Applications of Crossmodal Relationships in Interfaces for Complex Systems: A Study of Temporal Synchrony

by

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AUTHOR'S DECLARATION

I hereby declare that I am the first and main author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners. Chapter two of this thesis was adapted from a report for Defence Research and Development Canada to support the Joint Unmanned Aerial Vehicle Surveillance Target Acquisition System (JUSTAS) project. These materials were prepared under a government of Canada contract and are under crown copyright.

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Abstract

Current multimodal interfaces for complex systems, such as those designed using the Ecological Interface Design (EID) methodology, have largely focused on effective design of interfaces that treat each sensory modality as either an independent channel of information or as a way to provide redundant information. However, there are many times when operationally related information is presented in different sensory modalities. There is very little research that has examined how this information in different modalities can be linked at a perceptual level. When related information is presented through multiple sensory modalities, interface designers will require perceptual methods for linking relevant information together across modalities. This thesis examines one possible crossmodal perceptual relationship, temporal synchrony, and evaluates whether the relationship is useful in the design of multimodal interfaces for complex systems.

Two possible metrics for the evaluation of crossmodal perceptual relationships were proposed: resistance to changes in workload, and stream monitoring awareness. Two experiments were used to evaluate these metrics. The results of the first experiment showed that temporal rate synchrony was not resistant to changes in workload, manipulated through a secondary visual task. The results of the second experiment showed that participants who used crossmodal temporal rate synchrony to link information in a multimodal interface did not achieve better performance in the monitoring of the two streams of information being presented over equivalent unimodal interfaces.

Taken together, these findings suggest that temporal rate synchrony may not be an effective method for linking information across modalities. Crossmodal perceptual relationships may be very different from intra-modal perceptual relationships. However, methods for linking information across sensory modalities are still an important goal for interface designers, and a key feature of future multimodal interface design for complex systems.

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Chapter 1
Introduction

1.1 Overview

Human machine interfaces over the past half century have largely relied on the visual sensory modality as the primary method for communicating information between a system and its human operators. The reliance on the visual modality has often left operators overwhelmed with visual information, especially in domains such as aviation, process control, and healthcare, where there is an abundance of data and information. However, new display technologies and faster computer processors have allowed interface designers to explore methods of information presentation in other modalities such as audition (Davies, Burns, & Pinder, 2007; Sanderson & Watson, 2005) and touch (Hoggan & Brewster, 2006; Lee, Stoner, & Marshall, 2004). These sensory modalities have increased the design space and the complexity of the interface design problem for designers, but have allowed for multimodal interfaces that reduce the perceptual load for single modalities while leveraging the particular perceptual properties of each sensory modality (Nesbitt, 2005; Sarter, 2006).

There are many benefits for using multimodal displays. Humans live in a multi-sensory world, where they receive information from a variety of different senses. Thus, humans have learned to efficiently process and integrate information from different senses to make sense of the world, a process called multi-sensory integration (Stein & Meredith, 1993). At the same time, there are theories such as Multiple Resource Theory (Wickens, 1984; Wickens & McCarley, 2008) that state that separating information into different modalities also allows access to separate pools of attention resources. Separating information presentation into different sensory modalities could allow for better workload management and concurrent processing of different streams of information. While more recent research has shown that the different sensory modalities are not as independent as stated by MRT, these cross-modal linkages can still be leveraged to create better alarms and alerts (Ferris &

Sarter, 2008; Spence, 2010). Finally, different sensory modalities have characteristics that best align themselves to different types of abstract data (Nesbitt, 2004). For example, vision is often used to show and compare spatial information, while temporal information is often mapped into auditory stimuli.

While there are many reasons for using multimodal interfaces, one current limitation is the lack of well-tested and effective systematic guidelines and design methodologies that can assist interface designers with the creation of these complex interfaces (Sarter, 2006). Thus, it may be advantageous to extend current design methodologies to include the use of multiple modalities. One such methodology, ecological interface design (EID), is well suited for the design of interfaces for complex systems. EID is a design methodology that makes use of perceptual relationships to reduce the need for analytical processing in favour of perceptual processing (Vicente & Rasmussen, 1992). In the past, EID has often been used in the visual and auditory domains (see Burns & Hajdukiewicz, 2000 for examples), and these interfaces have benefited from the study of perceptual relationships in the visual and auditory modalities. Due to the focus on the perceptual forms used to present complex information, EID is a good foundational method for examining the interface design problem for multimodal interfaces. Further description of the EID methodology can be found in Chapter 2.

However, multimodal interfaces exist as entities beyond their individual modalities, yet many current interfaces have limited interaction between the different sensory modalities. The methods that interface designers currently use to perceptually display information to operators are largely intra-modal, which limits how interface designers are able to organize information and draw relationships between data that is presented in different modalities. Without these perceptual links, information in each modality must first be understood at a higher level of cognition before it is compared or grouped with information in a different modality. Crossmodal perceptual links may be used to make these data linkages more accessible to operators, and is further explored in Chapter 3. The use of perceptual relationships that cross sensory modality boundaries for interface design is an area of research that is still in its infancy. The investigation of this line of research will provide future multimodal interface designers with perceptual tools for building better holistic multimodal interfaces that allow operators to easily comprehend the large amount of sensory information that they will encounter.

1.2 Objectives

This thesis examines the use of crossmodal perceptual relationships in the design of interfaces for complex systems. These relationships may prove to be a key tool that interfaces designers may use in the creation of effective interfaces where information must be presented across multiple sensory modalities. Currently, there is a lack of methods that interface designers can use to link related information in different modalities at a perceptual level. The goal of this thesis to identify one possible perceptual relationship and examine methods for evaluating the relationship's effectiveness. There are a large number of possible crossmodal perceptual relationships; one such relationship is temporal synchrony, a crossmodal judgement of whether stimuli in different modalities are synchronous. Crossmodal temporal synchrony was evaluated to determine whether it may be an appropriate perceptual relationship that interface designers may use in future multimodal interfaces for complex systems.

1.3 Focus of Investigation

The focus of the investigation will be the use of temporal rate synchrony, a type of crossmodal perceptual relationship, in the design of interfaces for complex systems using a performance-based approach. This research was inspired by the Ecological Interface Design (EID) methodology, created by Vicente and Rasmussen (1992) and the thesis will investigate how crossmodal relationships can be used to support the use of EID in the design of interfaces for multimodal interfaces. In particular, this research supports the design of interfaces that must provide information about a large number of data variables in different sensory modalities that describe the operation or the status of a complex system. In addition, the focus of the thesis is to examine the perceptual qualities of crossmodal temporal synchrony detection and its usefulness for interface design. Other very important interface design problems, such as semantic mapping and meaning-making, are beyond the scope of this research.

1.4 Structure of Thesis

The remainder of this thesis is structured as follows:

- Chapter 2 provides a brief introduction to complex systems and Ecological Interface Design, multimodal interfaces, and crossmodal perception.
- Chapter 3 introduces the need for crossmodal perceptual relationships and proposes two methods for evaluating the efficacy of crossmodal relationships for interface designers. Also introduces the concept for crossmodal temporal synchrony perception and describes the development of a method for using temporal synchrony for the monitoring of data in auditory and tactile multimodal interfaces.
- Chapter 4 describes a first experiment that evaluates how well individuals are able to make judgements of auditory and tactile temporal rate synchrony under different workload conditions.
- Chapter 5 describes a second experiment that evaluates how well individuals are able to monitor discrete streams of information when they are presented across two sensory modalities versus when they are presented within the same modality.
- Chapter 6 draws conclusions from the results from of the two experiments and describes the implications for multimodal interface design.

Chapter 2
Background – Interfaces for Complex Systems

The study of multimodal interface design is one that draws from a large body of research. This chapter describes some of the research that is directly relevant to the examination of crossmodal temporal synchrony perceptual judgements and the use of these relationships in the design of interfaces for complex systems. Two bodies of literature form the foundation for the literature review of this thesis: research on multimodal interface design and research on multisensory perception. This chapter examines the Ecological Interface Design methodology as a foundation for understanding what tools interface designers require for designing interfaces for complex systems, examines current examples of multimodal interfaces, and finally concludes with a brief review of current findings in crossmodal perception. This chapter is adapted from a report written for Defence Research and Development Canada (DRDC) to support the Joint Unmanned Aerial Vehicle Surveillance Target Acquisition System (JUSTAS) project (Giang et al., 2010). These materials were prepared under a government of Canada contract and are under crown copyright.

2.1 Ecological Interface Design

Ecological interface design (EID) is a design approach that has been used to great success in complex socio-technical systems (Vicente, 2002; Vicente & Rasmussen, 1992). It is a design methodology that is focused on supporting the control and monitoring of large systems by supporting an operator's understanding of the underlying constraints of the system (Vicente & Rasmussen, 1992). EID also focuses on interfaces, which are "designed to reflect the constraints of the work environment in a way that is perceptually available to the people who use it." (Burns & Hajdukiewicz, 2000, p. 1) These attributes make EID a versatile design methodology for support operators who must monitor and control large complex systems that are governed by a large number of interacting variables.

In Vicente and Rasmussen's (1992) theoretical foundation paper for EID, the authors outline the structure of the interface design problem for complex systems. This structure consists of three objects: the complex work domain that is being monitored and controlled, the interface between the system and the operator, and the human operator. The main goal of the interface designer is to design and organize the content, structure, and form of the interface so that operators can easily control the complex system. Vicente and Rasmussen identify two fundamental questions that must be understood by the interface designer to accomplish this task. First, the interface designer must understand the work domain, and second, the designer must understand how this information can be communicated to the operator as effectively as possible.

Vicente and Rasmussen propose two methods for answering these two fundamental problems to the interface design problem. To understand the work domain, a method called the abstraction hierarchy is used to represent and analyze the complexity and constraints of the complex system. The abstraction hierarchy models the work domain at multiple levels of complexity, starting from very concrete physical characteristics of the system (i.e., the physical form of the work domain) at the bottom of the hierarchy, and progressing in abstraction to the overall functional goal of the system (i.e., the functional purpose). Each level describes the work domain at a different level of complexity, but the abstraction hierarchy also describes the links and relationships that exist between and within the different levels. The abstraction hierarchy provides interface designers with many of the relationships that exist between the data that operators must understand to effectively control the state of the complex system.

The second fundamental question in the interface design problem, dealing with how to communicate the information to the operator, is the one that is more relevant to the perceptual structure of the interface being designed. Vicente and Rasmussen make use of Rasmussen's skills, rules, knowledge (SRK) taxonomy as a method for understanding how the work domain should be communicated to the operator (Vicente & Rasmussen, 1992). The SRK taxonomy describes different levels of cognitive control that operators can use to control a system. Operators of complex systems are capable of using control strategies based on Skill-Based Behaviour (SBB), Rule-Based Behaviour (RBB), or Knowledge-Based Behaviour (KBB). SBB represents behaviour that arises due to extensive training and experience or are naturally intuitive, resulting in almost automatic responses to incoming signals. RBB occurs when operators are able to follow a rule or procedure. KBB exists when events that are unforeseen by both of the operator and designers or are not well practiced occur, and operators must use their knowledge of the system to diagnosis the problem.

Vicente and Rasmussen (1992) describe three fundamental principles of design that make use of the SRK taxonomy:

- SBB: To support interaction via time-space signals, the operator should be able to act directly on the display and, the structure of the displayed information should be isomorphic to the part-whole structure of movements.
- RBB: Provide a consistent one-to-one mapping between the work domain constraints and the cues or signs provided by the interface.
- KBB: Represent the work domain in the form of an abstraction hierarchy to serve as an externalized mental model that will support knowledge-based problem solving

By supporting all three levels of cognitive control, operators are able to choose the lowest level of control required for the task at hand, while still allowing intuitive access to more detailed information when required.

2.1.1 Perceptual Relationships and Perceptual Thesauruses

One of the key benefits of the EID methodology is the use of perceptual processing to support skill- and rule-based behaviour. Instead of presenting information in abstract forms that require the operator to make use of analytical processing (such a mental arithmetic or other cognition heavy calculations), designers make use of perceptual forms that are directly mapped onto the relationships that individuals are required to monitor. For example, instead of monitoring a display of numbers for values that lie beyond a certain range, these values can be represented using different colours, changing the task to one that makes use of rule based perceptual processing. Vicente (2002) reviewed a number of papers that made use of the EID methodology and found that many of the performance advantages of EID interfaces were due to the unique visual forms that were used to support RBB by loading spatial processing rather than verbal processing. Vicente and Rasmussen (1992) also state that perceptual judgements have reduced variability when compared to analytical judgements. Thus, the benefits of using EID come partially from the use of perceptual judgements to represent the constraints and relationships that exist within the work domain.

Therefore, perceptual relationships are a key tool that interface designers invoke in the creation of effective interfaces. Designers using the EID methodology are able to create interfaces that integrate multiple data variables into a single perceptual form that takes advantage of the perceptual processing capabilities that humans possess. One example of this advantage is the use of emergent features, where individual perceptual characteristics of an object are integrated together and appear as a single salient form (Wickens and Hollands, 2000). To help support interface designers, Burns and Hajdukiewicz (2004) catalogued a number of different visual perceptual relationships that could be used to represent many of the data variables and relationships that are typically encountered in the design of interfaces for complex systems. This visual thesaurus for data relationships describes perceptual methods for showing single variable, multi-variable, and structural relationships. Some examples of these methods are shown in Figure 1.

