 3.

The accuracy of the participants in each experimental condition was recorded and scored as the number of clicks on the left mouse button required to end a trial. A score of 1.00 equals one click (shot) and was considered perfect. The higher the number, the more shots required, and the lower the accuracy. The mean accuracy for each condition and their standard deviations are shown in Figure 17 and given in Table 30 (see Appendix C).

The test of within-subjects effects failed to find a significant difference between the six experimental conditions, Wilks' $\Lambda = .633$, $F(5, 25) = 2.432$, $p = .069$, multivariate $\eta^2 = .367$.

Shadowing Analysis

Scoring

The shadowing task was scored in the same manner as it was scored in Experiments 1 and 2.

Analysis

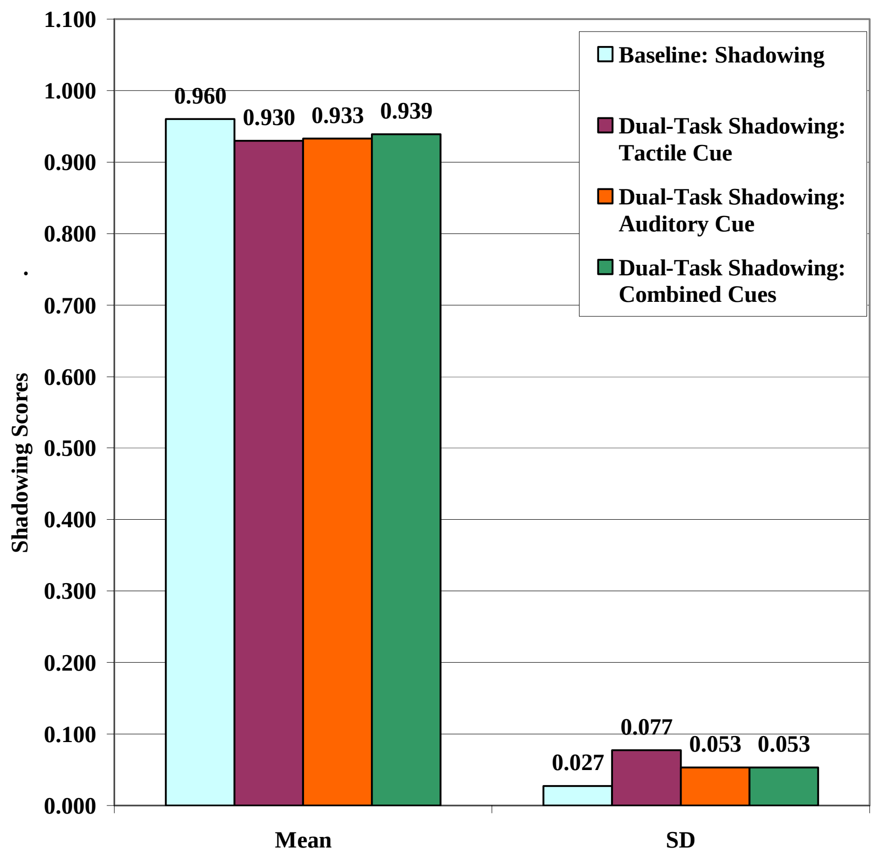


Figure 18: Means and Standard Deviations for Shadowing Conditions in Experiment 3.

A repeated measures procedure was used to compare shadowing performance in terms of accuracy (the ratio of works correctly repeated to the total number of words) for the shadowing baseline and the three dual-task conditions. The mean shadowing score and the standard deviation for each of the three dual-task conditions (Auditory cue only, Tactile cue only and Tactile/Auditory cues combined) and the baseline shadowing condition are shown in Figure 18 and given in Table 31 (see Appendix C).

The test of within-subjects effects failed to find a significant difference between the four shadowing conditions, Wilks' $\Lambda = .796$, $F(3, 27) = 1.885$, $p = .162$, multivariate $\eta^2 = .204$.

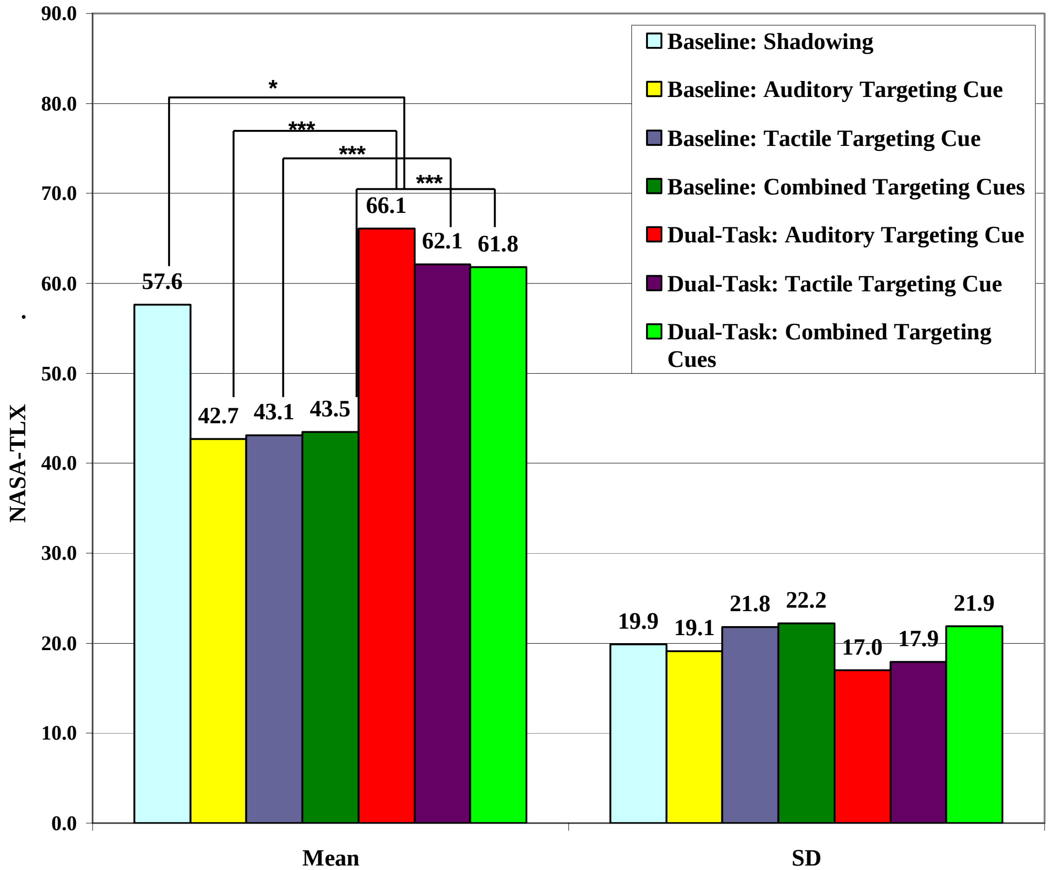
NASA-TLX Analysis

A repeated measures procedure was used to compare the scores of the NASA-TLX workload measure for all baseline and dual-task conditions. The means and standard deviations for the seven NASA-TLX administrations are shown in Figure 19 and are given in Table 32 (see Appendix C).

The analysis found a significant difference in the participants' subjective interpretation of the workload of the different conditions in the experiment, Wilks' $\Lambda = .216$, $F(6, 24) = 12.124$, $p = .000$, multivariate $\eta^2 = .784$.

The mean NASA-TLX scores for each condition were compared using Fisher's Least Significant Difference (LSD) technique. The results of these comparisons are shown in Figure 19 and given in Table 33 (see Appendix C).

According to the results of the post hoc analysis, there was no difference in the mean perceived workload associated with the different targeting cues in the baseline portion of the experiment, nor was there a difference in the mean perceived workload associated with the different targeting cues in the dual-task portion of the experiment.



*, The mean difference is significant at α = .05.
***, The mean difference is significant at α = .001.

Figure 19: Means and Standard Deviation, and Results of Pairwise Comparisons for the NASA-TLX for Experiment 3.

A significant difference was found when the mean perceived workload associated for each targeting cue in the baseline was compared with the mean perceived workload for the same cue in the dual-task portion. On average, participants perceived the targeting task to be more difficult when the shadowing task was added for all targeting cue conditions. Finally, on average, the participants only perceived there to be a significant increase in the difficulty of the shadowing task when combined with the targeting task using the auditory cue.

Discussion

Overall, the results of experiment 3 support the hypothesis that there would be no difference between the auditory and tactile targeting cues. Since the pattern of results is basically the same as those for experiment 1, the results of experiment 3 suggest that the use of headphones in experiment 1 had little effect. Overall, no difference was found between the auditory and tactile targeting cues. Participants took approximately the same amount of time to locate the target, made their initial move in the direction of the target, and were just as accurate when using the auditory cue as they were when using the tactile cue. They also reported that the two tasks required the same amount of work. The only measure on which the two cues differed was the initial response time. When using the auditory cue, the participants were significantly slower to respond to the targeting cue in both the baseline and dual-task conditions than they were when using the tactile cue. That this result could be due to resource allocation is not a good explanation for two reasons. First, there should be no competition in the baseline condition. Second, if resource competition is responsible for the difference then it should have also shown up in the analysis of the response time.

Another explanation is that the difference is the result of characteristic differences between audition and touch. Because touch is considered to be a proximal sense, whereas audition is considered to be a distal sense (Eimer et al., 2002), the tactile cue originates at the sensory receptor while the auditory cue must travel to the receptor. In addition, even though left-right localization is the easiest auditory localization task, it still takes time to locate the cue. These two factors combined could account for the difference in initial response time. Thus, the difference in the initial response time is more than likely due to the natural state of the senses being used. It is also possible that the tactile sense just has a faster response time than audition.

The comparisons of the two targeting cues alone to the set of combined cues suggest that the use of speakers in experiment 3 did have some affect on the results. Participants were slower to respond to the cue and to locate the target when using the auditory cue than when use the combined cues in both the baseline and dual-task conditions. This result is easily explained by an additive effect of the combination of tactile and auditory cues. When combined the cues act to reinforce and confirm the information provided by each other which results in faster times. In other words, the one targeting cue acts to draw attention to the location of the target and the second cue confirms the location resulting in faster reaction time just as precuing the location of a target does in studies of spatial cuing (Hawkins et al., 1990).

The comparison of the baseline conditions with the dual-task conditions is also consistent with the idea that sensory modality affects the allocation of resources. Participants were consistently slower to locate the target and to respond to the cue in the dual-task condition no matter whether the cue being used was auditory or tactile. This makes sense, because the dual-task involves two tasks both of which require the participants' attention. An MRT explanation explains the difference for the auditory cue as being due to competition for auditory resources by two auditory tasks. This explanation does not explain the difference for the tactile cue. Only the additional workload of a second task can explain both results. It also explains why it took participants longer to locate the target in the dual-task condition when using the combination of cues. Once again it is simply the addition of another task that slowed the participants' response time. This is further supported by the results of the NASA-TLX which showed that the participants' felt that the dual-task condition was more taxing than the baseline condition for all of the targeting cues.