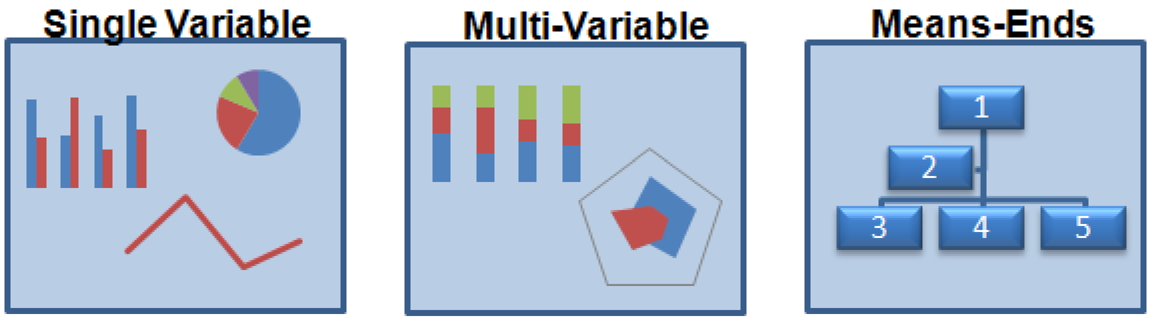


Figure 1: Examples of Different Perceptual Relationships in the Visual Thesaurus (Burns & Hajdukiewicz, 2004)

Sanderson and Watson (2005) extended the use of EID to the auditory domain and created the beginnings of an analogous auditory thesaurus. The auditory thesaurus contains a number of auditory perceptual relationships and described how they could be used to represent a number of different relationships between data variables (Figure 2). The auditory thesaurus, similarly to the visual thesaurus, provides interface designers with a set of "tools" to effective communicate information and relationships about the complex work domain to the operator. However, both the visual thesaurus and the auditory thesaurus only demonstrate methods for presenting information within a single modality. In multimodal interfaces where data is presented across different modalities, there are no clearly identified perceptual relationships that interface designers can use to link information across the sensory modalities. The goal of this thesis is to identify one possible crossmodal perceptual relationship to bridge this gap.

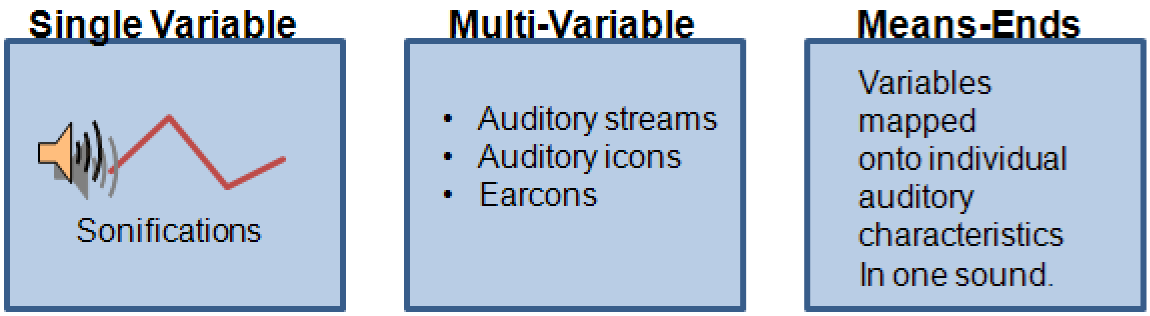


Figure 2: Examples of Different Possible Auditory Perceptual Methods for Showing Data Relationships (Sanderson & Watson, 2005)

2.2 Multimodal Interfaces

The study of multimodal interfaces is wide raging, covering methods of information presentation and input that deviate from the traditional visual keyboard and mouse human computer interaction paradigm. This thesis focuses on multimodal information presentation, a field of study that examines the use of multiple sensory modalities for communicating data from the system to the human operator. Multimodal presentation research is often an application focused area of research that draws from a strong engineering philosophy of finding working solutions. As such, many of the current guidelines for multimodal interfaces are abstract and vague and do not link back to the neurological and psychophysical data that is available in the scientific literature (Sarter, 2006). However, multimodal interfaces have demonstrated performance benefits in terms of decreased workload, (Trouvain & Schlick, 2007) and faster response times in certain crossmodal attention cuing situations (Ho & Spence, 2008). In addition, multimodal interfaces are often used when the visual modality is overloaded (Sanderson, Anderson, & Watson, 2000).

2.2.1 Multimodal Applications of EID

While the majority of research done using EID has been done using visual displays, the framework is not restricted only to the visual modality (Vicente, 2002). However, there have been relatively few researchers who have extended EID to other modalities. The following table provides a list of these lines of research.

Table 1: Lines of Multimodal Research using EID.

Papers	Application Domain	Modalities Used	End Results
Lee, Stoner, and Marshall (2004)	Driving	Haptic, Visual	Guidelines for haptic design based on SRK
Davies, Burns, and Pinder (2007)	Sonar mobility devices	Auditory	Prototype interface (Usability study / Cognitive walkthrough evaluation)
Watson, Anderson, and Sanderson (2000)	Aircraft landing and approaches	Auditory, Visual	Sonification for landing (not tested)
Sanderson, Anderson, and Watson (2000); Watson, Anderson, and Sanderson (2000); Sanderson, and Watson (2005); Watson and Sanderson (2007); Anderson and Sanderson (2009)	Anaesthesia	Auditory, Visual	Sonification anaesthesia interface (non-clinical tests)

As can be seen, the majority of the non-visual research has been done in the auditory modality. None of the research done has resulted in testing the EID interface against interfaces designed using other design methodologies. In fact, the majority of the research has not been formally evaluated in published studies. The research done by Sanderson, Anderson and Watson is on-going, and consists of the most complete extension of the EID process to date. Out of the four domains of research that have been explored using non-visual EID interfaces, one of these, Davies et al. (2007), focuses on only the auditory modality. The focus on the auditory modality was because the project was modelled after sonar systems that have previously been designed for visually impaired individuals. The other three projects all consist of some degree of presentation in multiple modalities because the application domains that were used (driving, anaesthesia, and to a lesser degree aircraft landings) involved tasks which the operators gather a portion of the required information through direct perception of the environment.

Two problems exist with the current multimodal EID research. Firstly, the current research into multimodal interfaces using EID has not included explicit methods for linking information across sensory modalities. Secondly, formal methods for deciding which modality information should be presented in is still not common and has only recently begun to be addressed (Burns, Ho, & Arrabito, 2011). Burns, Ho, and Arrabito (2011) suggest that a new process should be included in the EID methodology for identifying the perceptual fit requirements of the multimodal interface display. The perceptual fit requirements stage determines the modality that can best represent a data variable given its semantic and contextual characteristics. While information can be presented and mapped onto perceptual characteristics in each modality, each sensory modality also has specific qualities that are better suited for displaying certain types of information (Nesbitt, 2005; Sarter, 2006).

2.2.2 Multimodal Display Types

There are a large variety multimodal displays, and these displays vary by the complexity of the data being presented and the degree of symbolic or analogicness of the display method. Walker and Kramer (2006) describe symbolic displays as ones that "establish a mapping between a sound and an intended meaning, with no intrinsic relationship existing." (p. 1022) In contrast, analogic displays "contain an immediate and intrinsic relationship between the display dimension and the information that is being conveyed." (p. 1022) Walker and Kramer (2006) established a taxonomy of auditory coding methods based on a symbolic-analogic continuum. The symbolic-analogic continuum can also be applied in other modalities such as vision and touch. Table 2 lists examples of different types of multimodal displays and their equivalents in each sensory modality.

Table 2: Comparisons of Display Types in Different Modalities

Audition	Vision	Touch
Earcons: "a discrete sound that is a member of a set of sounds that are related to each other through a syntactic structure" (Sanderson & Watson, 2005). Earcons tend to make use of generic tones that rely heavily on the symbolic link between the tone and a concept. *Example: "A three-note pattern representing a file, in which a decrease in loudness and pitch represents "file deletion" – the diminishing loudness and pitch of the sound is a metaphor for the destruction of the file." (Walker & Kramer, 2004, p. 152)*	**Analogous Icons:** an icon that visually captures a constraint in the environment. (Burns & Hajdukiewicz, 2004). *Example: A map captures spatial relationships and visually depicts them.*	**Tacton**: a brief tactile message that can be used to represent complex concepts and information in a vibrotactile display. *Tactons* can be generated by exerting different rhythms and waveforms to a single tactor (Brewster & Brown, 2004). *Example: Different Types of alerts (e.g. voice call, text message) can be encoded using different rhythms of a single tactor. (Brewster & Brown, 2004)*
Auditory Icons: sounds that represent a thing that draws heavily from its real-world equivalent (Sanderson & Watson, 2005) *Example: The sound of a door closing to signify a person leaving a chatroom.*	**Icons**: graphic symbols that represent a concept or process due to the similarities between the graphical element and its real-world equivalent (Burns & Hajdukiewicz, 2004). *Example: Small pictograms used in Microsoft Windows.*	**Ecological valid tactile patterns:** tactile stimuli that produces an easily recognizable real-world sensation. Not a formal term, and has not be explored in detail within the literature. *Examples: Vibrations generated by a pair of vibrotactors located on the left and right side of the body to monitor imbalance in a vehicle.*
Sonification: the mapping of a source or multiple sources in the world into auditory dimensions of an auditory signal (Sanderson & Watson, 2005). *Example: Geiger counter.*	**Data Visualization:** a visual graphical object created to represent the status one or many data variables *Example: Polar star diagrams.*	**Spatio-temporal tactile patterns:** a pattern created by the sequential activation of a series of vibrotactors to intuitively present information using multiple dimensions. *Example: Sequentially activating a horizontal array of vibrotactors from right to left, a "left turn" concept can be generated (Jones, Lockyer, & Piateski, 2006).*

Audition	Vision	Touch
Audification: a translation of some physical stimuli into an auditory representation (Sanderson & Watson, 2005). *Example: Guitar amplifier.*	**Signal visualization:** a translation of some physical stimuli into a visual representation. *Example: Voltage or amplitude on an oscilloscope display.*	**Tactification:** a translation of some physical stimuli into a vibro-tactile representation. This is not a formal term, and has not been studied in detail in the literature. *Example: Seismic data presented through a tactor.*

It is important to note that each of these examples of multimodal displays was designed for a single modality. However, research by Hoggan and Brewster (2006; 2007) has explored the use of crossmodal icons for information presentation in mobile devices. The crossmodal icons created by the authors make use of both an auditory earcon and a tactile tacton that are “intuitively equivalent and can be compared as such.” (2006, p. 859) Some of the proposed benefits of crossmodal icons are that each modality may have situations where it is more appropriate and that crossmodal icons provide redundancy through another equivalent perceptual icon in a different modality. Hoggan and Brewster (2006) chose to implement auditory and tactile icons because they both share many temporal characteristics and that modalities that share multiple properties are more likely to be perceived as coming from the same source, which is termed the “unity assumption”. Hoggan and Brewster (2007) found that participants who were trained on earcons or tactons were able to quickly and intuitively recognize the equivalent icon in the other modality. These findings suggest that crossmodal links can be formed using similar characteristics in different modalities.

2.3 Crossmodal Perception

While research into the perception of multisensory information is numerous, research that applies the basic perception literature to interface design is rare. Furthermore, the applied multisensory perception literature has largely focused on the use of multisensory stimuli to direct attention. In this section, a basic review of current crossmodal perception literature is discussed with a focus on findings that are relevant to interface design. The crossmodal perception literature covers two major topics: multisensory integration and crossmodal attention.

2.3.1 Multisensory Integration and Crossmodal Matching

Multisensory integration is the process combining information from the different senses into a single cohesive picture of the world (Stein & Meredith, 1993). Multisensory integration is responsible for many perceptual phenomena and illusions that humans encounter in their daily life. It is the process that allows an individual to recognize that the sound of a car coming around a corner is the same object as the headlights that are off in the distance. Illusions such as the ventriloquism effect and the double flash illusion demonstrate that the integration of information of multiple modalities can actually change some perceived characteristics of the information in a single modality. For example, the spatial origin of a sound is influence by location of visual stimuli in ventriloquism, while a single visual flash appears as two separate events when accompanied by a double auditory signal in the double flash illusion (Shams, Kamitani, & Shimojo, 2004).

Another type of intersensory phenomenon is that of crossmodal matching, where comparisons are made between stimuli in different modalities. Stein and Meredith (1993) describe that crossmodal judgements, while being similar to multisensory integration in that they relate stimuli in different modalities, may use different underlying mechanisms. Multisensory integration tends to be much more automatic of a process, while judgements about crossmodal matches require a conscious decision to make. Stein and Meredith (1993) provide a number of possible neurological mechanisms that could underlie crossmodal matching. Some examples of these are that information in each modality is represented in a modality specific form but are still accessible by each other, information in each modality is first converted to an amodal form for comparison, or that information is converted into the form of a reference modality that all comparisons are made in.

Currently, there is very little research on how multisensory integration and crossmodal matching can be applied to interface design, especially interface design for the complex systems that EID is used to support. However, there are some key factors that may be useful in the design of interface. One such factor is the principles which help facilitate integration in multimodal stimuli. Similar to the assumption of unity described by Hoggan and Brewster (2006), where modalities that share multiple similar characteristics tend to be viewed as coming the same source, Stein and Meredith (1990) identify three characteristics that influence multisensory integration: the spatial rule, the temporal rule, and the principle of inverse effectiveness (Figure 3).

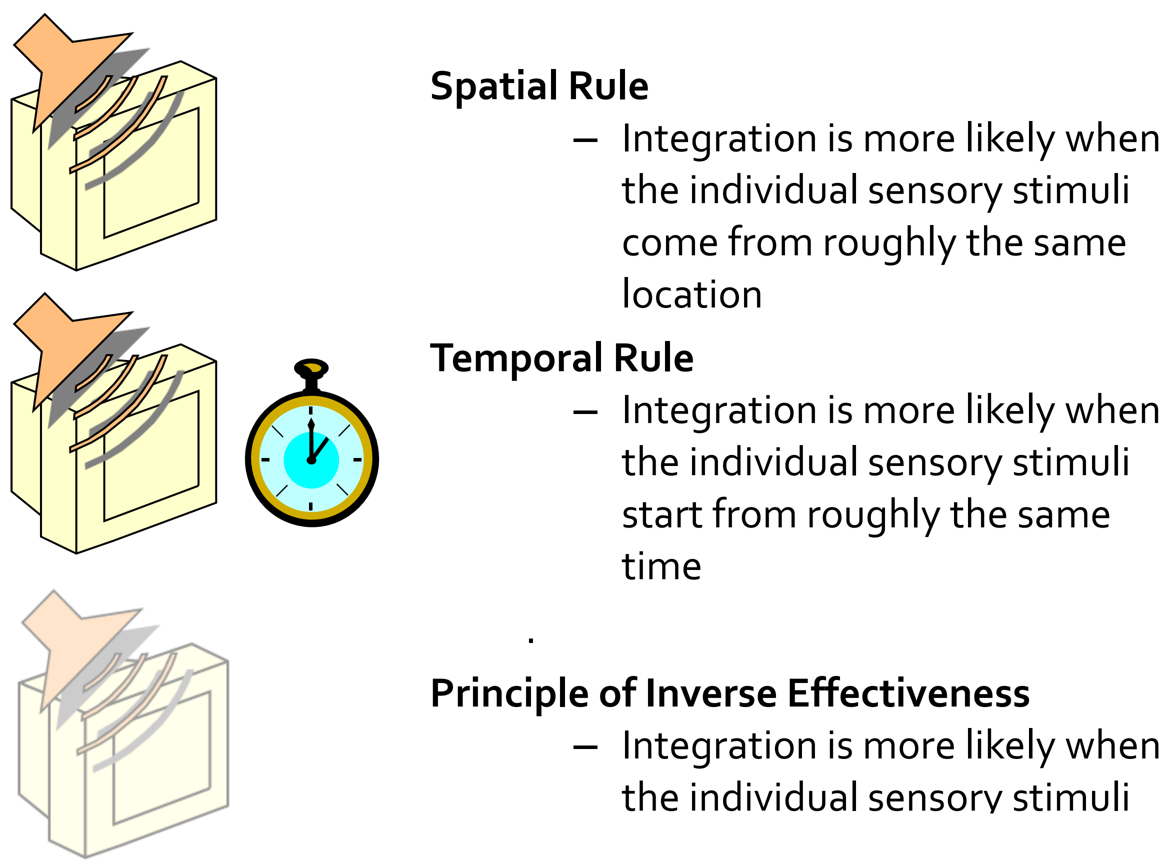


Figure 3: Three Principles of Multisensory Integration (Stein & Meredith, 1993)

2.3.2 Crossmodal Attention Resource Models

A second branch of crossmodal perception that is relevant to interface design deals with how attention is controlled and directed across multiple sensory modalities. There are many proposed theories of how this process is accomplished, and it is a very important topic for interface designers who often are required to direct the operator's attention using saliency, alarms, and other attention direction methods. The topics covered in this section are only an introduction to a very large body of active and ongoing research.

A common aspect of both recent and past research on crossmodal attention is the concept that resources can be combined and allocated according to different theories of attention. Within the literature, there are four commonly cited theories of crossmodal attention. These four theories are: a independent modality-specific attentional resources system, a single supramodal attention system, independent but linked attentional systems, and a hybrid hierarchical supramodal attention system with independent modality-specific attentional resources (Spence, 2009). The four models for attention can be seen in the figure below.

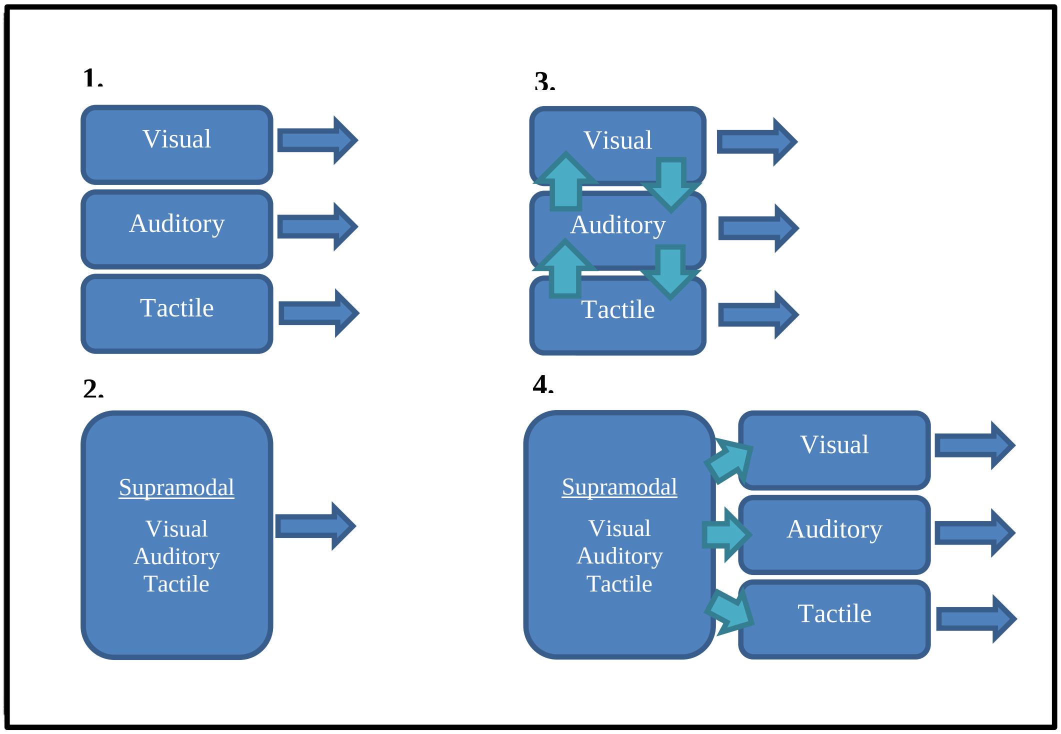


Figure 4: Four Models for Crossmodal Attention (Adapted from Spence, 2009)

2.3.2.1 Independent Modality-Specific Attentional Resources

The first theory for the allocation of crossmodal attention is that each modality has a specific and relatively independent pool of attentional resources which are used for information processing. Multiple Resource Theory (MRT) is one example of a theory that makes use of independent modality-specific attentional resources (Wickens, 1984). Instead of having a single pool of attention which is used during information processing, MRT proposes that there are a number of resources that can be accessed concurrently. MRT categorizes the pools of resources along four dimensions: modality (visual, auditory, etc.), stage of processing (perception, cognition, and responding), code (spatial vs. verbal), and response (manual spatial vs. vocal verbal). Tasks and activities that share the same characteristics will draw from the same pool of resources, while ones that make use of different characteristics will draw from different pools of resources allowing for better concurrent performance. MRT is an often cited theory behind the design of multimodal interfaces because it suggests that by offloading information to different modalities the operators will have access to a greater pool of attentional resources.

2.3.2.2 Single Supramodal Attention Systems

A contrasting model is that there is only a single pool of resources that is shared between each of the sensory modalities. In this theory, a single attention system is used to direct attention and individuals are only able to attend to a single spatial location at any time, though this location may be attended to across multiple sensory modalities (Santangelo, Fagioli, & Macaluso, 2010). There is evidence that supports a single supramodal attention system. In one study by Farah et al. (1989), the authors investigated whether spatial attention is separated into modality-specific subsystems, or if there is a single supramodal attention system that encompassed all modalities. The results supported the existence of a single supramodal attention system rather than pools of attention for each modality. More recent work has suggested that common cerebral regions may promote the construction of higher order representations in working memory for both visual and tactile information. These findings also support the theory of supramodal organization in memory applications (Gallace & Spence, 2009).

2.3.2.3 Separable but Linked Attentional Systems

Spence and Driver (1996) suggested that attention controls for different sensory modalities are connected, but are also capable of acting independently. This theory attempts to address discrepancies seen in the earlier models where strong links between different modalities have been shown, but it also provides evidence for the ability to direct attention to different spatial locations for different modalities (Spence & Driver, 1996). The author’s tested whether goal directed spatial orienting in hearing and vision were linked. The participants were required to respond to auditory and visual stimuli with elevation guesses (either up or down). There were several important observations in this study. Firstly, when participants were aware that the stimuli would be located on a specified side of the body, response times were shorter, regardless of the modality of the target. Secondly, when participants were aware of the modality of the target, a shift of attention occurred in the other modality, which also resulted in shorter reaction times. Lastly, when participants were aware that the targets would be presented in two modalities, auditory and visual attention was often divided. These results suggest that while attention could be divided in different modalities, there were links between the different modalities that could help direct attention in both modalities to the same location.

2.3.2.4 Hierarchical Supramodal plus Modality Specific Attentional Systems

Lastly, a hybrid model has been proposed which encompasses the interconnections of the modality-specific attentional resources and the attention systems of the supramodal modal. The work of Posner, Spence, and Driver (1996) suggested that a supramodal plus modality-specific attentional system may also describe their own experimental observations. They describe this model as one where the unimodal attentional subsystems supply into a higher-level supramodal system. Therefore, individual modalities may have their individual pools of resources, which are used when tasks are modality specific, while tasks that require crossmodal attention may draw from a supramodal pool of attentional resources.

2.4 Chapter Summary

This chapter examined three topics relevant to the study of crossmodal perceptual relationships: ecological interface design, multimodal interfaces, and crossmodal perception. EID was shown to be a methodology that is used to support the design of interfaces for situations where operators are required to process and understand a large amount of information about a complex system. EID makes use of perceptual processing to support skill and rule based behaviour, allowing for operators to quickly process information through perception rather than using cognitively demanding analytical processing. However, this chapter describes a lack of methods for perceptually displaying links between information that is presented in different modalities. The current research into multimodal interfaces and crossmodal perception provides some insights into the types of design characteristics, such as spatial and temporal patterns, that can be manipulated to create crossmodal perceptual relationships. The need for crossmodal relationships will be described in further detail in Chapter 3.

Chapter 3
The Search for Crossmodal Relationships – Temporal Synchrony

This chapter describes why crossmodal relationships are important and describes possible methods for determining whether a crossmodal relationship may be useful in a multimodal EID interface. One such crossmodal relationship is proposed and discussed.

3.1 The Need for Crossmodal Relationships

In the previous chapter, current research into multimodal interfaces was shown to have very little support for interfaces where individuals must recognize relationships between data shown in different modalities. Instead, most current interfaces focus on displaying information within a single modality. This research has led to a wealth of information about the effective design of interfaces for auditory and tactile modalities, with the discovery of many intra-modal perceptual relationships that interface designers can use. However, even when multiple modalities are used, each modality is often used for a separate channel of information that is treated as being relatively independent.

With the advent of new display methods and a better understanding about the types of information that are best presented within each modality, interface designers will most likely be required to display related variables in different sensory modalities. EID has shown that there are performance benefits from mapping these data relationships onto perceptual relationships. In current multimodal interfaces, these data relationships must be first perceived and understood as two independent streams on which an analytical comparison of the values is made. If, instead, operators are able to make these judgements at a perceptual level, the data relationships that exist across sensory modalities will be much more accessible to the operator.

Thus, it is important to examine the types of crossmodal perceptual relationships that are available for interface designers to use in the design of interfaces for complex systems. This search should begin by examining the current research in crossmodal perception to determine what types of possible candidate perceptual relationships are available. Afterwards, the candidate perceptual relationships should be evaluated to determine whether they may be appropriate for use in interfaces. The end goal of this process is to build a crossmodal perceptual thesaurus much like the visual thesaurus (Burns & Hajdukiewicz, 2004) that currently exists for EID.

3.2 Metrics and Criteria for Judging Crossmodal Relationships

One difficult question that must be answered in the search for crossmodal relationships is how to judge whether or not they are suitable for interface design. While it is possible to construct interfaces which make use of the perceptual relationships, this process is often time consuming and the results are often confounded with the design of other elements of the interface. Therefore, deciding on metrics and criteria for the judgement of crossmodal relationships is a key step in the search. In this thesis two metrics are proposed for this evaluation process: resistance to changes in workload and awareness in stream monitoring.

3.2.1 Resistance to Changes in Workload

As operators monitor complex systems, they are often working under many different workload conditions. Occasionally, they will be overloaded and responsible for multiple tasks that are all highly demanding. At other times, they will be able to focus all of their attention on the monitoring task at hand. Ideally, interfaces built for these operators should be usable under all of these situations. Therefore, a crossmodal perceptual relationship that is to be used in such an interface should aim to be perceivable under all conditions and be resistant to changes in operator workload.

Indeed, one of the goals of EID is to make the underlying relationships in the complex system readily accessible to the operator. To achieve this, the processing of the perceptual relationship used to represent the relationship should be simple, efficient, and almost automatic. Automatic processes are “rapid, accurate, and relatively resource free.” (Wickens & Hollands, 2000, p. 440) When a process is automatic, time-sharing between the process and other tasks becomes much easier because the automatic process requires very few mental resources. Many simple perceptual tasks, such as recognizing colours, are automatic and even more complex perceptual tasks, such as recognizing letters, can become relatively automatic with training (LaBerge, 1973 as cited in Wickens & Hollands, 2000). An automatic process requires fewer resources to achieve maximum performance and once this level of maximum performance is reached, performance is linked to the amount of data available rather than the amount of resources available. Therefore, a crossmodal perceptual judgement which is relatively automatic and provided the same level of information would lead to similar levels of performance even when the workload of other concurrent tasks is changed. This metric will be tested in Experiment 1 (Chapter 4).

3.2.2 Awareness in Stream Monitoring

In the auditory perception literature, stream segregation refers to our auditory systems ability to group together relevant parts of complex auditory stimuli into different streams (Bregman, 1990). Each stream is often linked to real-world event and the information which is grouped together is often about the same event. It is a process that is very similar to the visual systems ability to group together visual features into a single perceptual object. In auditory display design, a similar concept of stream analysis is used to describe when a designer “intentionally maps information distinctions onto different streams.” (Walker & Kramer, 2004, p. 155) Each of the different streams can represent different sources of information or data sets, and allows a designer to provide a variety of different pieces of information through the same display. The concept of streaming can also be applied to multimodal interfaces. In this context, a stream is a perceptually grouped set of stimuli that the designer has mapped onto some set of information. On a visual display a stream could be presented through a single display dial, while in a tactile display a stream could be represented through tactor presenting tactons.

The definition of a stream is flexible, but in most cases a stream represents continuous information about an “object” which the interface designer wishes to present to the operator through a set of related perceptual stimuli. In a multimodal interface for a complex system, designers often wish to present multiple streams of information to the operator. As mentioned previously, there will be occasions when multiple streams of information will be presented in different modalities. The goal of the crossmodal perceptual relationship, in these situations, is to link the streams of information together when it is appropriate. However, processing and monitoring of the underlying information is still very important, and the crossmodal relationship should not impede the operator’s ability to stay aware about the information presented in each of the streams. The use of crossmodal relationships to link streams across modalities is similar to how a well-designed configural display allows individuals to monitor the low-level data (the different streams) at the same time as monitoring the high-level constraints (which is represented by the crossmodal relationship) (Bennett, Toms, & Woods, 1990). This metric is examined in Experiment 2 (Chapter 5).