The participants' performance on the shadowing task was not affected by the addition of the targeting task, but participants did feel that the shadowing task was made more difficult when the targeting task was added, but this difference was only significant when the auditory cue was used. This suggests that although no differences were found in performance, the participants felt the shadowing task was harder when combined with the targeting task.

In summary, the results of the third experiment provide further support for the idea that the sensory modality and its characteristics influence the allocation of resources. Since the targeting task is a spatial task and the shadowing task is a verbal task, they did not share central processing resources and since the response modes were different, they did not share response resources. This leaves the sensory modalities as the only other stage where resources could be in conflict. However, even when the tasks use the same sensory system, there may be no conflict when the characteristics of the sensory modality lend themselves to the task, as they do when the auditory cue is used. Since auditory localization and verbal communication are tasks we are practiced at, there is little conflict between them when the tasks are easier. For this reason, there is little if any difference in performance when the two tasks are performed using two different sensory modes.

CHAPTER 5: CROSS-EXPERIMENTAL ANALYSIS

Introduction

Although the results of experiment 3 suggest that using speakers or headphones to deliver the auditory cue had no significant affects on the results, it is still necessary to compare the two experiments to determine if there is a difference between the results when using headphones to deliver the auditory cue versus using speakers to deliver the cue. It is hypothesized that although using the headphones alters the characteristics of the auditory cue, the alteration is not enough to cause the results of the two experiments to be significantly different.

Speaker vs. Headphone Hypothesis:

Whether the auditory cue is delivered by headphones or speakers will have no effect on the performance of the targeting task.

Also, since it was hypothesized that characteristics of the sensory systems being used would affect the participants' performance it is necessary to compare the results of the three experiments to see if the apparent differences in performance across the three experiments are statistically significant.

The hypotheses for the overall study are given in Table 1 in Chapter 1.

Results of the Cross-Experimental Analysis

A MANOVA was conducted to compare the participants' performance on all measures across the three experiments. The alpha level was set to .05 to distinguish significant effects.

Targeting Analysis

The means and standard deviation for each targeting measure (Response Time, Initial Response Time, Initial Direction of Movement, and Accuracy) for each targeting cue are listed under the results sections for each experiment.

The results of the between subjects analysis of the three experiments are presented in Table 34 in order of measure.

In terms of response time, only the response time for the auditory cue was significantly different across the three experiments. This was true for both the auditory cue in the baseline condition and in the dual-task condition.

For the initial response time, which is the time it took participants to make their first move following the onset of the targeting cue, a significant difference was found between the three experiments for every cue in every condition with the exception of the tactile cue in the dual-task condition.

The results also showed that the participants in the three experiments significantly differed in the number of times their initial movement was in the wrong direction in the dual-task condition for all three targeting cues, and for the auditory cue in the baseline condition, but not for the tactile cue or the auditory and tactile cues combined in the baseline condition.

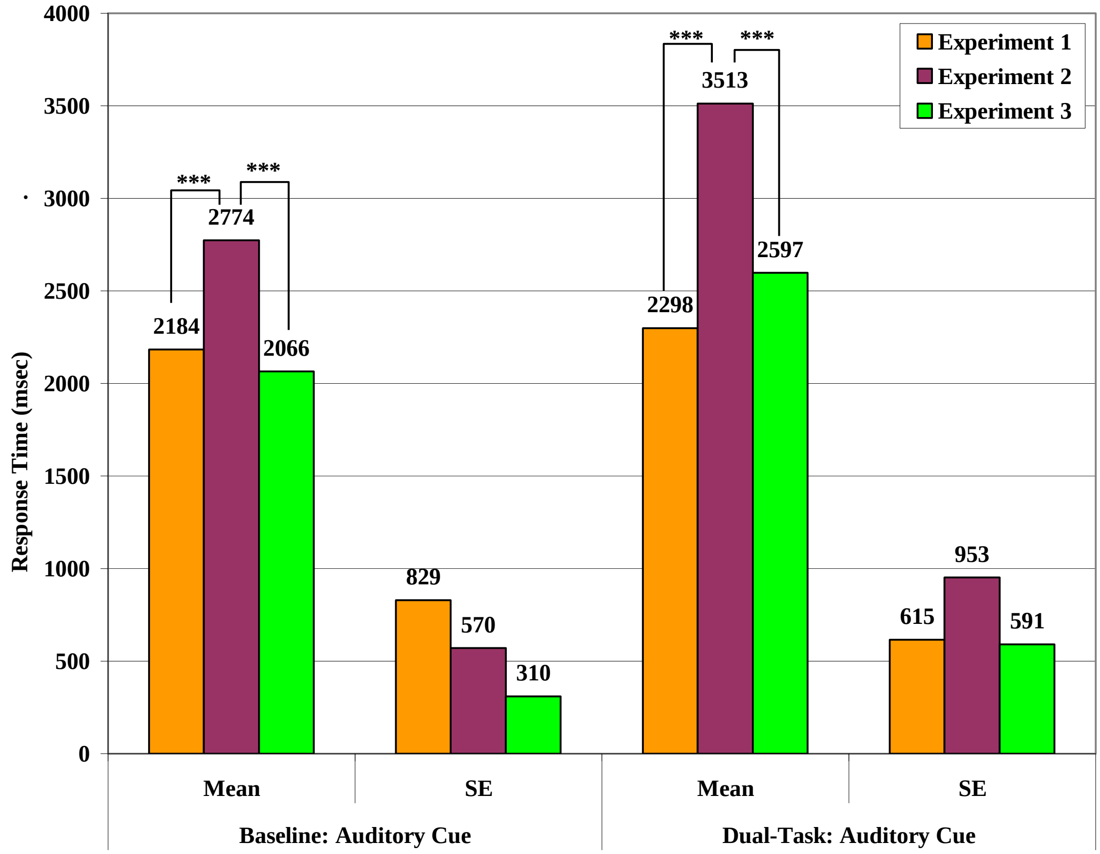
Table 34: *Results of Multivariate Analysis of Targeting Measures for all Three Experiments*

	F	df1	df2	Sig.	Partial η^2
Measure: Response Time					
Baseline: Auditory Cue Only	10.929	2	87	.000***	.208
Baseline: Tactile Cue Only	.985	2	87	.378	.023
Baseline: Auditory/Tactile Cues Combined	2.009	2	87	.141	.046
Dual-Task: Auditory Cue Only	21.654	2	87	.000***	.343
Dual-Task: Tactile Cue Only	.976	2	87	.381	.023
Dual-Task: Auditory/Tactile Cues Combined	1.663	2	87	.196	.039
Measure: Initial Response Time					
Baseline: Auditory Cue Only	21.007	2	87	.000***	.336
Baseline: Tactile Cue Only	4.473	2	87	.014*	.097
Baseline: Auditory/Tactile Cues Combined	5.388	2	87	.006**	.115
Dual-Task: Auditory Cue Only	8.693	2	87	.000***	.173
Dual-Task: Tactile Cue Only	1.879	2	87	.159	.043
Dual-Task: Auditory/Tactile Cues Combined	3.423	2	87	.037*	.076
Measure: Direction of Initial Movement					
Baseline: Auditory Cue Only	3.634	2	87	.031*	.079
Baseline: Tactile Cue Only	1.477	2	87	.234	.034
Baseline: Auditory/Tactile Cues Combined	1.002	2	87	.372	.023
Dual-Task: Auditory Cue Only	22.752	2	87	.000***	.349
Dual-Task: Tactile Cue Only	3.229	2	87	.044*	.071
Dual-Task: Auditory/Tactile Cues Combined	4.877	2	87	.010**	.103
Measure: Accuracy					
Baseline: Auditory Cue Only	1.184	2	87	.311	.027
Baseline: Tactile Cue Only	1.128	2	87	.329	.026
Baseline: Auditory/Tactile Cues Combined	1.213	2	87	.303	.028
Dual-Task: Auditory Cue Only	.697	2	87	.501	.016
Dual-Task: Tactile Cue Only	.776	2	87	.464	.018
Dual-Task: Auditory/Tactile Cues Combined	.685	2	87	.507	.016

*, The mean difference is significant at $\alpha = .05$.
**, The mean difference is significant at $\alpha = .01$.
***, The mean difference is significant at $\alpha = .001$.

Finally, no significant difference was found between the three experiments in terms of the participants' accuracy.

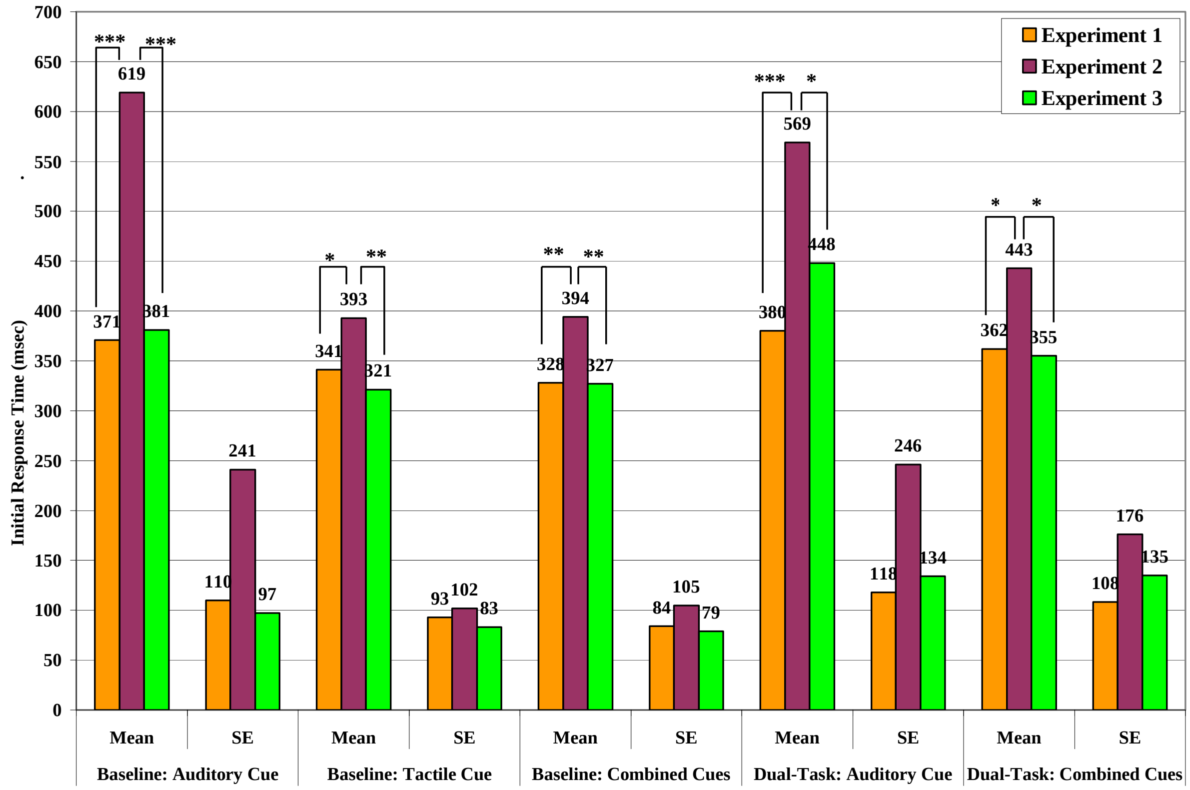
The three experiments were compared for those cues and measures found to be significantly different using Fisher's Least Significant Difference (LSD) technique. The results of the comparisons for response time are shown in Figure 20 and given in Table 35; the results of the comparisons for initial response time are shown in Figure 21 and given in Table 36; and the results of the comparisons for the direction of initial movement are shown in Figure 22 and given in Table 37. Tables 35, 36, and 37 are located in Appendix D.



***, The mean difference is significant at α = .001.

Figure 20: Results of Post Hoc Comparisons for the Response Time Analysis of the Auditory Cue across the Three Experiments.

The post hoc analysis showed that participants in experiment 2 were, on average, significantly slower than the participants in either experiment 1 or 3 for both the baseline and dual-task conditions. No significant difference was found between the response times of participants in experiments 1 and 3 for any of the conditions.

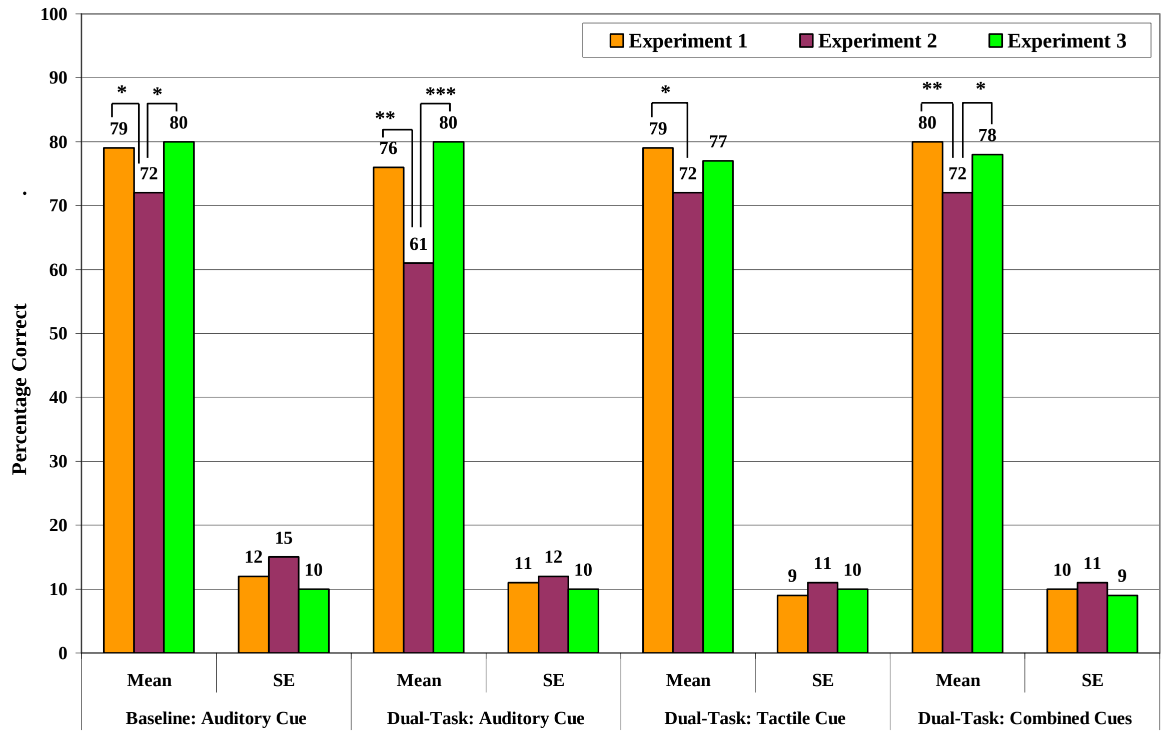


*, The mean difference is significant at $\alpha = .05$.
**, The mean difference is significant at $\alpha = .01$.
***, The mean difference is significant at $\alpha = .001$.

Figure 21: Results of Post Hoc Comparisons for the Initial Response Time Analysis across the Three Experiments.

The results of the analysis showed that for the auditory cue, participants in experiment 2 were, on average, slower to respond the cue's onset than the participants in the other two experiments in the baseline conditions no matter which targeting cue was used to locate the target. In the dual-task conditions, when the participants used the tactile targeting cues, no significant difference was found between the three experiments. However, when they used either the auditory cue or the combined cues, participants in experiment 2 were significantly slower than participants in either of the other two experiments.

No significant difference was found between the initial response times of participants in experiments 1 and 3 for any of the targeting cues in any of the conditions.



*, The mean difference is significant at $\alpha = .05$.
**, The mean difference is significant at $\alpha = .01$.
***, The mean difference is significant at $\alpha = .001$.

Figure 22: Results of Post Hoc Comparisons for the Mean Accuracy & Standard Deviations of the Direction of Initial Movement across the Three Experiments.

The results show that the participants in experiment 2, on average, moved in the wrong direction following the onset of the auditory cue significantly more often than participants in experiments 1 and 3 in both the baseline and dual-task conditions. The difference between experiment 1 and 3 was not significant.

In addition, the results also showed that participants in experiment 2 also moved in the wrong direction following the onset of the tactile cue and the onset of the auditory/tactile cues combined significantly more often than participants in experiment 1 in the dual-task condition. A similar difference was found between the participants in experiment 2 and experiment 3, but this difference was only significant for the combined cues. Also, the differences found between experiments 1 and 3 were not significant.

Shadowing Analysis

The mean shadowing score and the standard deviation for each of the three dual-task conditions (Auditory cue only, Tactile cue only and Tactile/Auditory cues combined) and the baseline shadowing condition are listed under the results sections for each experiment.

Table 38: *Results of Multivariate Analysis of Shadowing Task for all Three Experiments.*

	F	df1	df2	Sig.	Partial η^2
Baseline: Shadowing	2.573	2	87	.082	.058
Shadowing for Dual-Task with Tactile Cue	1.574	2	87	.213	.036
Shadowing for Dual-Task with Auditory Cue	2.614	2	87	.079	.059
Shadowing for Dual-Task with Auditory/Tactile Cues Combined	1.870	2	87	.161	.043

The results of the between subjects analysis revealed no significant difference in the participants performance on the shadowing task across the three experiments as shown in Table 38.

NASA-TLX Analysis

The mean NASA-TLX scores and the standard deviation for each of the dual-task conditions (Auditory cue only, Tactile cue only and Tactile/Auditory cues combined) and the baseline conditions (Shadowing, Auditory cue only, Tactile cue only and Tactile/Auditory cues combined) are listed under the results sections for each experiment.

A between subjects multivariate analysis was used to compare the scores of the NASA-TLX workload measure for all baseline and dual-task conditions. The results are given in Table 39.

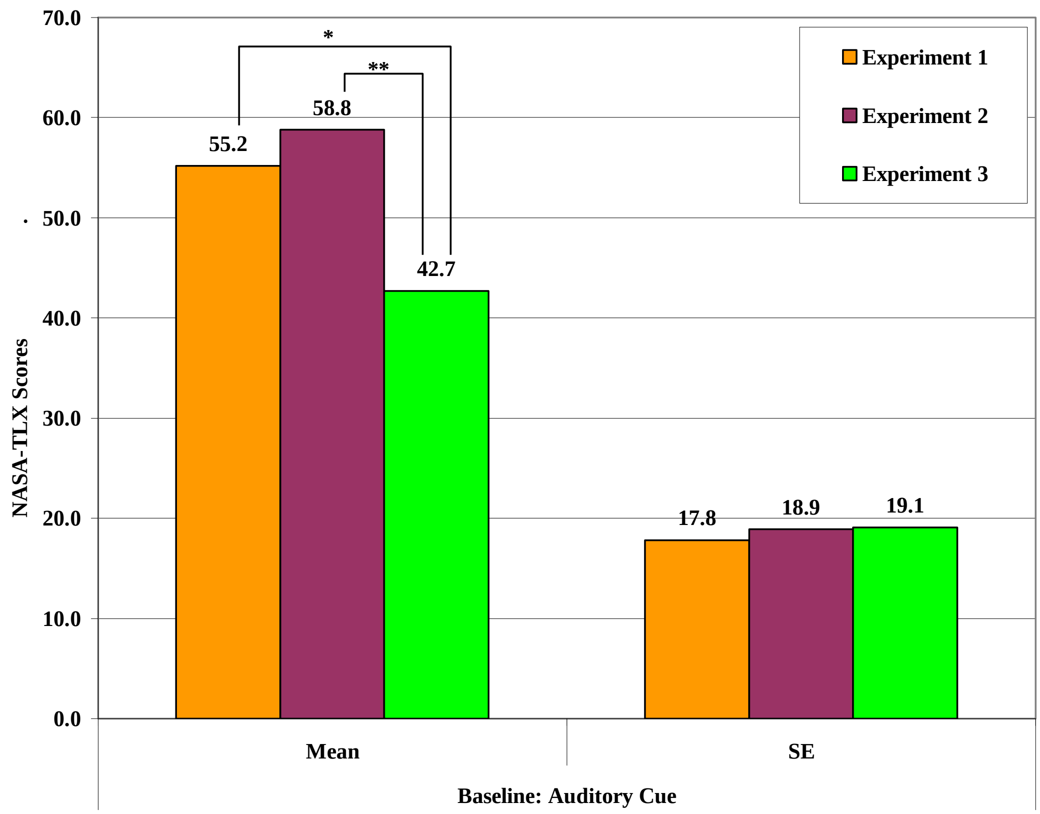
Table 39: *Results of Multivariate Analysis of NASA-TLX for all Three Experiments*

	F	df1	df2	Sig.	Partial η^2
Baseline: Shadowing	1.340	2	87	.267	.030
Baseline: Auditory Cue Only	5.772	2	87	.004**	.118
Baseline: Tactile Cue Only	2.335	2	87	.103	.052
Baseline: Auditory/Tactile Cues Combined	1.593	2	87	.209	.036
Dual-Task: Auditory Cue Only	3.051	2	87	.052	.066
Dual-Task: Tactile Cue Only	2.677	2	87	.075	.059
Dual-Task: Auditory/Tactile Cues Combined	2.253	2	87	.111	.050

**, The mean difference is significant at $\alpha = .01$.

Fisher's Least Significant Difference (LSD) technique was used to compare the NASA-TLX scores across the three experiments for the auditory cue in the baseline condition and the results are shown in Figure 23 and given in Table 40 (see Appendix D).