3.3 Temporal Synchrony – Description and Background

For the purposes of this thesis, one possible crossmodal perceptual relationship was examined using the two metrics. The choice of the relationship was heavily influenced by the principles of multisensory integration (Stein & Meredith, 1993) because multisensory integration is often a very automatic process. One of the principles of multisensory integration, the temporal rule, states that stimuli that occur at roughly the same time tend to be integrated together. Time is also a dimension that exists across all sensory modalities and because it is a characteristic that is not dependent on the modality it is “amodal” (Lewkowicz, 2000). In addition, the most common type of cross-modal relationship comes in the form of cross-modal matching tasks. These tasks require the observer to judge whether a stimuli in two modalities are equal along some dimension. These factors led to the selection of temporal synchrony as the candidate crossmodal perceptual relationship.

When stimuli in different modalities occur at the same time, it is possible for individuals to make judgements of whether the two events are synchronous. An individual's ability to recognize when two modalities are synchronous is a well studied phenomena and there is evidence that infants are able to perceive and respond to inter-modal synchrony events at ages as young as 2 months (Lewkowicz, 2000). While much of the study of temporal synchrony has been done on visual and auditory stimuli, there has also been work examining how sensitive individuals are to haptic-audio asynchrony. One such study by Adelstein, Begault, Anderson, & Wenzel (2003), found that individuals were able to identify when a tactile hammer tap differed from its auditory sound when there was a temporal asynchrony of 24 ms. This finding, along with a multitude of other research (Conrey & Pisoni, 2006) shows that there is a "synchrony window" in which stimuli in two different modalities is perceived as being synchronous. This is an important finding for interface designers because of issues such as hardware and display technology response times.

Temporal synchrony can be represented using many methods. The most basic of these is detecting the synchrony of stimuli onsets and offsets (Figure 5). In this situation, two stimuli are considered to be synchronous when they start at the same time or end at the same time. Duration is another possible temporal dimension that inter-sensory stimuli can be matched across (Figure 6). Two streams can be considered synchronous when the durations of the signal are the same. Finally, two streams can be matched by considering the temporal pattern of the stimuli in both modalities. For example, the rate of signal presentation can be equivalent in both modalities, leading to a perception of synchrony (Figure 7). For the purposes of this thesis, temporal rate synchrony was chosen as the best possible representation of temporal synchrony. This choice was made because synchrony in temporal rate requires synchronous onset, offset, duration, as well as the rate.

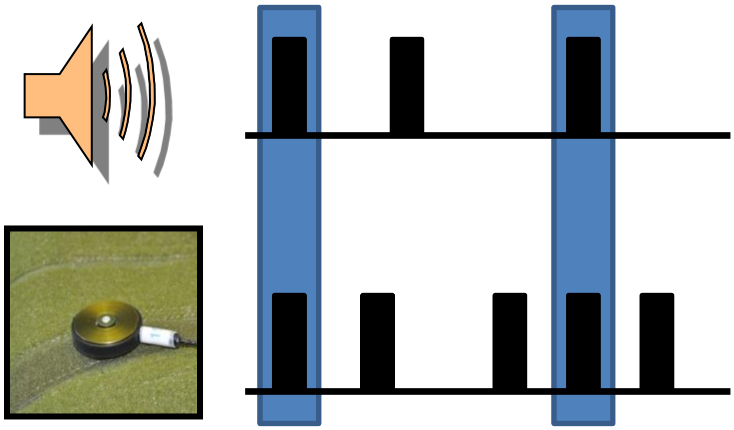


Figure 5: Onset Based Temporal Synchrony

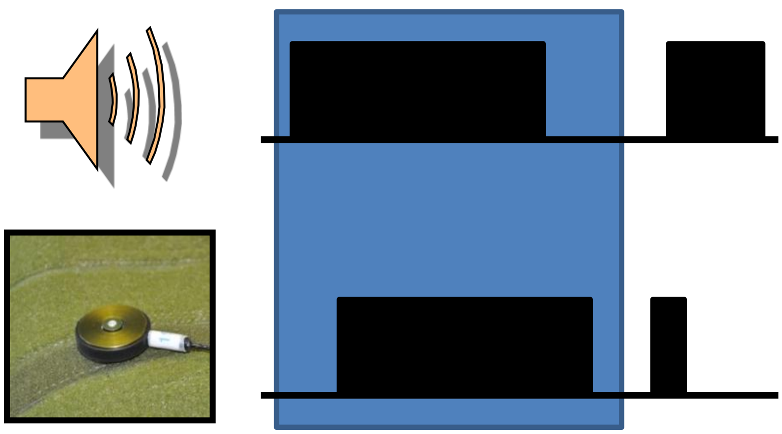


Figure 6: Duration Based Temporal Synchrony

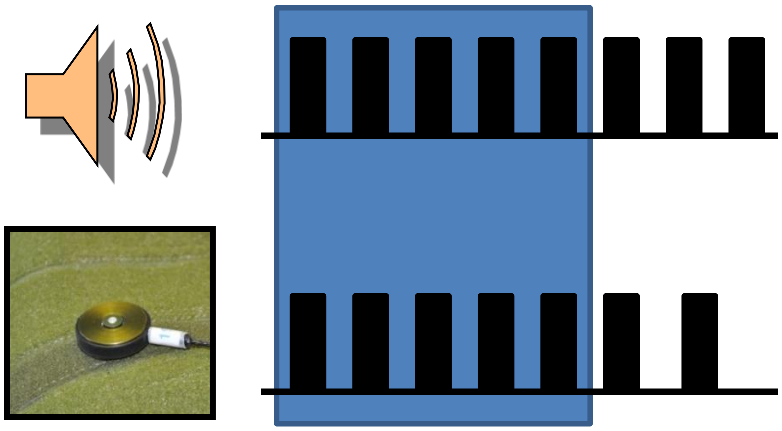


Figure 7: Rate Based Temporal Synchrony

3.4 Temporal Rate in Current Interfaces

Tempo and rhythm are characteristics that often appear in auditory interfaces. They are auditory characteristics that can be easily modified and used to code information about a data variable. The tempo of a signal has been found to influence the perceived urgency of an auditory signal (Edworthy, Loxley, & Dennis, 1991), as well as operator trust and perceived workload (Spain & Bliss, 2008). Research has found that the auditory modality is highly sensitive to changes in the temporal characteristics of the signal (Walker & Kramer, 2004), which makes the auditory modality a very good candidate for the monitoring of continuous information. Some examples of auditory displays where the temporal rate of the sonification is mapped onto a monitored variable include Geiger counters (Walker & Kramer, 2004) and pulse oximetry (Anderson & Sanderson, 2009). Geiger counters map the amount of radiation detected onto the rate of the auditory clicks. As the amount of radiation increases the rate of the clicks also increases. Pulse oximeters map a patient's heart rate onto the rate of auditory beeps.

Tempo has also been used in the tactile modality. Tactile stimuli are often controlled using very similar characteristics as auditory stimuli. These characteristics include frequency, intensity, and temporal rate and rhythm of the vibration. Brown, Brewster, and Purchase (2006) used rhythm as one of the dimensions for the design of tactons. In that experiment, the tactons were used to represent alerts from an electronic diary. The rhythm of the tacton was mapped onto the type of appointment: meeting, lecture, or tutorial. The rhythms used varied in their complexity and speed. The results showed that participants were able to recognize the type of appointment being presented 96.7% of the time.

Hoggan and Brewster (2007) also made use of rhythm as a dimension in their design of auditory and tactile crossmodal icons. Similar to the work done in the tactile modality, the type of message being received by a mobile device (text, email, or voicemail) was coded into three different auditory and tactile rhythms. The results of that experiment showed that participants were able to recognize auditory icons when they were trained on the equivalent tactile icon and vice versa. Recognition rates for the crossmodal icons were all relatively high, with average rates of 85.1% for the auditory earcons when the participants were trained with tactons and recognition rates of 76.5% for the tactile tactons when trained with earcons.

Taken together, these examples of temporal rate and rhythm in current multimodal interfaces suggest that temporal rate is a dimension that can be used to code information in a multimodal interface for complex systems. None of the interfaces explicitly use temporal synchrony or asynchrony as a dimension for coding. However, the Hoggan and Brewster (2007) crossmodal icon study does show that participants are able to transfer their perceptions of rate from one modality to another. It is also evident that the auditory and tactile modalities are best suited for using temporal rate as a coding dimension. Therefore, these two dimensions were chosen to be used in the following experiments.

3.5 Chapter Summary

This chapter described the need for crossmodal relationships in interfaces for complex systems. Two metrics for evaluating the effectiveness of the relationship in interface design were proposed: resistance to changes in workload and awareness in stream monitoring. The first metric, resistance to changes in workload, examines how easily a relationship can be identified under periods of low and high workload. An effective crossmodal relationship would perform similarly under both conditions. The second metric, awareness in stream monitoring, examines how well the underlying information that is being linked together by the crossmodal relationship can be monitored. An effective crossmodal relationship would not interfere with the monitoring of the information in each modality.

One possible crossmodal relationship, temporal rate synchrony, was identified and described. The temporal rate synchrony relationship used in this thesis is a judgement of whether two stimuli share the same temporal onset, duration, and rate. Temporal synchrony was chosen as a candidate relationship because time is an amodal characteristic that exists across multiple modalities. Chapters 4 and 5 evaluate the effectiveness of temporal rate synchrony using the two metrics introduced in this chapter.

Chapter 4
Experiment I – Temporal Synchrony Detection under different Workload Conditions

This chapter describes a first experiment that examines temporal rate synchrony detection under different workload conditions. All materials related to the study are included in Appendix A.

One possible metric for determining whether a crossmodal relationship would be a useful method for linking abstract data across modalities is how easily it can be interpreted and used by the individual whenever it is required. An operator may need to make use of the information provided by the multimodal interface in situations when they're already heavily taxed by other work, and their performance in these situations may be critical to the safety of the system. However, the operator's performance during times of relative calm, when they can focus on interpreting the multimodal interface, is also very important. Thus, temporal rate synchrony performance in a temporal rate synchrony task should be highly resistant to changes in workload for it to be a useful crossmodal relationship.

4.1 Objectives

The objective of this study was to examine how well individuals are able to make judgements of temporal synchrony under different workload conditions. If individuals are able to detect temporal rate synchrony at the same level of performance across different workload conditions, then there would be evidence that it is a perceptual relationship that is resistant to changes in workload. To examine this research question, participants were asked to make judgements about the synchrony of auditory and tactile stimuli in a monitoring task, while changing workload through the use of a secondary visual task. The hypothesis was that performance in the cross-modal synchrony task would be similar under both high and low workload conditions.

4.2 Experimental Design

The experiment used a single factor within-subjects design to compare the performance of participants in three different workload conditions: no secondary task, low workload secondary task, and a high workload secondary task. The workload condition was manipulated using a secondary visual task that was adapted from a “wind-shear” monitoring secondary task created by Sethumadhavan (2009). A second factor, rate type (5 levels), was also designed into the experiment, but was analyzed separately.

The experiment was divided into three blocks, one for each of the workload conditions. The order of the workload blocks and the temporal synchrony scenarios were counter balanced to control for learning effects. However, the first session completed was always the no visual task condition. This was done to ensure that participants were comfortable with the temporal synchrony task before the addition of the secondary task. Each workload condition was run as a separate 10 minute block and participants were given a break between each of the blocks to reduce the risk of fatigue and the effect of adaptation and habituation to the tactile stimuli.

Participants were responsible for two tasks during the experiment: a temporal synchrony task and a visual secondary task. In the temporal synchrony task, participants monitored auditory and tactile stimuli for occurrences of cross-modal temporal rate synchronies. When the participant identified one of these synchrony events, they responded by hitting a button with their left hand. In the visual task, participants were asked to monitor the magnitude of a number visually displayed on the screen. Participants performed this visual task concurrently with the temporal synchrony task. The participant was required to respond to the visual task whenever the number displayed was below or equal to 130 or above or equal to 170. They accomplished this by hitting a button with their right hand. Percentage of hits, misses, false alarms, correct rejections and response times were collected for both the temporal synchrony task and the visual task. In addition, participants were asked to fill out questionnaires about their perceived performance, workload, strategies, and how they perceived the stimuli.

4.3 Methodology

4.3.1 Participants

A total of twenty-seven undergraduate and graduate students from the University of Waterloo were recruited through e-mail and posters for this study. All participants had self-reported normal or corrected-to-normal vision and normal hearing. In addition, each of the participants in the study was right-handed. This was done to control for handedness effects on responses. Out of the twenty-seven participants, twenty-four sets of data were used for further analysis. One participant's data was lost due to an experiment software malfunction. Two other participants' data were removed due to poor performance (extremely high false alarm rates) in temporal synchrony task. All three participants were replaced and their data were excluded from the subsequent analysis. All participants were compensated $10 for their time.

4.3.2 Apparatus

The experiment occurred in a normal office environment, with lights dimmed and ambient noise kept to a minimum. Figure 8 shows the experimental setup used for the experiment. Participants were seated in front of a 22 inch liquid crystal display monitor that displayed information pertaining to the temporal synchrony task, and a laptop with a 14 inch display which displayed the visual task. Participants responded to the tasks using two keyboards with clearly marked buttons for responses. One button on the left keyboard, used for the temporal synchrony task, was controlled using their left hand, and the other button on the right keyboard, for the visual task, was controlled using their right hand.

Figure 8: Experimental Setup for Experiment 1

Auditory stimuli was generated using CSound (http://csounds.com/) and was presented through bi-aural headphones. Auditory files were generated for each of the different auditory rate types and were stored as WAV files on the experiment computer. The tactile stimuli were presented through two Engineering Acoustics Inc. C2 tactors secured onto the outsides of the wrists of the participants using double sided tape. An example of a C2 tactor can be seen in Figure 9. The tactors were driven using a custom built tactor controller. The controller consisted of a controllable digital unit, a digital to analog convertor, a series of power amplifiers and outputs to the tactors. A thorough description of the tactor control unit and its construction process can be found in Masnavi (2011). The tactor control unit was connected through a USB interface and was controlled by the experimental software which was created using the open-source PsychoPy framework (Pierce, 2007).

Figure 9: An EAI C2 Tactor

4.3.3 Stimuli

Auditory and tactile stimuli of varying temporal rhythms were used as the stimuli for the temporal rate synchrony task. The auditory stimuli consisted of 200 Hz pure tones that were repeated at 5 different temporal rates. The tactile stimuli were presented through tactors that vibrated at 250 Hz and were also repeated at 5 different temporal rates at moderate intensities.

Five different levels of the temporal rate were created for the auditory and tactile stimuli. The different temporal rate levels were created using "rate units" that represented the different levels. Each "rate unit" had a duration of 2 seconds, and the rate of the signal was varied by changing the number of times the auditory or tactile signal was turned on (a "beat") within this 2 second interval. Each beat had a duration of 300 milliseconds. The fastest rate contained 5 beats within the 2 second unit, with separations of 400 milliseconds seconds between the onsets of each beat, as seen in Figure 10. The other rates consisted of 4, 3, 2, and 1 beat(s) distributed evenly within the 2 second unit and can be seen in Table 3.

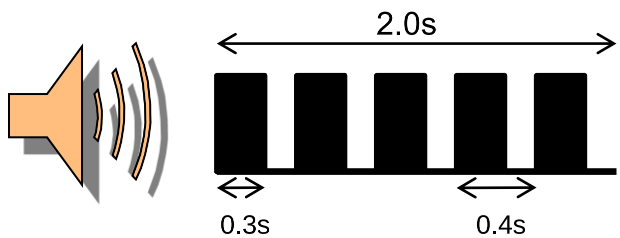


Figure 10:Example of a Rate Unit with a Temporal Rate of 5

Table 3: Beat Onsets for Temporal Rate Conditions

Condition	Beat Onsets
5	0s, 0.4s, 0.8s, 1.2s, 1.6s
4	0s, 0.5s, 1.0s, 1.5s
3	0s, 0.67s, 1.33s
2	0s, 1.0s
1	0s

The individual temporal rate units were combined into longer auditory and tactile "streams" which were used to represent more complex monitoring tasks that would be found in multimodal interfaces and human supervisory control situations. In these situations, the rate information could be used to represent information about a variable or system characteristic that the operator is required to monitor. The auditory and tactile streams were paired together to create scenarios that contained temporal rate synchrony events when the rates in both streams were the same, as shown in Figure 11.

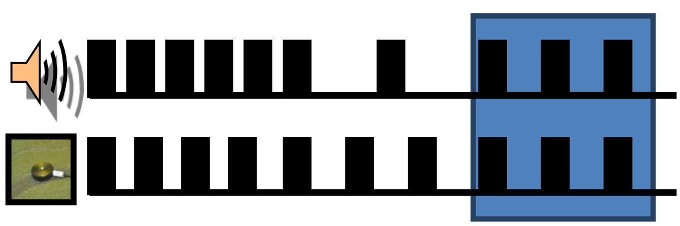


Figure 11: Temporal Rate Synchrony Event between Auditory and Tactile Streams

Three 10 minute scenarios were generated for the experiment. Each scenario had 300 rate units, of which 50 were temporal rate synchrony events (10 for each of the 5 different rate levels). The synchrony events accounted for roughly 16.67% of the scenario and were distributed throughout the

10 minute duration. No synchrony events occurred immediately after another synchrony event. On average across all three of the scenarios, synchrony events were separated by 3.55 rate units, with a maximum separation of 20 rate units and a minimum separation of 1 rate unit. A fourth 2 minute scenario was generated for training purposes.

A visual monitoring secondary task adapted from Sethumadhavan (2009) was used to manipulate the participant's workload. In the secondary visual task, a series of numbers between 100 and 199 were presented sequentially in the middle of a blank screen, as shown in Figure 12. In the no visual task condition, the monitor displaying the visual task was turned off. In the low workload condition, the number on the screen would change every 6 seconds, and in the high workload condition would change every 2 seconds.

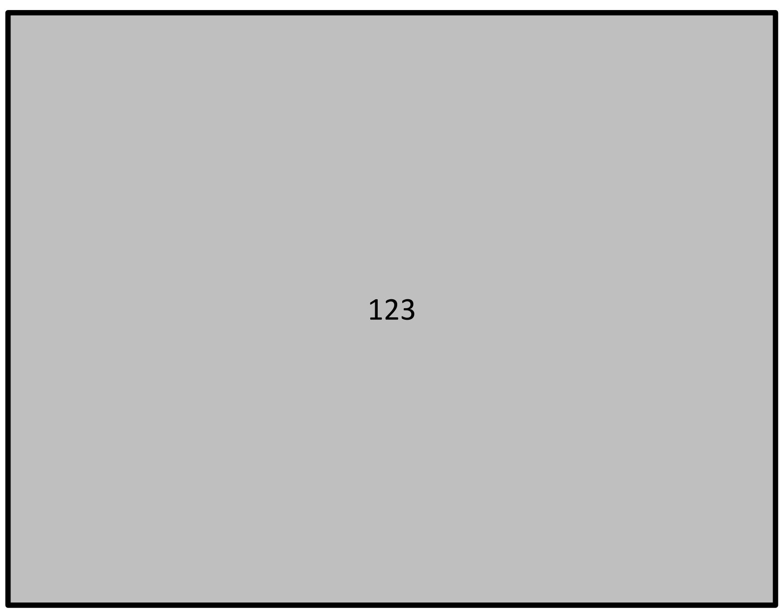


Figure 12: Example of the Display for the Secondary Visual Task

Participants were responsible for responding whenever the number displayed was below or equal to 130 or above or equal to 170. Whenever the participant's failed to respond to one of these critical events the screen would flash briefly between presenting the next number, indicating to the participant that they had missed a response. This was done to ensure that participants were focused on the visual task and that the workload manipulation would be effective. The numbers presented were randomly selected between 100 and 199. However, no more than two sequential number presentations could require the same response (e.g., after two numbers which required no response, the next number would require a response). No other feedback was given to the participant for other responses (correct detections, correct rejections, false alarms).

4.3.4 Procedure

The experiment consisted of a single 1.5 hour session where the participant was run through all three of the workload conditions. Before beginning the experimental tasks, participants were given an information sheet that described the purpose and procedures for the experiment. Afterwards, participants were given a consent form and asked to fill it in. If they agreed to participate in the experiment, they were asked to remove wristwatches and other wrist jewellery as well as turning off any cell phones or other personal communication devices.

Each participant was given a training session to familiarize the participant with the experiment stimuli and the experimental tasks. The training session consisted of a tactile and auditory familiarization activity where the participant was allowed to hear and feel the different auditory rates. Participants were allowed to repeat all of the stimuli as often as they required. Following this, the participant was instructed to run through a practice block of the temporal synchrony task without the visual task, and then the visual task without the temporal synchrony task. If the participant felt that they needed additional practice, they were allowed to repeat any of the training activities.

After completing the practice session, the participants began the experimental tasks. In the temporal synchrony task, participants monitored both the auditory and tactile streams for occurrence of cross-modal temporal rate synchronies. When the participant identified one of these synchrony events, they responded by hitting a button with their left hand. In the visual task, participants were asked to monitor the magnitude of a number visually displayed on the screen. Participants performed this visual task in addition to monitoring for temporal rate synchronies. The participant was required to respond to the visual task whenever the number displayed was below or equal to 130 or above or equal to 170. They accomplished this by hitting a button with their right hand. Participants were asked to fill out the questionnaire at the end of each experimental block and they were given a short break before continuing with the experiment.

4.4 Data Analysis Techniques

During the experiment, each of the rate units for the temporal synchrony task was logged; this included information about the rate of the tactile and auditory stimuli, and if a temporal rate synchrony event had occurred. The participant's response and its correctness, based on the current stimuli presented, were also recorded. In the visual task, each number presented was logged, along with any responses by the participant.

Two large corrections were made to the data during the data analysis process. The first correction was made after an initial analysis based on the rate type factor. The analysis showed that participants had extremely low performance in the tactile 5-beat rate condition. Further investigation showed that the experimental software did not present the tactile 5-beat rate condition correctly during the experiment. Thus, all rate units containing a tactile 5-beat rate condition were removed from the analysis, and the 5-beat rate condition was removed from analysis. This reduced the total number of temporal rate synchrony events to 40 per scenario and also changed the number of valid rate units in each scenario. The number of rate units removed from each scenario varied due to the random nature of the scenarios, but all analysis was adjusted for this correction.

The second correction occurred when many participants reported that they responded after the stimuli were presented. Subsequent analysis revealed that many of the responses during the temporal synchrony task actually occurred after the two second stimuli-presentation window. An adjustment was applied to the temporal synchrony task results; responses that occurred during the first 0.75 seconds of a stimuli presentation are attributed to the previous stimuli presentation. The delays in responses may be attributed to the lack of distinguishable breaks between the presentations of different rate units. No adjustment was made for the visual task.

All post-hoc comparisons were done using a Bonferroni correction and the p-values reported for the post-hoc tests are taken from SPSS's Bonferroni adjusted p-values, unless otherwise stated. All error bars in the following graphs represent 95% confidence intervals.

4.5 Results

4.5.1 Temporal Synchrony Task

4.5.1.1 Workload

Across all conditions, the mean hit rate (the number of correct detections of temporal rate synchronies divided by the total number of targets present in the scenario) was 0.441 with a standard deviation of 0.175. A one-way repeated measures ANOVA was conducted with workload (high vs. low vs. no visual task) as the independent factor. This revealed that the hit rate differed significantly between the different levels of workload, $F(2,46)=9.074$, $p<.001$ (Figure 13). Post-hoc tests showed that the no visual task workload condition ($M=.488$, $SD=0.168$) produced higher hit rates than the high workload condition ($M=.395$, $SD=0.183$), $p=.002$. The low workload condition ($M=.441$, $SD=0.169$) did not differ significantly from the no visual task ($p=.144$, *ns*) conditions, and was only marginally different from the high workload ($p=.069$). The hit-rates were low (0.395 for the high workload condition, 0.441 for the low workload condition, and 0.488 for the no workload condition), which represented performance below chance performance (50% - participants randomly guessing whether a rate unit is a synchrony event). However, it is important to note that the majority of the stimuli that were presented to the participants were of non-synchrony events, and only ~16% of the events encountered were synchronous.

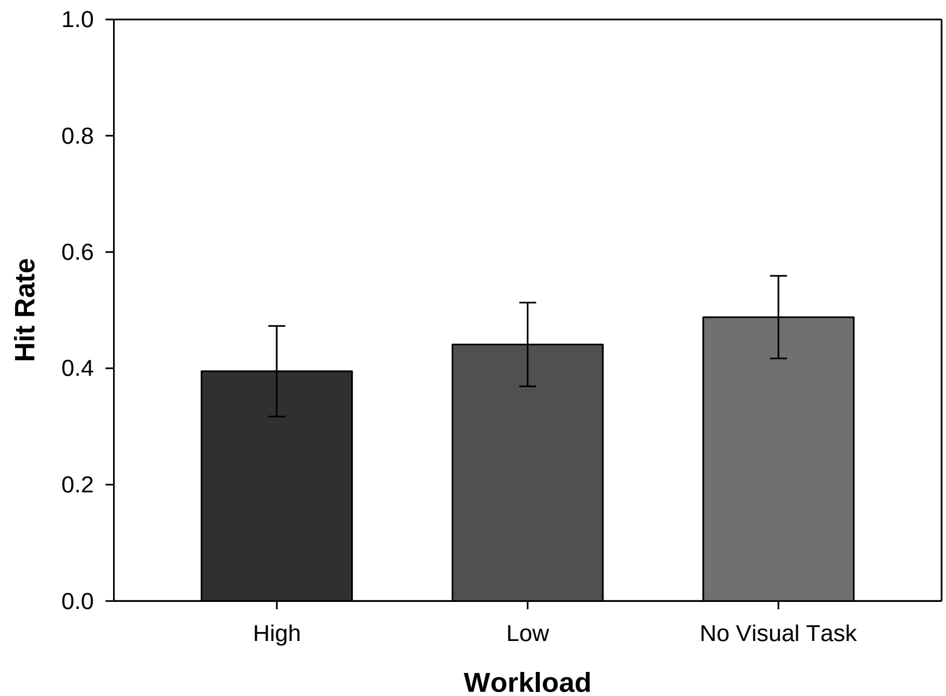


Figure 13: Hit Rate for Temporal Synchrony Task

The false alarm rate, a measure indicating how likely a participant was incorrectly indicating that a synchrony event had occurred when there was no event present, was also subjected to a similar analysis using a one-way repeated measures ANOVA. This analysis did not reveal any significant difference between the high workload (*M* = .068, *SD*= 0.046), low workload (*M*=.056, *SD*=0.045), and no visual task (*M*=.060, *SD*=0.039) conditions for the false alarm rate, $F(2,46)=2.338$, $p>.05$, *ns*. The mean false alarm rate across all conditions was 0.061 with a standard deviation of 0.043. In an average scenario, a false alarm rate of 0.061 would result in 12.2 incorrect responses from the participant while a hit rate of 0.441 would result in 17.6 correct responses.

Signal detection theory was used to further analyze the results of the temporal synchrony task. Signal detection indices for sensitivity (d') and criterion (c) were calculated for each workload condition (high vs. low vs. no visual task). In the temporal synchrony task, sensitivity referred to the ability for the participant discriminate between stimuli with rate synchrony and stimuli that were not synchronous. When the participants had a hit rate or false alarm rate of 1 or 0 a correction of either 1-1/(2N) or 1/(2N) was used, where N was either the total number of temporal synchrony events or total number of non-synchrony events (Macmillan & Creelman, 1991).

A one-way repeated measures ANOVA showed that participant's sensitivity (d') differed between workload conditions, $F(2,46) = 7.913$, $p=.001$ (Figure 14). Post-hoc comparisons revealed that participants performed with lower sensitivity in the high workload condition (M=1.295, SD=0.747) when compared to the no visual task condition (M=1.617, SD=0.662), $p=.009$, and the low workload condition (M=1.555, SD=0.662), $p=.013$. No other comparisons were significant.