The results show that the participants in experiment 3 considered that the targeting task using only the auditory to have a significantly lower workload than the participants of either of the other two experiments. However, the participants in experiments 1 and 2 did not differ significantly their assessment of the task's workload.



**, The mean difference is significant at α = .01.

Figure 23: Results of Post Hoc Comparisons for the NASA-TLX Analysis of the Baseline Auditory Cue across the Three Experiments.

Discussion

It was hypothesized that no significant differences would be found between experiments 1 and 3 due to the use of headphones versus speakers. The results of the analysis support this hypothesis confirming that there was no difference in performance on the targeting task due to presenting the auditory targeting cues through speakers or through headphones.

The major difference between the three experiments was that in experiments 1 and 3, the targeting cues were delivered from the left or right thus matching the location of the target, while in experiment 2 the cues came from in front or behind the participants requiring them to first locate the signal in space, and then to translate that signal into the direction of the target. It was hypothesized that since this task is the most difficult localization task for audition due to front-back reversal, performance using the auditory cue would suffer more in experiment 2. However, since determining if a location is to the left or right is the easiest localization task, performance in these two experiments should be better than that in experiment 2. This is exactly what was found.

When using the auditory cues, participants in experiment 2 were significantly slower to respond to the onset of the targeting cue, and took longer to locate the target, and made initial moves in the wrong direction more often than those in experiments 1 and 3. No difference, however, was found between the participants in experiments 1 and 3.

Since this prediction was based on a limitation in the auditory modality based on its structure that does not exist in the tactile system, it was also predicted that there would be not difference in performance between the three experiments when using the tactile cue. Our system of touch is not affected by front-back reversal, mainly because the skin covers the whole body so no matter where we are touched the response is basically the same (Bear et al., 2001). The only instance where the prediction did not hold was for the initial response time for the tactile task in the second experiment. Participants in the second experiment were significantly slower to respond the onset of the tactile targeting cue than were those in experiments 1 and 3. The reason for this is most likely that the task was harder in experiment 2 and this was the only measured where it showed up.

The analysis of the combined cues also agrees with the predictions concerning the auditory and tactile cues. Since the participants were still subject to front-back reversal because of the presence of the auditory cue, it was not surprising to find that the participants in experiment 2 were slower to respond than those in experiments 1 and 3, and that there was no difference between experiments 1 and 3. The same results were found for the direction of initial movement, but only for the dual-task. The reason that no differences were found between the three experiments in the baseline condition and the fact that there was no difference in the amount of time it took the subjects to locate the target indicates that the presence of the tactile cue enabled the participants to overcome the front-back reversal caused by the auditory cue.

The analysis of the shadowing task showed that the addition of the targeting task had no affect on performance in any of the experiments which indicates that the two tasks differed enough in their processing so as to prevent a significant decrement in performance when they were combined. This is not really surprising since the two tasks rely on different central processing codes and different response modes, and localization and communication are tasks that we regularly perform together.

The analysis of the subjective workload showed that the participants only differed in their assessment of the tasks workload when dealing with the auditory cue in the baseline condition. Surprisingly, while the participants in experiment 2 did think the targeting task was harder than they participants in experiment 3 which matches the predictions, the participants in experiment 1 also thought the task was harder than those in experiment 3. No difference was found between experiments 1 and 2, which was also a surprise. Based on the predictions made, the participants in one and three should not have differed and should have differed in their assessment from those in 2. The best explanation for this is that since the baseline was the first conditions run, the participants in 1 found the strangeness of the task uncomfortable and rated it as having a higher workload while those in three did not.

In summary, the comparison of the three experiments support the idea the characteristics of the sensory modalities involved in multiple tasks can affect the allocation of processing resources, which shows up as performance decrement. Participants in experiment 2 performed more poorly than participants in the other two experiments when using the auditory cues but not the tactile cues because the structure of the auditory system made the targeting task more difficult in the second experiment. However, since the system of touch is not affected by the repositioning of a cue, there was no reason for the performance on the three experiments to differ. The results of the comparison confirm this outcome and suggest that the characteristics of a sensory system especially a limitation can influence performance and that these characteristics must be taken into account in order to effectively design for multiple task scenarios involving the allocation of tasks to modalities.

CHAPTER 6: GENERAL DISCUSSION

In the most recent version of MRT, Wickens (2002) makes no mention of any other sensory systems other than the visual and auditory systems.   This leaves the application of the theory to other sensory systems in question.   Wickens also focuses heavily on the idea the theory is a structural theory of human information processing which implies that the allocation of resources in related to the structure of our brains and is thus also limited by structural differences (Wickens, 1992).   He further supports this assertion by suggesting that vision may actually have two resource pools, one for focal vision and one for ambient vision.   This suggests that the difference in the sensory systems affect the allocation of resources and that those differences within a sensory system may influence the allocation of resources across tasks using that same sensory system.   The MRT, however, makes no account for these structural changes in terms of sensory processing. Taken together these points reflect one of the criticisms of the theory, which is that the theory is unduly restrictive in its account of resources (Boles & Law, 1998).

This undue restrictiveness is also reflected by the lack of processing codes in the theory.   The theory posits two processing codes, spatial and verbal at the central processing stage. It also posits perceptual encoding, but does not discuss this as a processing code.   This is perhaps due to the fact that research indicates that perceptual encoding and central processing tasks use common resources while response processing uses separate resources (Smith & Buchholz, 1991; Wickens & Holland, 2002). Nevertheless, there are, as pointed out by other researchers, a likelihood of the existence of additional processing codes (Boles & Law, 1998; Luck et al., 1994).

The point of this study was to show that the characteristics or nature of the sensory modalities themselves must be taken into account when predicting how resources will be allocated in a multiple task situation. The results of the three experiments supported this by showing that as the characteristics of the sensory modalities used changed, so did the allocation of resources necessary for the completion of the tasks. However, the allocation was not the same for the two sensory systems, which indicates that the differences in the two systems handled the changes differently.

This is not a unique idea, especially in design. Research on the design of displays has shown that the characteristics of different sensory modalities affect their uses in displays. For example, visual signals need to be presented as near to the operator's line of sight as possible, as well as making them sufficiently large and bright, whereas auditory signals can be presented in the periphery (Proctor & Van Zandt, 1994b).

When combined with the limitations of MRT and what is known about the workings of the theory, the results of this study suggests that an addition needs to be made to the theory. Beginning with the input of sensory information, the model needs to be expanded so that each sensory system has its own pool of processing resources. In addition, within each system, there may exist a further division resulting in either a larger pool of resources or, more likely, multiple resource pools. Wickens (2002) has already suggested this with the visual system by differentiating between focal and ambient vision. This can be easily expanded for the other senses.

Our sense of touch has multiple components dictated by the receptors in the skin. Thus, we not only feel pressure, but also temperature and pain (Bear et al., 2001; Schiffman, 2001). In addition, Katz (1925/1989) argued that the detection of vibration was at least a separate component of touch if not a separate sense all together. Finally, researchers also differentiate between active touch in which we deliberately contact an item and manipulate it to learn about the object, and passive touch in which contact is not initiated deliberately by the individual (Rochat & Senders, 1991). Thus, the sense of touch could describe a group of resource pools.

Our sense of hearing can also be subdivided in a similar manner. In the central cochlear duct is the Organ of Corti which contains columns of specialized hair cells arranged in two sets, divided by an arch. One column is called the inner hair cells, and the outer hair cells (Bear et al., 2001; Schiffman, 2001). Given the structural-neural differences between the inner and outer hair cells, they likely transmit different types of auditory information. It has been proposed that the inner hair cells encode frequency information, whereas the corresponding outer hair cells sharpen the frequency response of the inner hair cells, register low-amplitude, weak sounds and are essential for sound detection close to the absolute threshold (Schiffman, 2001).

As with the visual and tactile systems, it can be theorized that there are separate resource pools connected to the auditory systems, one for the inner hair cells and one for the outer hair cells. Since real world sounds such as those produced by different musical instruments and human voices consist of the simultaneous combination of different frequency waves at different intensities (Bear et al., 2001), it is conceivable that the inner hair cells serve as a channel for communication while the outer hair cells serve as a sound detection channel. Thus, in situations such as those created in these studies, the language channel would be responsible for encoding the shadowing task, while the outer channel would handle the encoding of the targeting cue.

The literature on spatial cuing provides support for this by suggesting that stimulus features can also effect the allocation of resources when two tasks use the same sensory modality (Luck et al., 1996). Evidence for unlimited-capacity target detection is typically found when observers can use simple stimulus features such as color to segregate the target and distractors into separate perceptual groups, whereas capacity limitations are typically found when the target and distractors are similar and multiple features must be conjoined for accurate target discrimination (Duncan & Humphreys, 1989, 1992; Treisman, 1991).

The sensory processing stage includes the activation and identification of the stimuli, and the selection of the relevant information for processing. This information is then passed on to the central processing stage. Research indicates that the perceptual encoding and central processing share resources (Boles & Law, 1998). This suggests a need for an intermediary stage between the perceptual processing and central processing stages. This transition stage shares the resource pools of the perceptual processing stage and the central processing stage, as well as handling the combination of the multiple sensory inputs involving the same task, such as the combination of the auditory and tactile cues in the present study.

The establishment of a perceptual processing stage and a transition stage also match closely with the structure of our brains and our sensory systems. Research in virtually every sensory system, but especially with vision, indicates that the processing of information begins at the receptor level with encoding and determination of what information we will focus on and what information is excluded. Then, as the information processes through the system further processing is conducted. As the information is processed, the higher levels of the brain are also involved. These are the areas where the central processing occurs (Bear et al., 2001; Schiffman, 2001).

Furthermore, we know from neurological research that feedback systems exist throughout the brain. The inclusion of such a system in the theory can explain how the initial exposure to a task uses more resources and performance changes than performance later in the task. Specifically, as the initial information is processed to the central processing stage, feedback to the perceptual processing stage streamlines the process by helping focus resources on the most salient and important information which reduces the allocation of resources to the task over time. This serves to explain why performance improves when a subject is required to engage in two tasks at the same time following training (Spelke, Hirst, & Neisser, 1976).

With this front end modification, this modified multiple resource theory begins with the perceptual processing at the level of the specific sense. Here resources are allocated based on the match between the characteristics of the tasks and the characteristics of the sensory system. If the tasks focus on different aspects or dimensions of a sensory system, then there should be little interference because of the existence of separate resource pools for each dimension. At this stage another factor that comes into play is the familiarity or experience with a task. Those tasks within a sensory modality which we perform often or regularly require fewer resources than those that are new or novel. This information is also passed on through the processing system. This fits with the concept of a continuum of resources (Wickens, 2002).