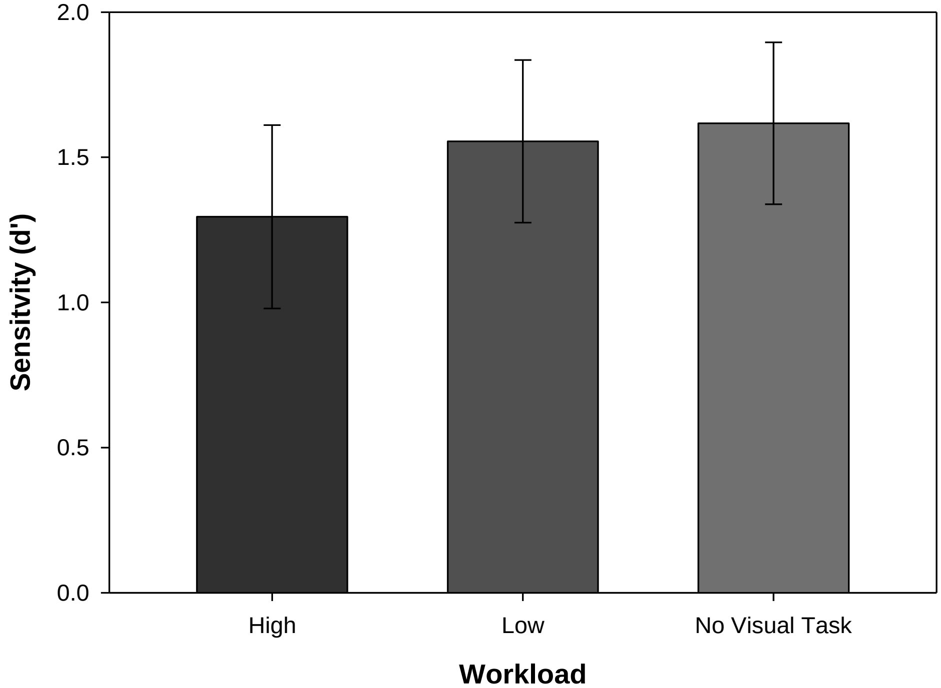


Figure 14: Sensitivity (d') for Temporal Synchrony Task

As was done for sensitivity, a one-way repeated measures ANOVA was conducted for the criterion values. In the temporal synchrony task, criterion referred to the decision bias a participant may have with regards to indicating that a rate unit was a synchrony event. A participant with a conservative decision bias would be much more likely to indicate that a rate unit was not a synchrony event while a participant with a risky decision bias would be much more likely to indicate that a rate unit was a synchrony event. The results showed that the participants' decision criterion differed between workload conditions, $F(2,46)= 5.451$, $p= .008$ (Figure 15). The criterion values for each condition were all less than 0, which meant that participants adopted risky decision biases. However, post-hoc comparisons showed that participants' responses during the high workload condition (M= -.952, SD=.278) used a much riskier decision criterion than the responses during the no visual task condition

(*M*= -.8412, *SD*=.241). The low workload condition (*M*= -.946, *SD*=.305) did not differ from the high workload condition (*p*=1.00, *ns*) and was only marginally different than the no visual task conditions (*p*=.065).

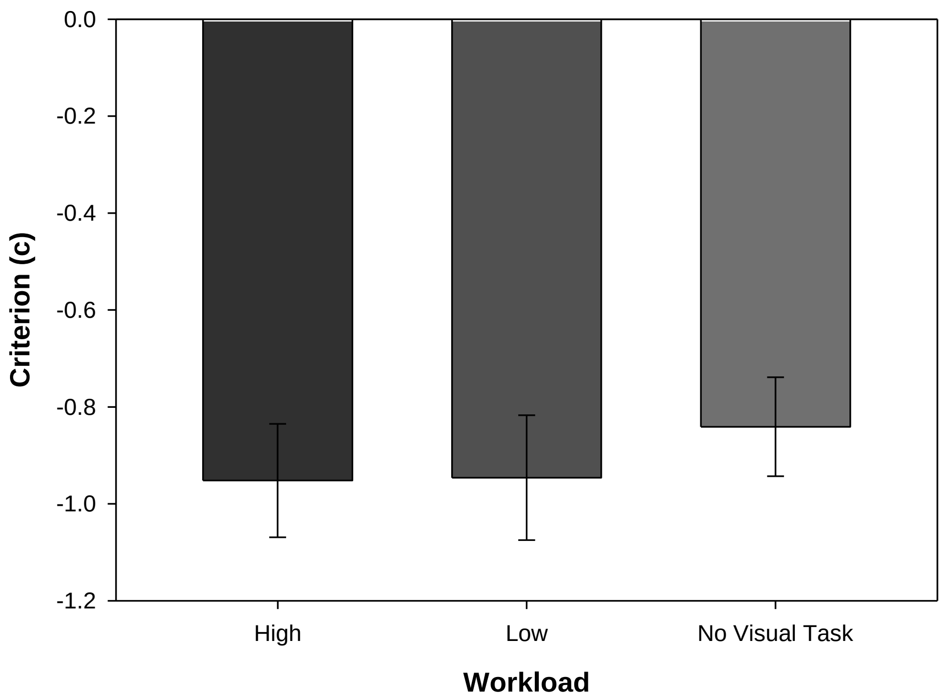


Figure 15: Criterion c for the Temporal Synchrony Event

4.5.1.2 Rate Type

A separate analysis was conducted for the different rates. This analysis was focused on discovering if participants were better able to detect certain rate types. As mentioned previously, all 5-beat rates were removed from the analysis due to an error with the experimental software. Hit rates were calculated for the remaining 4 rate types and are shown in Table 4 and are shown in Figure 16.

Table 4: Hit Rates for Different Rate Types

Rate Type	Mean	Standard Deviation
1-Beat	0.125	0.129
2-Beat	0.472	0.231
3-Beat	0.571	0.221
4-Beat	0.596	0.204

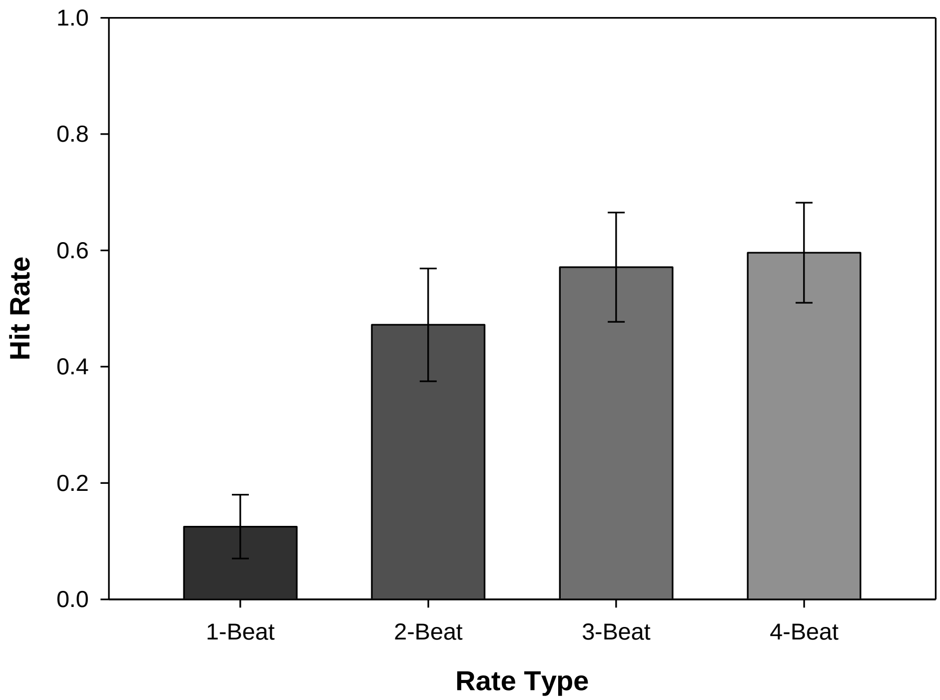


Figure 16: Hit Rate for Different Rate Types

A one-way repeated measures ANOVA was conducted for the hit rate values across the different rate types. The results showed that there was a significant difference in hit rate between the four different rate types, $F(3,69)=61.35$, $p<.001$. Post-hoc analysis showed that the hit rate for the 1-beat rate type differed from each of the other conditions, $p<.001$. In addition, the 2-beat rate type also differed from the 3-beat, $p=.014$, and 4-beat, $p=.005$, conditions. No significant differences were found between the 3-beat and 4-beat conditions, $p=1.00$.

4.5.2 Visual Task

A series of analyses were conducted for performance on the secondary visual task across the different workload conditions. Overall performance was much higher in the visual task for both hit rate (M=0.927, SD=0.109) and false alarm rate (M=0.057, SD=0.035). A paired samples t-test for hit rate revealed that the hit rate for the high workload condition (M=0.887, SD=0.125) was significantly lower than the hit rate for the low workload condition (M=0.966, SD=0.072), $t(23)= -6.125$, $p<.001$. A second paired samples t-test for false alarm rate also found that the high workload condition (M=0.0712, SD=0.028) resulted in more false alarms than the low workload condition (M=0.0432, SD=0.036), $t(23)=3.761$, $p=.001$.

Signal detection analysis was also used to analyze the visual task by calculating sensitivity (d') and criterion (c). A paired samples t-test was conducted to examine the effects of workload on sensitivity (d'). As to be expected, the test revealed that the high workload condition (M=2.820, SD=0.553) reduced the ability of participants to detect the critical visual stimuli (numbers below or equal to 130 or above or equal to 170) when compared to the low workload condition (M=3.796, SD=0.599), $t(23)=-10.555$, $p<.001$. Similarly, a paired samples t-test on the effects of workload on criterion c showed that participants adopted a riskier response bias in the high workload condition (M=-0.085, SD=0.233) than the low workload condition (M=0.097, SD=0.270), $t(23)=-3.917$, $p=.001$.

4.5.3 Questionnaire

At the conclusion of each workload block, participants were asked to complete a questionnaire on a number of different metrics including:

1. their perceived performance on the experimental tasks,
2. the difficulty of the experimental tasks,
3. how distracting they found each of the experimental tasks,

4. which experimental task they focused on, and

5. how well they were able to integrate the stimuli between modalities.

Each question was answered using a 7-point scale, and answers were coded from 0 to 6. Specific anchor points for each question are provided in detail in the following sections. In addition, each participant provided some feedback on their strategies for completing the tasks, and any thoughts they had on the experiment. The questionnaire can be found in Appendix A. The different questionnaire answers were subjected to a series of non-parametric tests; Friedman tests for the questions relating to the temporal synchrony task and Wilcoxon signed-ranked tests for the questions relating to the visual task, unless stated otherwise.

4.5.3.1 Perceived Performance

Each participant was asked to gauge their own performance on both the temporal synchrony task and the visual task. For the temporal synchrony task, they were asked to rate it on a scale from "Extremely Well", which was coded as 0, and "Extremely Poorly", which was coded as 6. IFor the visual task, participants were asked to rate their performance across all three workload conditions (high vs. low vs. no visual task). The results of the Friedman test suggested that participants felt their own performance in the temporal synchrony task differed across the three workload conditions, $\chi^2(2)=9.975$, $p=.007$. Descriptive statistics for the perceived performance in the temporal synchrony task can be found in Table 5. Post-hoc analysis using Wilcoxon signed-ranked tests was conducted with a Bonferroni correction applied with an adjusted significance level of $\alpha=.05/3=.017$. This revealed that participants rated their own performance to be better in the low workload condition (median=3) when compared to the high workload condition (median=3). The no visual task condition (median=2.5) did not differ from any of the other conditions. This performance slightly differed from the actual performance in the temporal synchrony task where participants did better in both the low and no visual task conditions when compared to the high workload condition. This may be partially explained by the fact that the no visual task condition was always first, and participants were better able to gauge their actual performance after additional blocks. Overall, participants felt that they performed adequately, but this was not well reflected in the actual performance data.

Table 5: Perceived Performance on the Temporal Synchrony Task across Workload Conditions

	Mean	Std. Deviation	Percentiles		
			25^{th}	50^{th}	75^{th}
High Workload	3.3333	1.129	3	3	4
Low Workload	2.5833	0.929	2	3	3
No Visual Task	2.6667	1.204	2	2.5	4

Perceived performance in the visual task was also analyzed using a Wilcoxon signed-ranked test. This revealed that participants felt that they performed better in the low workload visual task (median=1) than in the high workload visual task (median=2), Z=-3.012, p=.003.This performance matched the participant’s actual performance in the visual task.

4.5.3.2 Difficulty

Participants were also asked to judge the difficulty of both the temporal synchrony task and the visual task for each of the workload conditions (high vs. low vs. no visual task) using a scale from “extremely easy” (coded as 0) and “extremely difficult” (coded as 6). The results of the Friedman test suggested that the high (median=4), low (median=4), and no visual task (median=4) workload conditions did not significantly change the participant’s judgements of the difficulty of the temporal synchrony task, χ^2 (2)=3.354, p=.187, *ns*. Participants consistently rated the temporal synchrony task as difficult. However, for the visual task, a Wilcoxon signed-ranked test revealed that participants found the high workload condition (median=2) more difficult than the low workload condition (median=1), *Z*= -3.132, *p*=.002. This showed that the workload manipulation using the visual task worked in its intended direction, but participants still found the task easy.

4.5.3.3 Distraction

Participants were asked how distracting each of the experimental tasks was across the different workload conditions (high vs. low) using a scale coded from “not distracting” (coded as 0) and “extremely distracting” (coded as 6). Distraction was not a relevant question in the no visual task condition. In the temporal synchrony task, a Wilcoxon signed-ranked test revealed that there were no significant differences between the high workload condition (median=4) and the low workload condition (median=4), *Z*= -.873, *p*=.382, *ns*. In both of the workload conditions with a secondary task, participants found the temporal synchrony task to be distracting, but the level of distraction did not change due to the manipulation of the speed of the visual task. However, as expected with the visual task, a Wilcoxon signed-ranked test showed that the visual task in the high workload condition (median=4) was reported as being more distracting that the visual task in the low workload condition (median=2), *Z*=-3.685, *p*<.001.