From the specific sensory modality, the processing continues to the transition stage where the information is combined with other information from the other sensor systems. It is here that additive effects occur, as well as the dominance of one sense over another, and interference of one system with another. From this stage, the information proceeds on to the central processing stage where it is coded as spatial or verbal and the appropriate response is determined.

Applications and Implications for Design

Currently, sensory modalities other than vision are being introduced into complex event-driven environments that involve a high risk of data overload due to their traditional overreliance on visual information presentation. Both auditory and tactile cues are increasingly being introduced in an effort to support time-sharing and attention management (Sarter, 2005). For example, vibrotactile cues have been successfully used for indicating the location and severity of in-flight icing conditions (McGuirl & Sarter, 2001). Such endeavors are increasing, and more and more alternative uses for nonvisual sensory systems are being investigated.

Nevertheless, the characteristics of the sensory systems may be ignored. This can result in problems in the adaptation of nonvisual sensory systems for use in these complex environments. Thus, before any sensory system is used in design, developers much first look at the characteristics of the sensory system in relations to situation. Not only will this speed up development, but it should also help developers discover and eliminate potential shortfalls of new systems using nonvisual sensory systems. Furthermore, by examining the different sensory systems in depth, developers may arrive at new possible applications for sensory systems that have been underused to date.

Because the primacy of touch and the fact that it can receive input from 360 degrees without the problems encountered by audition, touch can be used to provide information about the location of a target which lies in any direction from the user. For example, a vibrotactile system could be used to provide information about incoming missiles or other planes that are approaching from a pilot's blindspot. Such a system could be linked with the plane's radar so that the pilot receives the information even if he isn't monitoring the radar. Such a system can also be useful for commercial pilots in busy areas of the country to alert them to the presence of other planes and to stationary objects. In addition to the location of the object, by altering the intensity of the signal, distance can also be transmitted to the pilot.

By considering the characteristics of sensory systems beforehand, it is possible to identify uses for sensory systems that may have escaped developers previously because of the limitations of the sensory system. Olfaction, for example, has often been overlooked because odors are hard to clear and tend to linger which could cause confusion. However, odors also have very strong affects on people. One of these is that odors are particularly good for cuing memories. They are also quite effective for discouraging people from entering an area, or for getting them to leave. This is basically the principle behind a skunk's spray. It is so nauseating that it drives aggressors away. One application of this sensory advantage would be to create an odorant that could be released in a building or enclosed area when evacuation is necessary, for example during a fire. The odorant would need to be so particularly foul that it drives people from the danger zone and to safety. In such a situation, the limitations of odor are not a problem, and may even be an advantage.

Future Research

The results of this study and the suggested modifications to MRT suggest several additional directions for future research. Further research needs to be done using multiple tasks and multiple sensory systems (vision, audition, and touch) to first confirm and second further the findings of these studies by using more complicated tasks. For example, the difficulty of the targeting task used in this study should be increased to include multiple directions and distances to determine if it is possible to include this information in the cues. In addition, studies that combine various cues from different sensory systems should be conducted which compare the effectiveness of the combined cues. This is important to determine if the cues from several sensory systems can be combined effectively and which combinations work best in a given situation. One area of current research that can be easily adapted to this line of investigation is the research of displays because researchers have established which sensory systems are most effective for specific displays.

Another line of research needs to be undertaken to focus on and confirm the existence of multiple components within each sensory system. While the existence of these components have been confirmed in terms of physiological differences, it is still not clear that they can be used for information processing without interfering with each other. Such research will involve multiple-task designs involving different tasks that utilize different types of information that are still processed through the same sensory system. For example, such research could be done using two tasks that use auditory communication and auditory alerts to see if there is any interference.

Finally, while the research presented here along with our structural knowledge of the brain supports the addition of the sensory processing stage, they merely suggest the existence of a feedback system and a transition stage. Thus, future research must be conducted to further demonstrate the existence of these modifications. The existence of feedback systems, for example, can be inferred from studies in which the subjects show improvements over time through repeated execution of the tasks. However, research into the existence of the feedback systems needs to also show that operators can alter their behavior during the tasks based on feedback. One of testing this would be to vary the characteristics of the cues during the study and then determine is accompanying adjustments were made to overcome these change.

APPENDIX A: TABLES FOR EXPERIMENT 1

Table 3: *Mean Response Times and Standard Deviations for Experiment 1*

	Mean (msec.)	SD
Baseline: Auditory Cue Only	2184	829
Baseline: Tactile Cue Only	2240	668
Baseline: Tactile/Auditory Cues Combined	1846	419
Dual-Task: Auditory Cue Only	2298	615
Dual-Task: Tactile Cue Only	2564	786
Dual-Task: Tactile/Auditory Cues Combined	2283	721

Table 4: *Results of Pairwise Comparisons Response Times for Experiment 1*

Comparison	Mean Difference (msec.)	Standard Error	Significance
Baseline: Tactile Cue vs. Auditory Cue	56	72.91	.450
Baseline: Auditory Cue vs. Auditory/Tactile Cues Combined	338	99.32	.002**
Baseline: Tactile Cue vs. Auditory/Tactile Cues Combined	394	69.67	.000***
Dual-Task: Tactile Cue vs. Auditory Cue	266	66.12	.000***
Dual-Task: Auditory Cue vs. Auditory/Tactile Cues Combined	15	69.60	.835
Dual-Task: Tactile Cue vs. Auditory/Tactile Cues Combined	281	55.84	.000***
Dual-Task Auditory Cue vs. Baseline Auditory Cue	114	116.34	.334
Dual-Task Tactile Cue vs. Baseline Tactile Cue	324	85.32	.001***
Dual-Task Auditory/Tactile Cues vs. Baseline Auditory/Tactile Cues Combined	437	87.51	.000***

**, The mean difference is significant at $\alpha = .01$.

***, The mean difference is significant at $\alpha = .001$.

Table 5: *Mean Initial Response Times and Standard Deviations for Experiment 1*

	Mean (msec.)	SD
Baseline: Auditory Cue Only	371	110
Baseline: Tactile Cue Only	341	93
Baseline: Tactile/Auditory Cues Combined	328	84
Dual-Task: Auditory Cue Only	380	118
Dual-Task: Tactile Cue Only	387	135
Dual-Task: Tactile/Auditory Cues Combined	362	108

Table 6: *Results of Pairwise Comparison for Initial Response Times for Experiment 1*

Comparison	Mean Difference (msec.)	Standard Error	Significance
Baseline: Auditory Cue vs. Tactile Cue	30	14.71	.051
Baseline: Auditory Cue vs. Auditory/Tactile Cues Combined	43	13.99	.004**
Baseline: Auditory/Tactile Cues Combined vs. Tactile Cues	13	13.81	1.000
Dual-Task: Tactile Cue vs. Auditory Cue	7	20.21	.767
Dual-Task: Auditory Cue vs. Auditory/Tactile Cues Combined	18	13.96	.206
Dual-Task: Tactile Cue vs. Auditory/Tactile Cues Combined	25	13.99	.096
Dual-Task Auditory Cue vs. Baseline Auditory Cue	9	19.68	.650
Dual-Task Tactile Cue vs. Baseline Tactile Cue	46	21.80	.048*
Dual-Task Auditory/Tactile Cues Combined vs. Baseline Auditory/Tactile Cues Combined	34	16.84	.049*

*, The mean difference is significant at $\alpha = .05$.

**, The mean difference is significant at $\alpha = .01$.

Table 7: *Mean Accuracy and Standard Deviations of Direction of Initial Movement for Experiment 1*

	Mean (Percent Correct)	SD (Percent)
Baseline: Auditory Cue Only	79	12
Baseline: Tactile Cue Only	83	10
Baseline: Tactile/Auditory Cues Combined	81	10
Dual-Task: Auditory Cue Only	76	11
Dual-Task: Tactile Cue Only	79	09
Dual-Task: Tactile/Auditory Cues Combined	80	10

Table 8: *Accuracy Means and Standard Deviations for Experiment 1*

	Mean	SD
Baseline: Auditory Cue Only	1.03	.05
Baseline: Tactile Cue Only	1.05	.09
Baseline: Tactile/Auditory Cues Combined	1.07	.20
Dual-Task: Auditory Cue Only	1.23	.65
Dual-Task: Tactile Cue Only	1.15	.36
Dual-Task: Tactile/Auditory Cues Combined	1.17	.46

Table 9: *Means and Standard Deviations for Shadowing Conditions for Experiment 1*

	Shadowing Scores	
	Mean	SD
Baseline: Shadowing	.952	.061
Shadowing for Dual-Task with Tactile Cue	.958	.059
Shadowing for Dual-Task with Auditory Cue	.954	.055
Shadowing for Dual-Task with Auditory/Tactile Cues Combined	.959	.041

Table 10: *NASA-TLX Means and Standard Deviations for Experiment 1*

	NASA-TLX Scores	
	Mean	SD
Baseline: Shadowing	64.0	19.0
Baseline: Auditory Targeting Cue Only	55.2	17.8
Baseline: Tactile Targeting Cue Only	54.6	16.9
Baseline: Auditory/Tactile Cues Combined	53.2	18.1
Dual-Task: Auditory Targeting Cue Only	70.7	14.4
Dual-Task: Tactile Targeting Cue Only	71.5	15.5
Dual-Task: Auditory/Tactile Cues Combined	71.3	17.2

Table 11: *Results of Pairwise Comparisons for the NASA-TLX for Experiment 1*

Comparison	Mean Difference	Standard Error	Significance
Baseline: Auditory Cue vs. Tactile Cue	0.6	2.1	.770
Baseline: Auditory Cue vs. Auditory/Tactile Cues Combined	0.2	2.4	.410
Baseline: Tactile Cue vs. Auditory/Tactile Cues Combined	0.1	2.0	.490
Dual-Task: Tactile Cue vs. Auditory Cue	0.8	1.9	.660
Dual-Task: Auditory/Tactile Cue vs. Auditory Cues Combined	0.6	2.1	.767
Dual-Task: Tactile Cue vs. Auditory/Tactile Cues Combined	0.2	1.6	.896
Dual-Task Auditory Cue vs. Baseline Auditory Cue	15.5	2.9	.000***
Dual-Task Tactile Cue vs. Baseline Tactile Cue	16.9	2.8	.000***
Dual-Task Auditory/Tactile Cues Combined vs. Baseline Auditory/Tactile Cues Combined	18.1	3.2	.000***
Shadowing Dual-Task Auditory Cue vs. Baseline Shadowing	0.7	2.3	.006**
Shadowing Dual-Task Tactile Cue vs. Baseline Shadowing	0.8	1.9	.000***
Shadowing Dual-Task Auditory/Tactile Cues Combined vs. Baseline Shadowing	0.7	1.9	.001***

**, The mean difference is significant at $\alpha = .01$.

***, The mean difference is significant at $\alpha = .001$.

APPENDIX B: TABLES FOR EXPERIMENT 2

Table 13: *Mean Response Times and Standard Deviations for Experiment 2*

	Mean (msec.)	SD
Baseline: Auditory Cue Only	2774	570
Baseline: Tactile Cue Only	2203	517
Baseline: Tactile/Auditory Cues Combined	2025	387
Dual-Task: Auditory Cue Only	3513	953
Dual-Task: Tactile Cue Only	2728	765
Dual-Task: Tactile/Auditory Cues Combined	2545	676

Table 14: *Results of Pairwise Comparisons Response Times for Experiment 2*

Comparison	Mean Difference (msec.)	Standard Error	Significance
Baseline: Auditory Cue vs. Tactile Cue	571	68.71	.000***
Baseline: Auditory Cue vs. Auditory/Tactile Cues Together	749	93.15	.000***
Baseline: Tactile Cue vs. Auditory/Tactile Cues Together	178	78.83	.031*
Dual-Task: Auditory Cue vs. Tactile Cue	785	112.45	.000***
Dual-Task: Auditory Cue vs. Auditory/Tactile Cues Together	968	106.75	.000***
Dual-Task: Tactile Cue vs. Auditory/Tactile Cues Together	183	76.54	.023*
Dual-Task Auditory Cue vs. Baseline Auditory Cue	738	134.51	.000***
Dual-Task Tactile Cue vs. Baseline Tactile Cue	525	98.95	.000***
Dual-Task Auditory/Tactile Cues Combined vs. Baseline Auditory/Tactile Cues Combined	520	112.10	.001***

*, The mean difference is significant at $\alpha = .05$.
***, The mean difference is significant at $\alpha = .001$.

Table 15: *Mean Initial Response Times and Standard Deviations for Experiment 2*

	Mean (msec.)	SD
Baseline: Auditory Cue Only	619	241
Baseline: Tactile Cue Only	393	102
Baseline: Tactile/Auditory Cues Combined	394	105
Dual-Task: Auditory Cue Only	569	246
Dual-Task: Tactile Cue Only	455	197
Dual-Task: Tactile/Auditory Cues Combined	443	176

Table 16: *Results of Pairwise Comparisons for Initial Response Times for Experiment 2*

Comparison	Mean Difference (msec.)	Standard Error	Significance
Baseline: Auditory Cue vs. Tactile Cue	226	32.72	.000***
Baseline: Auditory Cue vs. Auditory/Tactile Cues Combined	225	33.77	.000***
Baseline: Auditory/Tactile Cues Combined vs. Tactile Cue	1	12.40	.907
Dual-Task: Auditory Cue vs. Tactile Cue	114	22.35	.000***
Dual-Task: Auditory Cue vs. Auditory/Tactile Cues Combined	126	24.21	.000***
Dual-Task: Tactile Cue vs. Auditory/Tactile Cues Combined	12	16.08	.486
Baseline Auditory Cue vs. Dual-Task Auditory Cue	50	27.07	.073
Dual-Task Tactile Cue vs. Baseline Tactile Cue	62	27.95	.036*
Dual-Task Auditory/Tactile Cues Combined vs. Baseline Auditory/Tactile Cues Combined	49	25.88	.069

*, The mean difference is significant at $\alpha = .05$.

***, The mean difference is significant at $\alpha = .001$.

Table 17: *Mean Accuracy and Standard Deviations of Direction of Initial Movement for Experiment 2*

	Mean (Percent Correct)	SD (Percent)
Baseline: Auditory Cue Only	72	15
Baseline: Tactile Cue Only	78	12
Baseline: Tactile/Auditory Cues Combined	78	12
Dual-Task: Auditory Cue Only	61	12
Dual-Task: Tactile Cue Only	72	11
Dual-Task: Tactile/Auditory Cues Combined	72	11

Table 18: *Results of Pairwise Comparisons for Initial Direction of Movement for Experiment 2*

Comparison	Mean Difference In Direction of Movement	Standard Error	Significance
Baseline: Tactile Cue vs. Auditory Cue	6	.030	.043*
Baseline: Auditory/Tactile Cues Combined vs. Auditory Cue	6	.032	.048*
Baseline: Tactile Cue vs. Auditory/Tactile Cues Combined	0	.023	.944
Dual-Task: Tactile Cue vs. Auditory Cue	11	.025	.002**
Dual-Task: Auditory/Tactile Cues Combined vs. Auditory Cue	11	.023	.001***
Dual-Task: Tactile Cue vs. Auditory/Tactile Cues Combined	0	.021	.805
Baseline Auditory Cue vs. Dual-Task Auditory Cue	11	.025	.003**
Baseline Tactile Cue vs. Dual- Task Tactile Cue	6	.025	.027*
Baseline Auditory/Tactile Cues Combined vs. Dual-Task Auditory/Tactile Cues Combined	6	.031	.046*

*, The mean difference is significant at $\alpha = .05$.
**, The mean difference is significant at $\alpha = .01$.
***, The mean difference is significant at $\alpha = .001$.

Table 19: *Accuracy Means and Standard Deviations for Experiment 2*

	Mean	SD
Baseline: Auditory Cue Only	1.05	.06
Baseline: Tactile Cue Only	1.07	.09
Baseline: Tactile/Auditory Cues Combined	1.04	.07
Dual-Task: Auditory Cue Only	1.11	.09
Dual-Task: Tactile Cue Only	1.10	.08
Dual-Task: Tactile/Auditory Cues Combined	1.09	.16

Table 20: *Results of Pairwise Comparisons for Accuracy for Experiment 2*

Comparison	Mean Difference In Accuracy	Standard Error	Significance
Baseline: Tactile Cue vs. Auditory Cue	.024	.015	.134
Baseline: Auditory Cue vs. Auditory/Tactile Cues Combined	.005	.011	.606
Baseline: Tactile Cue vs. Auditory/Tactile Cues Combined	.029	.013	.030*
Dual-Task: Auditory Cue vs. Tactile Cue	.005	.015	.725
Dual-Task: Auditory Cue vs. Auditory/Tactile Cues Combined	.020	.026	.446
Dual-Task: Auditory/Tactile Cues Combined vs. Tactile Cue	.005	.015	.585
Dual-Task Auditory Cue vs. Baseline Auditory Cue	.058	.016	.001***
Dual-Task Tactile Cue vs. Baseline Tactile Cue	.029	.014	.047*
Dual-Task Auditory/Tactile Cues Combined vs. Baseline Auditory/Tactile Cues Combined	.044	.024	.079

*, The mean difference is significant at $\alpha = .05$.

***, The mean difference is significant at $\alpha = .001$.

Table 21: *Means and Standard Deviations for Shadowing Conditions for Experiment 2*

	Shadowing Scores	
	Mean	SD
Baseline: Shadowing	.933	.042
Shadowing for Dual-Task vs. Tactile Cue	.946	.035
Shadowing for Dual-Task vs. Auditory Cue	.923	.051
Shadowing for Dual-Task vs. Auditory/Tactile Cues Combined	.937	.049

Table 22: *NASA-TLX Means and Standard Deviations for Experiment 2*

	NASA-TLX Scores	
	Mean	SD
Baseline: Shadowing	64.9	15.3
Baseline: Auditory Targeting Cue Only	58.8	18.9
Baseline: Tactile Targeting Cue Only	50.8	22.0
Baseline: Auditory/Tactile Cues Combined	50.6	22.5
Dual-Task: Auditory Targeting Cue Only	75.8	13.7
Dual-Task: Tactile Targeting Cue Only	70.6	16.6
Dual-Task: Auditory/Tactile Cues Combined	70.2	15.6

Table 23: *Results of Pairwise Comparisons for the NASA-TLX for Experiment 2*

Comparison	Mean Difference	Standard Error	Significance
Baseline: Auditory Cue vs. Tactile Cue	8.0	3.0	.014*
Baseline: Auditory Cue vs. Auditory/Tactile Cues Combined	8.2	2.8	.006**
Baseline: Tactile Cue vs. Auditory/Tactile Cues Combined	0.2	1.7	.904
Dual-Task: Auditory Cue vs. Tactile Cue	5.2	2.4	.037*
Dual-Task: Auditory Cue vs. Auditory/Tactile Cues Combined	5.6	2.4	.024*
Dual-Task: Tactile Cue vs. Auditory/Tactile Cues Combined	0.4	2.2	.860
Dual-Task Auditory Cue vs. Baseline Auditory Cue	17.0	3.3	.000***
Dual-Task Tactile Cue vs. Baseline Tactile Cue	19.7	4.4	.000***
Dual-Task Auditory/Tactile Cues Combined vs. Baseline Auditory/Tactile Cues Combined	19.5	4.1	.000***
Shadowing Dual-Task Auditory Cue vs. Baseline Shadowing	10.9	2.9	.001***
Shadowing Dual-Task Tactile Cue vs. Baseline Shadowing	5.7	3.8	.140
Shadowing Dual-Task Auditory/Tactile Cues Combined vs. Baseline Shadowing	5.3	3.6	.148

*, The mean difference is significant at $\alpha = .05$.
**, The mean difference is significant at $\alpha = .01$.
***, The mean difference is significant at $\alpha = .001$.

APPENDIX C: TABLES FOR EXPERIMENT 3

Table 25: *Mean Response Times and Standard Deviations for Experiment 3*

	Mean (msec.)	SD
Baseline: Auditory Cue Only	2066	310
Baseline: Tactile Cue Only	2048	308
Baseline: Tactile/Auditory Cues Combined	1883	259
Dual-Task: Auditory Cue Only	2597	591
Dual-Task: Tactile Cue Only	2466	535
Dual-Task: Tactile/Auditory Cues Combined	2291	423

Table 26: *Results of Pairwise Comparisons Response Times for Experiment 3*

Comparison	Mean Difference (msec.)	Standard Error	Significance
Baseline: Auditory Cue vs. Tactile Cue	18	44.63	.692
Baseline: Auditory Cue vs. Auditory/Tactile Cues Combined	183	51.93	.002**
Baseline: Tactile Cue vs. Auditory/Tactile Cues Combined	165	42.81	.001***
Dual-Task: Auditory Cue vs. Tactile Cue	131	103.34	.217
Dual-Task: Auditory Cue vs. Auditory/Tactile Cues Combined	306	71.29	.000***
Dual-Task: Tactile Cue vs. Auditory/Tactile Cues Combined	175	66.80	.015*
Dual-Task Auditory Cue vs. Baseline Auditory Cue	531	106.46	.000***
Dual-Task Tactile Cue vs. Baseline Tactile Cue	418	81.62	.000***
Dual-Task Auditory/Tactile Cues Combined vs. Baseline Auditory/Tactile Cues Combined	408	63.41	.000***

*, The mean difference is significant at $\alpha = .05$.