4.5.3.4 Focus and Effort

In order to discover how participants were focusing their attention during the experiment and examine how they were sharing the workload, each participant was asked about the amount of effort they applied to the two different tasks, with a scale that ranged from “Exclusively focused on Visual task” (coded as 0) to “Exclusively focused on Synchrony task” (coded as 6). This was not a relevant question in the no visual task condition. A Wilcoxon signed-ranked test showed that participants in the high workload condition reported greater focus on the visual task (median= 2) then in the low workload condition (median= 4) where more effort was applied on the synchrony task, Z= -3.502, p<.001.

4.5.3.5 Integration

Two questions were asked about the temporal synchrony tasks that were related to how well the participant was able to integrate the information between the tactile and auditory streams. The first question referred to how "together or unified" the auditory and tactile streams were. If the auditory and tactile streams felt like they were coming from different sources than they would not have a feeling of "togetherness". On the other hand, if participants felt like they interpreted both streams as one single signal then it would be counted as "together and unified". Participants were asked to rate this question on a scale between "Extremely discrete" (coded as 0) and "Extremely together" (coded as 6). Descriptive statistics for the togetherness are shown in Table 6. Overall, participants seemed to perceive the auditory and tactile streams as two discrete sources of information.

Table 6: Degree of "Togetherness" across Workload Conditions

	Mean	Std. Deviation	Percentiles		
			25th	50th	75th
High Workload	2.208	1.062	1	1	3
Low Workload	2.708	0.999	2	3	3.75
No Visual Task	2.292	1.197	1	2	3.75

The participant's ratings for togetherness were compared across the three workload conditions using the Friedman test. The results suggested that participants felt that the "togetherness" of the auditory and tactile streams differed based on the workload of the visual task (high vs. low vs. no visual task), χ^2 (2)=10.308, *p*=.006. Post-hoc analysis using Wilcoxon signed-ranked tests was conducted with a Bonferroni correction applied with an adjusted significance level of α=.05/3=.017. A significant difference was found between the high workload (median= 2) and low workload (median= 3) conditions, *Z*=-3.00, *p*=.003. All other comparisons were not significant, *p*>.017. Participants found that the auditory and tactile streams seemed more discrete in the high workload condition when compared to the low workload condition. Surprisingly, the no visual task condition did not significantly differ from the high or low workload conditions, though this may partly be because the no visual task condition was always first, and the participants' scale of togetherness was refined over the subsequent trials.

The second integration question asked the degree that an auditory-tactile rate synchrony event seemed like a single perceptual event. This was rated on a scale between "Completely" (coded as 0) and "Not at all" (coded as 6). Descriptive statistics for this rating are shown in Table 7. The Friedman test was used to compare the ratings across the three workload conditions (high vs. low vs. no visual task), and no significant differences were found, χ^2(2)=2.492, *p*=.288, *ns*.

Table 7: Rating of "Perceptual Event" across Workload Conditions

	Mean	**Std. Deviation**	**Percentiles**		
			25th	**50th**	**75th**
High Workload	3.083	1.586	2	3.5	4
Low Workload	2.791	1.318	2	3	4
No Visual Task	2.958	1.781	2	3.5	4

4.5.3.6 Strategies

Many of the participants also mentioned that they found the temporal synchrony task very difficult in all conditions, and stated that it was a task that required a large degree of concentration, attention, and effort. With the addition of the visual task, most participants reported that they made use of a task switching strategy where they would attempt to finish off one task (such as the visual task) before switching their attention to the other task. This was much easier to accomplish in the low workload condition then in the high workload condition where both the visual and tactile-auditory stimuli switched at two second intervals.

4.6 Discussion

4.6.1 Temporal Synchrony Judgements and Use in Monitoring Tasks

The temporal rate synchrony task in this experiment was created to replicate a situation where an operator is responsible for monitoring two separate data variables (mapped onto auditory and tactile rates) for instances where the relationship between the two data variables satisfy some condition (which was represented as a temporal rate synchrony event). Participants were not provided any context information about the task, and were only asked to respond to perceptual stimuli whenever rate synchronies occurred.

Performance in the temporal synchrony task was relatively poor across all three workload conditions. On average, less than half of the temporal rate synchrony events presented in each scenario were detected by participants. If interface designers were to use temporal rate synchrony as a method for showing events or information in an interface, it would be important to provide redundant information to increase the chances of detecting the critical events.

Participants did indicate that they perceived the auditory and tactile streams as two separate channels of information instead of a single signal. This indicated that the auditory and tactile rate monitoring scenario was a plausible method for showing two data variables. However, participants did not find that the temporal rate synchrony events appeared as a single perceptual event. Thus, a "pop-out" effect did not occur, instead participants needed to devote a large amount of their attentional resources to detecting the synchrony events, a fact that was reported in the strategies section of the questionnaire.

Participants were also less accurate with judgements about the synchrony events with slow rates (1-beat and 2-beat). On average, only 12.5% of the 1-beat synchrony events were correctly detected. The 2-beat synchrony event fared better at 47% correct detection, but this performance was still 10% worse than the 3-beat and 4-beat events. Participants were not explicitly told when the 2-second rate units started and ended, and due to how the beats were arranged the first beat in every rate unit were synchronous. Thus, the optimal strategy for detecting when the rates were the same was to respond whenever two consecutive beats are in synch. This task is much easier with the faster rate types than it is for the 1-beat synchrony event where there is a 2 second break between consecutive beats.

4.6.2 Resistance to Workload Changes

In this experiment, participants were asked to monitor auditory and tactile streams for temporal rate synchrony events while completing a secondary visual monitoring task that changed in difficulty depending on the workload condition. As stated before, one possible metric for a useful crossmodal relationship is that performance at detecting the relationship is resistant to changes to workload. It was hypothesized that temporal rate synchrony would be easy to perceive under no secondary task, low workload, and high workload conditions.

However, the results of the temporal synchrony task suggest that participants were affected by the secondary visual task. During the high workload condition, participants' performance was much lower than the no visual task condition for both hit rate and sensitivity. In addition, participants in the low workload condition were much more sensitive to the temporal synchrony events than in the high workload condition and the differences between the low and high workload conditions for hit rate were approaching significance.

Participants were well aware of their own performance during the experiment. Participants rated their own performance as average or slightly above average in the different workload conditions, and the felt that they performed better in the low workload condition than in the high workload condition. These ratings of perceived performance matched relatively closely with the participants' actual performance in terms of sensitivity, and reinforce the fact that there were performance differences between the different workload conditions.

While there were strong differences between the high workload condition and then other two workload conditions (low workload and no visual task), surprisingly, the differences between the low workload condition and the no visual task condition were not evident. This suggests that it was not solely the addition of a secondary task that led to a decrease in performance; instead it was largely dependent on the workload. The addition of the secondary task did, however, change how participants made judgements on whether a rate unit was considered synchronous. The participants' criterions were similar between the two visual task workload conditions; they were much more likely to designate rate units as being synchronous because of a riskier decision bias.

In the visual task, under the high workload condition, participants had a lower percentage of correctly detected targets. Participants were also less able to detect the critical visual events, and they were riskier with their target designations, allowing for more false-alarms. This suggests that participants may have been partially compensating for the higher workload by spending less time on the visual task. This may have mitigated some of the detrimental effects of workload on the temporal synchrony task. Thus, the actual differences between performance on high and low workload conditions in the temporal synchrony task may be even larger if the amount of effort spent on the visual task was kept constant. Participants were not given any instructions about which of the two tasks (temporal synchrony vs. visual task) that they should prioritize during the experiment.

There are a number of reasons why performance on the temporal synchrony task may have been impacted by workload. Firstly, in this study, we asked participants to monitor for temporal rate information which was displayed over a 2 second interval. The length of the perceptual "units" may have made this task much more difficult by forcing the participants to make use of working memory. Many of the participants found the sustained attention and working memory required by the experimental task to be very fatiguing. By simplifying the detection task to a matching auditory and tactile onset and duration, participants may be able to make the synchrony judgements with less effort. This may in turn lead to performance that would be resistant to changes in workload.

Secondly, Multiple Resource Theory suggests that the same pool of resources is used for perceptual and cognitive tasks (Wickens & McCarley, 2008). Thus, the temporal synchrony task, which was presumed to be a highly perceptual task, and the visual task, which required participants to use working memory to make judgements about numbers, would draw from the same pool of resources even though the information was presented in different modalities. The fact that the temporal synchrony task may also have drawn heavily on working memory only increases the amount of interference between the two tasks.

Thirdly, both tasks required manual responses from the participants, responding using their left hand for the temporal synchrony task and their right hand for the visual task. Even if judgements of temporal synchrony was resistant to changes in workload, participants may have experienced interference between the two tasks at the response selection stage which draws from the same pool of resources (Wickens & McCarley, 2008). Thompson, Tear, and Sanderson (2010) examined differences between responding using mental count (a larger load on working memory) and a physical clicker (greater motor demand) in a study on multisensory integration while walking. Their results suggested that participants did worse on their primary multisensory task when using the clicker than when responding using a mental count, which was contrary to their original hypothesis. One possible explanation was that using the physical clicker might have interacted with a secondary button-press task, and increased the workload of the tasks overall. A similar effect may have forced participants to direct attention away from the temporal synchrony task more often in the high workload task due to an increased number of manual responses required.

4.7 Summary

Overall, it is evident that participants were unable to perform both the temporal synchrony task and the visual task concurrently and a bottleneck existed which prevented the participants from performing well on the task across different workload conditions. Reducing the amount of working memory required for the temporal synchrony task by simplifying it to detections of synchrony onset and duration may still prove that individuals are able to intuitively able to parse and group stimuli in different modalities together with low cognitive load.

The results of the first experiment did not find evidence that crossmodal temporal rate synchrony was a perceptual relationship that was resistant to changes in workload. Thus, it did not satisfy the first metric proposed to evaluate a perceptual relationship's effectiveness. However, this study did not examine the participant's ability to monitor information presented to each modality, a characteristic of the second metric proposed. Experiment 2, which is described in the following chapter, examines the second metric, awareness in stream monitoring, across unimodal and multimodal displays.

Chapter 5

Experiment II – Temporal Synchrony Performance across different Displays

This chapter describes the second experiment that examines temporal rate synchrony detection across unimodal and multimodal displays. All materials related to the study are included in Appendix B.

In the previous experiment, participants' ability to detect temporal synchrony in a crossmodal monitoring task was evaluated under the effects of different workload manipulations. The results suggested that participants found detecting crossmodal temporal synchrony judgements very difficult, and their performance decreased in the higher workload conditions. One drawback for the previous experiment was that participants were not provided a context for the monitoring task; their instructions only asked them to monitor for perceptual events without providing a mental model for the variables that they were supposed to be monitoring. In order to test whether the lack of context had a large effect, a second experiment made use of a plane refuelling scenario where the participant's goal will be to monitor for occasions when the speed of their plane and the speed of the refuelling plane are the same.

By providing additional context to the monitoring task it becomes possible to examine how well participants are able to monitor the individual streams of information while making crossmodal temporal rate synchrony judgements. One possible advantage of multimodal interfaces is that they make it easier for operators to monitor two separate variables than an equivalent unimodal interface. Multiple resource theory (Wickens & McCarley, 2008), suggests that by using different sensory modalities to present information participants are better able perform the two tasks concurrently. When two variables are presented within a single modality, there may be interference effects that may introduce confusion or delayed response times (Sanderson, Anderson, & Watson, 2000). Thus, temporal rate synchrony judgements may be an appropriate method of linking information across different modalities because it allows for better monitoring of individual channels of information.

5.1 Objectives

The objective of this second study was to examine how well participants are able to monitor different streams of related information when they are presented within a single sensory modality and when they are presented between two different sensory modalities and joined using a crossmodal temporal synchrony relationship. This study examined three different interfaces: two unimodal interfaces (a tactile interface and an auditory interface) and a multimodal tactile and auditory interface. If performance in monitoring the individual channels of information is better in the multimodal display condition than the unimodal display conditions, then there would be some evidence that crossmodal temporal rate synchrony improves stream monitoring performance over unimodal displays.

To examine this research question, participants were asked to make rate synchrony judgements across three different interfaces: an auditory only interface, a tactile only interface, and a crossmodal interface consisting of auditory and tactile stimuli. The following were hypothesized:

- Performance on the rate synchrony events will be better in the unimodal interface conditions than the multimodal interface condition. However,

- Awareness and monitoring performance of the individual channels would be higher in the multimodal interface condition than the unimodal interface conditions.

5.2 Experimental Design

The experiment used a single factor design with display type (auditory only vs. tactile only vs. multimodal) as the independent variable. Participants were asked to monitor two different streams of information, presented within the same modality in unimodal conditions and with one stream of information in each modality (auditory and tactile) for the multimodal condition. Participants were responsible for three different tasks during this monitoring situation. Firstly, participants were asked to respond when the information presented in both information streams was perceived to have synchronous rates. The rate synchrony represented a situation when the two planes (the refuelling plane and the participant's plane) were travelling at the same speed and were able to refuel. Secondly, participants were also required to monitor the two streams to determine which plane was faster. Participants were asked to indicate whether their plane was required to speed up or slow down to match the speed of the refuelling plane. Finally, occasionally the experiment would pause and participants were asked to answer situation awareness questions about the current refuelling scenario.

The experiment was divided into 6 blocks, two for each of the display conditions. This was done because participants in the first experiment reported that the 10 minute blocks were too long and the sustained attention required by the temporal synchrony task was fatiguing. The order of the display blocks and scenarios were counter balanced to control for learning effects. The first three blocks contained each of the three display types, and the second three blocks repeated this order. Each block was 5 minutes in length and participants were given a break between each of the blocks to reduce the risk of fatigue and the effect of adaption and habituation to the stimuli.

The dependent variables were the percentage of hits, misses, false alarms, correct rejections and response times for the temporal rate synchrony task, accuracy in a stream monitoring task, and accuracy in answer situation awareness questions. In addition, participants were given a questionnaire at the end of each block to gauge their perceived performance, awareness, and the degree of distraction caused by the different stimuli.

5.3 Methodology

5.3.1 Participants

A total of thirteen undergraduate and graduate students from the University of Waterloo were recruited through e-mail and posters for this study. All participants had self reported normal or corrected-to-normal vision and normal or corrected-to-normal hearing. One of the participant's data was excluded from the subsequent analysis due to low performance in the temporal rate synchrony task (very low hit rates in each of the three display conditions). The remaining twelve data sets were analyzed for this experiment. All participants were compensated $20 for their time.