**, The mean difference is significant at $\alpha = .01$.

***, The mean difference is significant at $\alpha = .001$.

Table 27: *Mean Initial Response Times and Standard Deviations for Experiment 3*

	Mean (msec.)	SD
Baseline: Auditory Cue Only	381	97
Baseline: Tactile Cue Only	321	83
Baseline: Tactile/Auditory Cues Combined	327	79
Dual-Task: Auditory Cue Only	448	134
Dual-Task: Tactile Cue Only	383	138
Dual-Task: Tactile/Auditory Cues Combined	355	135

Table 28: *Results of Pairwise Comparisons for Initial Response Times for Experiment 3*

Comparison	Mean Difference (msec.)	Standard Error	Significance
Baseline: Auditory Cue vs. Tactile Cue	60	12.69	.000***
Baseline: Auditory Cue vs. Auditory/Tactile Cues Combined	54	13.87	.001***
Baseline: Tactile Cue vs. Auditory/Tactile Cues Combined	-6	11.41	.636
Dual-Task: Auditory Cue vs. Tactile Cue	65	16.78	.001***
Dual-Task: Auditory Cue vs. Auditory/Tactile Cues Combined	93	12.64	.000***
Dual-Task: Tactile Cue vs. Auditory/Tactile Cues Combined	28	14.07	.061
Dual-Task Auditory Cue vs. Baseline Auditory Cue	67	15.37	.000***
Dual-Task Tactile Cue vs. Baseline Tactile Cue	62	15.53	.001***
Dual-Task Auditory/Tactile Cues Combined vs. Baseline Auditory/Tactile Cues Combined	28	20.05	.174

***, The mean difference is significant at $\alpha = .01$.

Table 29: *Mean Accuracy & Standard Deviations of Direction of Initial Movement for Experiment 3*

	Mean (Percent Correct)	SD (Percent)
Baseline: Auditory Cue Only	80	10
Baseline: Tactile Cue Only	82	10
Baseline: Tactile/Auditory Cues Combined	82	11
Dual-Task: Auditory Cue Only	80	10
Dual-Task: Tactile Cue Only	77	10
Dual-Task: Tactile/Auditory Cues Combined	78	09

Table 30: *Accuracy Means and Standard Deviations for Experiment 3*

	Mean	SD
Baseline: Auditory Cue Only	1.05	.06
Baseline: Tactile Cue Only	1.09	.12
Baseline: Tactile/Auditory Cues Combined	1.10	.11
Dual-Task: Auditory Cue Only	1.16	.17
Dual-Task: Tactile Cue Only	1.18	.26
Dual-Task: Tactile/Auditory Cues Combined	1.17	.32

Table 31: *Means and Standard Deviations for Shadowing Conditions for Experiment 3*

	Shadowing Scores	
	Mean	SD
Baseline: Shadowing	.960	.027
Shadowing for Dual-Task with Tactile Cue	.930	.077
Shadowing for Dual-Task with Auditory Cue	.933	.053
Shadowing for Dual-Task with Auditory/Tactile Cues Combined	.939	.053

Table 32: *NASA-TLX Means and Standard Deviations for Experiment 3*

	NASA-TLX Scores	
	Mean	SD
Baseline: Shadowing	57.6	19.9
Baseline: Auditory Targeting Cue Only	42.7	19.1
Baseline: Tactile Targeting Cue Only	43.1	21.8
Baseline: Auditory/Tactile Cues Combined	43.5	22.2
Dual-Task: Auditory Targeting Cue Only	66.1	17.0
Dual-Task: Tactile Targeting Cue Only	62.1	17.9
Dual-Task: Auditory/Tactile Cues Combined	61.8	21.9

Table 33: *Results of Pairwise Comparisons for the NASA-TLX for Experiment 3*

Comparison	Mean Difference	Standard Error	Significance
Baseline: Tactile Cue vs. Auditory Cue	0.4	3.3	.914
Baseline: Auditory/Tactile Cues Combined vs. Auditory Cue	0.8	2.7	.767
Baseline: Auditory/Tactile Cues Combined vs. Tactile Cue	0.5	2.3	.843
Dual-Task: Auditory Cue vs. Tactile Cue	4.0	2.2	.084
Dual-Task: Auditory Cue vs. Auditory/Tactile Cues Combined	4.3	2.6	.119
Dual-Task: Tactile Cue vs. Auditory/Tactile Cues Combined	0.3	2.0	.883
Dual-Task Auditory Cue vs. Baseline Auditory Cue	23.4	3.2	.000***
Dual-Task Tactile Cue vs. Baseline Tactile Cue	19.0	3.5	.000***
Dual-Task Auditory/Tactile Cues Combined vs. Baseline Auditory/Tactile Cues Combined	18.3	4.1	.000***
Shadowing Dual-Task Auditory Cue vs. Baseline Shadowing	8.5	3.2	.014*
Shadowing Dual-Task Tactile Cue vs. Baseline Shadowing	4.5	3.3	.182
Shadowing Dual-Task Auditory/Tactile Cues Combined vs. Baseline Shadowing	4.2	3.8	.273

*, The mean difference is significant at $\alpha = .05$.

***, The mean difference is significant at $\alpha = .001$.

APPENDIX D: TABLES FOR OVERALL ANALYSIS

Table 35: *Results of Post Hoc Comparisons for the Response Time Analysis of the Auditory Cue across the Three Experiments*

Comparison	Mean Difference (msec)	Standard Error	Significance
Baseline: Auditory Cue Only			
Experiment 2 to Experiment 1	591	158.98	.000***
Experiment 1 to Experiment 3	118	168.10	.484
Experiment 2 to Experiment 3	709	166.87	.000***
Dual-Task: Auditory Cue Only			
Experiment 2 to Experiment 1	1215	191.85	.000***
Experiment 3 to Experiment 1	299	202.86	.145
Experiment 2 to Experiment 3	916	201.37	.000***

***, The mean difference is significant at $\alpha = .001$.

Table 36: *Results of Post Hoc Comparisons for the Initial Response Time Analysis across the Three Experiments*

Comparison	Mean Difference (msec)	Standard Error	Significance
Baseline: Auditory Cue Only			
Experiment 2 to Experiment 1	248	42.81	.000***
Experiment 3 to Experiment 1	10	44.43	.820
Experiment 2 to Experiment 3	238	44.43	.000***
Baseline: Tactile Cue Only			
Experiment 2 to Experiment 1	52	24.11	.035*
Experiment 1 to Experiment 3	20	25.02	.427
Experiment 2 to Experiment 3	72	25.02	.005**
Baseline: Auditory/Tactile Cues Combined			
Experiment 2 to Experiment 1	67	23.35	.005**
Experiment 1 to Experiment 3	1	24.23	.973
Experiment 2 to Experiment 3	68	24.23	.007**
Dual-Task: Auditory Cue Only			
Experiment 2 to Experiment 1	188	45.73	.000***
Experiment 3 to Experiment 1	67	47.46	.159
Experiment 2 to Experiment 3	121	47.46	.013*
Dual-Task: Auditory/Tactile Cues Combined			
Experiment 2 to Experiment 1	81	36.92	.031*
Experiment 1 to Experiment 3	7	38.32	.848
Experiment 2 to Experiment 3	88	38.32	.024*

*, The mean difference is significant at $\alpha = .05$.

**, The mean difference is significant at $\alpha = .01$.

***, The mean difference is significant at $\alpha = .001$.

Table 37: *Results of Post Hoc Comparisons for the Mean Accuracy and Standard Deviations of the Direction of Initial Movement across the Three Experiments*

Comparison	Mean Difference (Percent)	Standard Error (Percent)	Significance
Baseline: Auditory Cue Only			
Experiment 1 to Experiment 2	7	3	.025*
Experiment 3 to Experiment 1	1	3	.867
Experiment 3 to Experiment 2	8	3	.021*
Dual-Task: Auditory Cue Only			
Experiment 1 to Experiment 2	15	3	.000***
Experiment 3 to Experiment 1	3	3	.260
Experiment 3 to Experiment 2	18	3	.000***
Dual-Task: Tactile Cue Only			
Experiment 1 to Experiment 2	7	3	.014*
Experiment 1 to Experiment 3	2	3	.367
Experiment 3 to Experiment 2	4	3	.137
Dual-Task: Auditory/Tactile Cues Combined			
Experiment 1 to Experiment 2	8	3	.004**
Experiment 1 to Experiment 3	2	3	.573
Experiment 3 to Experiment 2	6	3	.026*

*, The mean difference is significant at $\alpha = .05$.

**, The mean difference is significant at $\alpha = .01$.

***, The mean difference is significant at $\alpha = .001$.

Table 40: *Results of Post Hoc Comparisons for the NASA-TLX Analysis of the Baseline Auditory Cue across the Three Experiments*

Comparison	Mean Difference	Standard Error	Significance
Baseline: Auditory Cue Only			
Experiment 2 to Experiment 1	3.6	4.7	.447
Experiment 1 to Experiment 3	12.5	4.9	.013*
Experiment 2 to Experiment 3	16.1	4.9	.001***

*, The mean difference is significant at $\alpha = .05$.

***, The mean difference is significant at $\alpha = .001$.

REFERENCES

Banks, M. S., & Bennett, P. J. (1991). Chapter 7: Anatomical and physiological constraints on neonatal visual sensitivity and determinants of fixation behavior. In M. J. S. Weiss & P. R. Zelazo (Eds.), *Newborn attention: Biological constraints and the influence of experience* (pp. 177-217). Norwood, NJ: Ablex Publishing Corporation.

Batic, N., & Gabassi, P. G. (1987). Visual dominance in olfactory memory. *Perceptual and Motor Skills, 65,* 88-90.

Bear, M. F., Connors, B. W., & Paradiso, M. A. (2001). *Neuroscience: Exploring the brain* (2nd ed.). Baltimore, MD: Lippincott, Williams, & Wilkins.

Boles, D. B., & Law, M. B. (1998). A simultaneous task comparison of differentiated and undifferentiated hemispheric resource theories. *Journal of Experimental Psychology: Human Perception and Performance, 24(1),* 204-215.

Briand, K. A., & Klein, R. M. (1987). Is Posner's "Beam" the same as Treisman's "Glue"?: On the relation between visual orienting and feature integration theory. *Journal of Experimental Psychology: Human Perception and Performance, 13,* 228-241.

Campbell, S. B. G., & Taylor, P. M. (1980). Bonding and attachment: Theoretical issues. In P. M. Taylor (Ed.), *Parent-infant relationships* (pp. 3-23). New York: Grune & Stratton.

Cheal, M. L., & Lyon, D. R. (1992). Benefits from attention depend on the target type in location-precued discrimination. *Acta Psychologica, 81*, 243-267.

Clarkson, M. G., & Clifton, R. K. (1991). Chapter 4: Acoustic determinants of newborn orienting. In M. J. S. Weiss & P. R. Zelazo (Eds.), *Newborn attention: Biological constraints and the influence of experience* (pp. 99-119). Norwood, NJ: Ablex Publishing Corporation.

Duncan, J., & Humphreys, G. (1989). Visual search and stimulus similarity. *Psychological Review, 96,* 433-458.

Duncan, J., & Humphreys, G. (1992). Beyond the search surface: Visual search and attentional engagement. *Journal of Experimental Psychology: Human Perception and Performance, 18,* 578-588.

Eimer, M., & Driver, J. (2000). An event-related brain potential study of cross-modal links in spatial attention between vision and touch. *Psychophysiology, 37,* 697-705.

Eimer, M., van Velzen, J., & Driver, J. (2002). Cross-modal interactions between audition, touch, and vision in endogenous spatial attention: ERP evidence on preparatory states and sensory modulations. *Journal of Cognitive Neuroscience, 14*(2), 254-271.

Fernald, A. (2001). Chapter 2: Hearing, listening, and understanding: Auditory developments in infancy. In G. Bremner & A. Fogel (Eds.), *Blackwell handbook of infant development* (pp. 35-70). Oxford, England: Blackwell Publishers Ltd.

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,* 80-96.

Gibson, E. J., & Pick, A. D. (2000). *An ecological approach to perceptual learning and development.* Oxford: University Press.

Gopher, D., & Donchin, E. (1986). Chapter 41: Workload: An examination of the concept. In K. R. Boff, L, Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance, volume 2: Cognitive processes and performance* (pp. 1-49). Oxford, England: John Wiley & Sons.

Hart, S., & Staveland, L. (1988). Development of NASA-TLX: Results of empirical and theoretical research. In P. Hancock and N. Meshkati (Eds.), *Human mental workload.* Amsterdam: North-Holland.

Hawkins, H. L., Hillyard, S. A., Luck, S. J., Mouloua, M., Downing, C. J., & Woodward, D. P. (1990). Visual attention modulates signal detectability. *Journal of Experimental Psychology: Human Perception and Performance, 16,* 802-811.

Heller, M. A. (1983). Haptic dominance in form perception with blurred vision. *Perception, 12,* 607-613.

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

Kandel, E. R., Schwartz, J. H., & Jessell, T. M. (Eds.). (2000). *Principles of neural science* (4th ed.). New York: McGraw-Hill.

Katz, D. (1989). *The World of Touch* (L. E. Kruegar, Trans.). Hillsdale, NJ: Lawrence Erlbaum Associates. (Original work published 1925).

Kisilevsky, B. S., Stack, D. M., & Muir, D. W. (1991). Chapter 3: Fetal and infant response to tactile stimulation. In M. J. S. Weiss & P. R. Zelazo (Eds.), *Newborn attention: Biological constraints and the influence of experience* (pp. 63-98). Norwood, NJ: Ablex Publishing Corporation.

Lacreuse, A., & Fragaszy, D. M. (2003). Chapter 13: Tactile exploration in nonhuman primates. In Y. Hatwell, A. Streri, & E. Gentaz (Eds. & Trans.), *Touching for* *knowing* (pp. 221-234). Amsterdam/Philadelphia: John Benjamins Publishing Company. (Original work published 2000).

Luck, S. J., Hillyard, S. A., Mouloua, M., Clark, V. P., & Hawkins, H. L. (1994). Effects of spatial cuing on luminance detectability: Psychophysical and electrophysiological evidence for early selection. *Journal of Experimental Psychology: Human Perception and Performance, 20,* 887-904.

Luck, S. J., Hillyard, S. A., Mouloua, M., & Hawkins, H. L. (1996). Mechanisms of visual-spatial attention: Resource allocation or uncertainty reduction? *Journal of Experimental Psychology: Human Perception and Performance, 22*, 725-773.

Matlin, M. W. (2005). Chapter 3: Perceptual processes II: Attention and consciousness. In *Cognition* (6^{th} ed.) (pp. 67-96). Hoboken, NJ: John Wiley & Sons Inc.

McGuirl, J. & Sarter, N. B. (2001). Presenting in-flight icing information: A comparison of visual and tactile cues. *Proceedings of 20^{th} Digital Avionics Systems Conference (DASC).* Daytona Beach, Florida. October, 2001.

Montagu, A. (1986). *Touching: The human significance of the skin* (3^{rd} ed.). New York: Harper & Row.

Morange-Majoux, F., Cougnot, P., & Bloch, H. (1997). Hand tactual exploration of textures in infants from 4 to 6 months. *Early Development and Parenting, 6,* 127-135.

Moray, N. (1967). Where is capacity limited? A survey and a model. *Acta Psychologica, 27,* 84-92.

Navon, D. & Gopher, D. (1979). On the economy of the human processing system. *Psychological Review, 86,* 214-255.

Polson, M. C., & Friedman, A. (1988). Task-sharing within and between hemispheres: A multiple resources approach. *Human Factors, 30,* 633-643.

Posner, M. I., Nissen, M. J., & Klein, R. M. (1976). Visual dominance: An information processing account of its origins and significance. *Psychological Review, 83,* 157-171.

Prinzmetal, W., Presti, D. E., & Posner, M. I. (1986). Does attention affect visual feature integration? *Journal of Experimental Psychology: Human Perception and Performance, 12,* 361-369.

Proctor, R. W., & Van Zandt, T., (1994a). Chapter 9: Attention and the assessment of mental workload. In *Human Factors in Simple and Complex Systems* (pp. 186-209). Needham Heights, MA.: Allyn & Bacon.

Proctor, R. W., & Van Zandt, T., (1994b). Chapter 8: The display of visual, auditory, and tactile information. In *Human Factors in Simple and Complex Systems* (pp. 159-185). Needham Heights, MA.: Allyn & Bacon.

Regan, D., & Spekreijse, H. (1977). Auditory-visual interactions and the correspondence between perceived auditory space and perceived visual space. *Perception, 6,* 133-138.

Rochat, P. (1983). Oral touch in young infants: Responses to variations of nipple characteristics in the first months of life. *International Journal of Behavioral Development, 6,* 123-133.

Rochat, P., & Senders, S. J. (1991). Chapter 14: Active touch in infancy: Action systems in development. In M. J. S. Weiss & P. R. Zelazo (Eds.), *Newborn attention: Biological constraints and the influence of experience* (pp. 412-442). Norwood, NJ:

Ablex Publishing Corporation.

Rock, I., & Harris, C. S. (1967). Vision and touch. *Scientific American, 216,* 96-104.

Sachdev, R. N. S., Sellien, H., & Ebner, F. (2001). Temporal organization of multi-whisker contact in rats. *Somatosensory & Motor Research, 18*(2), 91-100.

Sanders, M. S., & McCormick, E. J. (1993). *Human factors in engineering and design* (7th. Ed.). *New York:* McGraw-Hill, Inc.

Sarter, N. (2005). Multiple resource theory as a basis for multimodal interface design: Success stories, qualifications, and research needs. Article in preparation.

Schiffman, H. R. (2001). *Sensation and perception: An integrated approach* (5th ed.). New York: John Wiley & Sons, Inc.

Sklar, A. E., & Sarter, N. B. (1999). Good vibrations: Tactile feedback in support of attention allocation and human-automation coordination in event-driven domains. *Human Factors, 4*(4), 543-552.

Smith, R. E., & Buchholz, L. M. (1991). Multiple resource theory and consumer processing of Broadcast advertisement: An involvement perspective. *Journal of Advertising, 20(3),* 1-7.

Spelke, E., Hirst, W., & Neisser, U. (1976). Skills of divided attention. *Cognition, 4,* 215-230.

Spence, C., Shore D. I., & Klein, R. M. (2001). Multimodal prior entry. *Journal of Experimental Psychology: General, 130*(4),

Spence, C., Kettenmann, B., Kobal, G., & McGlone, F. P. (2001). Shared attentional resources for processing visual and chemosensory information. *The Quarterly Journal of Experimental Psychology, 54A*(3), 775-783.

Stack, D. M., (2001). Chapter 13: The salience of touch and physical contact during infancy: Unraveling some of the mysteries of the somesthetic sense. In G. Bremner & A. Fogel (Eds.), *Blackwell handbook of infant development* (pp. 351-378). Oxford, England: Blackwell Publishers Ltd.

Staiger, J. F., Bisler, A., Schleicher, P., Gass, P., Stehle, J. H., & Zilles, K. (2000). Exploration of a novel environment leads to the expression of inducible transcription factors in barrel-related columns. *Neuroscience, 99*(1), 7-16.

Treisman, A. (1985). Preattentive processing in vision. *Computer Vision, Graphics, and Image Processing, 31,* 156-177.

Treisman, A. (1991). Search, similarity, and integration of features between and within dimensions. *Journal of Experimental Psychology: Human Perception and Performance, 17,* 652-676.

Toney, L. (1983). The effects of holding the newborn at delivery on paternal bonding. *Nursing Research, 32,* 16-19.

Weiss, M. J. S., & Zelazo, P. R. (1991). Chapter 16: A taxonomy of newborn attention. In M. J. S. Weiss & P. R. Zelazo (Eds.), *Newborn attention: biological constraints and the influence of experience* (pp. 466-511). Norwood, NJ: Ablex Publishing Corporation.

Welch, R. B., Dutton-Hurt, L. D., & Warren, D. H. (1986). Contributions of audition ad vision to temporal rate perception. *Perceptual Psychophysics, 39,* 294-300.

Wickens, C. D. (1980). The structure of attentional resources. In R. Nickerson (Ed.), *Attention and performance VIII* (pp. 239-257). Hillsdale, NJ: Erlbaum.

Wickens, C. D. (1984). Processing resources in attention. In R. Parasuraman & R.

Davies (Eds.), *Varieties of attention* (pp. 63-101). New York: Academic Press.

Wickens, C. D. (1992). *Engineering psychology and human performance* (2nd ed.). New York: Harper Collins.

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

Wickens, C. D., & Hollands, J. G. (2000). *Engineering psychology and human Performance* (3rd ed.). New Jersey: Prentice Hall.

Wickens, C. D., & Liu, Y. (1988). Codes and modalities in multiple resources: A success and a qualification. *Human Factors, 30,* 599-616.

Wickens, C. D., Mountford, S. J., & Schreiner, W. (1981). Multiple resources, task-hemispheric integrity, and individual differences in time-sharing. *Human Factors, 23,* 211-229.

Wickens, C. D., Vidulich, M., & Sandry-Garza, D. (1984). Principles of S-C-R compatibility with spatial and verbal tasks: The role of display-control location and voice-interactive display-control interfacing. *Human Factors, 26,* 533-543.

Woods, D. D. (1995). The alarm problem and directed attention in dynamic fault management. *Ergonomics, 38*(11), 2371-2394.