5.3.2 Apparatus

The experiment occurred in a normal office environment, with lights dimmed and ambient noise kept to a minimum. Participants were seated in front of a Dell 20 inch liquid crystal display monitor that displayed information about the plane refuelling task and instructions for the experiment. Auditory output was generated using a Tucker Davis Technology System 3 real-time digital signal processing system and saved as WAV files on the experiment computer. The auditory stimuli were presented through bi-aural headphones. Similar to the first experiment, tactile stimuli were presented through two Engineering Acoustics Inc. C2 tactors secured onto the outsides of the wrists of the participants using double sided tape and were driven by the custom built tactor controller. The experimental software was also created using the open-source PsychoPy framework (Pierce, 2007).

The participants were provided with a keyboard with three clearly marked buttons for responses. One of the buttons (space bar) was used to respond to the temporal rate synchrony task (the refuelling event detection) and two of the buttons were used to indicate whether the participant's plane was supposed to speed up or slow down to match the speed of the refuelling plane (up and down arrow keys).

5.3.3 Stimuli

Auditory and tactile stimuli of varying temporal rhythms were used as the stimuli for the plane refuelling task. The auditory stimuli consisted of 200 and 400 Hz pure tones played from a set of headphones which were repeated at 8 different temporal rates. The tactile stimuli consisted of a set of EAI C2 tactors secured onto the outsides of the wrists of the participants which vibrated at 250 Hz and were repeated at 8 different temporal rates at moderate intensities.

As in the first experiment, temporal rate units were 2 second in length, and the rate of the signal was varied by changing the number of "beats" (when the auditory or tactile signal is turned on) in the rate unit. Each beat was of equal length, and was on for 0.1 seconds. This differed from the first experiment where each beat was on for 0.3 seconds. In experiment 1, 5 different temporal rate levels were used and participants had trouble with the low rate temporal rate conditions. In this experiment, 8 different temporal rates were used, the slowest of which was 3 beats. The fastest rate contained 10 beats within the 2 second unit, with separations of 0.1 seconds between the onsets of each beat. The other rates consisted of 9, 8, 7, 6, 5, 4, and 3 beats distributed evenly within the 2 second unit. An example of a 5-beat rate unit is shown in Figure 17. Beat onsets for each condition are listed in Table 8.

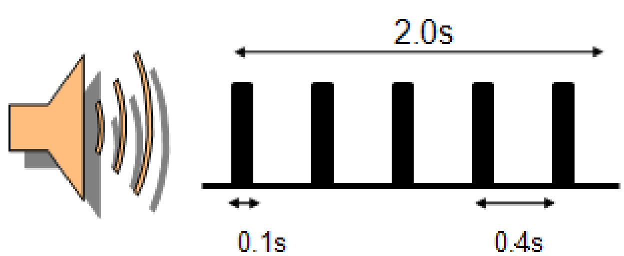


Figure 17: Example of a 5 Beat Temporal Rate Condition for Experiment 2

Table 8: Beat Onsets for Temporal Rate Conditions for Experiment 2

Condition	Beat Onsets
10	0s, 0.2s, 0.4s, 0.6s, 0.8s, 1.0s, 1.2s, 1.4s, 1.6s, 1.8s
9	0s, 0.22s, 0.44s, 0.67s, 0.89s, 1.11s, 1.33s, 1.55s, 1.77s,
8	0s, 0.25s, 0.5s, 0.75s, 1.0s, 1.25s, 1.5s, 1.75s
7	0s, 0.29s, 0.57s, 0.86s, 1.14s, 1.43s, 1.71s
6	0s, 0.33s, 0.67s, 1.0s, 1.33s, 1.67s
5	0s, 0.4s, 0.8s, 1.2s, 1.6s
4	0s, 0.5s, 1.0s, 1.5s
3	0s, 0.67s, 1.33s

The individual temporal rate units were combined into longer auditory and tactile “streams” which represent a stream of data that the participant was required to monitor. In this experiment, each of these rates represented the velocity of either the participant’s plane or a refuelling plane, with faster temporal rates representing faster velocity and slower temporal rates representing slower velocity. Thus, each of the streams of information represented the velocity of one of the aircraft over that two second period which would continuously change as the two aircraft attempt to refuel midflight. In each stream, consecutive rate units would either stay at the same speed or increase or decrease by 1 rate. This was done to simulate a plane staying at the same speed, speeding up, or slowing down.

These streams were generated into scenarios which contained temporal rate synchrony events when the rates in both the information streams are the same, as shown in Figure 18. In the auditory unimodal condition, each of the data streams were represented by pulses of different pitches (either

200 Hz or 400 Hz). The 200 Hz signal represented the refuelling plane and as presented to the left ear while the 400 Hz signal represented the participant's plane and was presented to the right ear. In the tactile unimodal condition, both tactors vibrated at 250 Hz. The refuelling plane was presented by the tactor on the participant's left wrist, while the participant's plane was presented through the tactor on the right wrist. In the multimodal condition, the auditory stimuli consisted of pulses of 200 Hz presented to both ears which represented the participant's plane, and the tactile stimuli consisted of pulses of 250 Hz presented to both tactors which represented the refuelling plane.

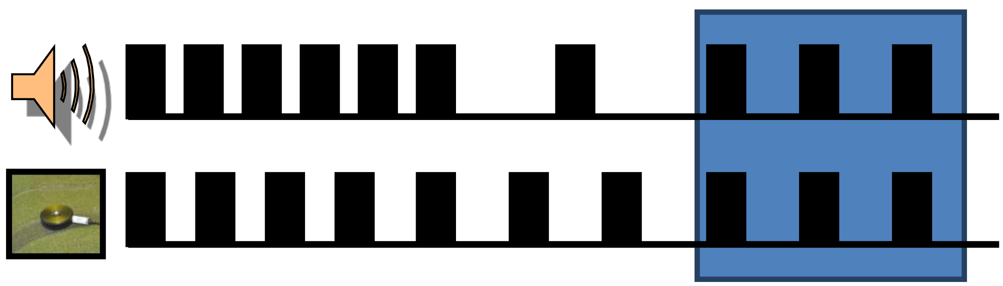


Figure 18: Temporal Rate Synchrony Event

Seven 5 minute scenarios were pre-generated, each containing 2 temporal rate synchrony events for each of the 8 rates. The 16 synchrony events represented opportunities for the two planes to refuel. The synchrony events accounted for roughly 11% of the scenario. One of the 5 minute scenarios was broken into three smaller sections and used for training purposes.

An example of the visual display is shown in Figure 19. The visual display showed information about the current display type including a reminder of which signal represented the participant's plane and which signal represented the refuelling plane. The visual display also showed whether the participant had indicated that their plane should speed up or slow down to match the speed of the refuelling plane (the real-time speed monitoring task). If the participant had not yet responded to the real-time monitoring task then the bottom of the screen would be blank.

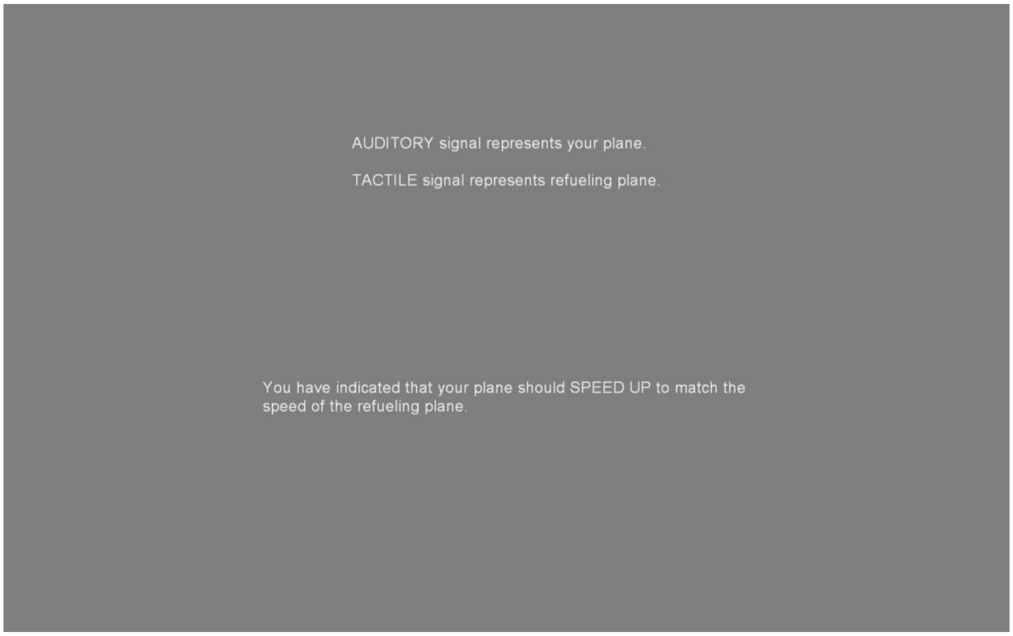
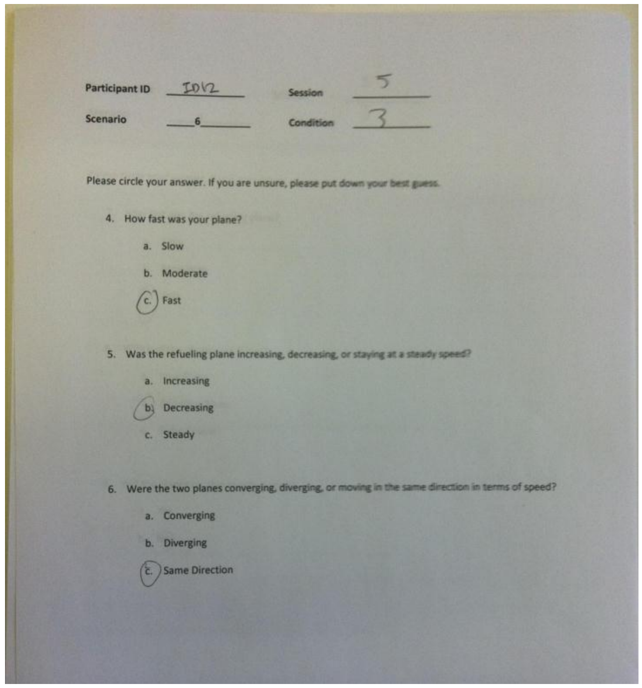


Figure 19: Visual Display for the Plane Refuelling and Real Time Speed Monitoring Task

During each of the scenarios, the scenario would pause and participants were asked questions about the current state of the aircraft. These situation awareness pauses were presented on paper in the form of written questionnaires. Each page of the situation awareness questionnaire presented three questions and participants were asked to answer one page for each pause. An example of the situation awareness questionnaire can be seen in Figure 20. Participants were responsible for answering the questions before resuming the experiment.



Participant ID ID12 Session 5

Scenario 6 Condition 3

Please circle your answer. If you are unsure, please put down your best guess.

4. How fast was your plane?
   a. Slow
   b. Moderate
   c. Fast

5. Was the refueling plane increasing, decreasing, or staying at a steady speed?
   a. Increasing
   b. Decreasing
   c. Steady

6. Were the two planes converging, diverging, or moving in the same direction in terms of speed?
   a. Converging
   b. Diverging
   c. Same Direction

Figure 20: Situation Awareness Questionnaire

5.3.4 Procedure

The experiment consisted of a single 1.5 hour session where the participant was run through all six blocks. Before beginning the experimental tasks, participants were given an information sheet which described the purpose and procedures for the experiment. Afterwards, participants were given a consent form and asked to fill it in. If they agreed to participate in the experiment, they were asked to remove wristwatches and other wrist jewellery as well as turning off any cell phones or other personal communication devices.

Each participant was given a training session to familiarize the participant with the experiment stimuli and the experimental tasks. The training session consisted of a tactile and auditory familiarization activity where the participant was allowed to hear and feel the different rates and the different display types. The training session also introduced the participant to the context of the experiment, and described the different types of synchrony events that could occur. Additionally, participants were introduced to rates that represented slow (3-4 beats), medium (5-7 beats), or fast (8-10 beats) velocities and rate-mismatch situations. Participants were also told which signal would represent their plane and which signal would represent the refuelling plane in each of the display types.

After the familiarization, participants were given three practice scenarios, one for each of the display types (auditory vs. tactile vs. multimodal). The practice scenarios were $1/3^{rd}$ of the length of a regular scenario and each contained exactly one situation awareness pause. The order of the practice scenarios were always the same. Participants were always given the auditory, tactile, and then the multimodal display. Participants were allowed to repeat any of the familiarization or practice activities before continuing with the experimental task.

Participants were responsible for three tasks during the main experimental phase of the study: a refuelling opportunity monitoring task (temporal rate synchrony matching), a real-time speed monitoring task, and a situation awareness task. In the refuelling opportunity monitoring task, participants monitored both of the information streams for occurrences of temporal rate synchronies. These synchrony events occurred within a modality or between modalities, depending on the display condition. The synchrony events represented times when the velocity of the refuelling plane and the participant's plane were the same and that refuelling was possible. When the participant identified one of these refuelling opportunities they were asked to respond using the keyboard as quickly and as accurately as possible. Participants were not told how many synchrony events were in the scenarios and no feedback on accuracy was provided.

The real-time speed monitoring task and the situation awareness task were both used to gauge how well participants were monitoring the two streams of information. In the real-time speed monitoring task, participants were asked to constantly monitor the speeds of both planes and make judgements about which plane was faster. Whenever the participant's plane was slower than the refuelling plane, participants were asked to hit the up-arrow key to indicate that their plane should speed up to match the speed of the refuelling plane. Similarly, whenever the participant's plane was faster than the refuelling plane, participants were asked to hit the down-arrow key to indicate that their plane should slow down. The responses to the real-time monitoring task had no effect on the actual speeds of the two planes. A secondary purpose of the task was to ensure that participants were not solely focused on the refuelling opportunity task.

In the situation awareness task, participants were required to respond to situation awareness questions during each of the scenarios. If the participants were able to easily monitor both streams concurrently, then their awareness of the current state of the aircraft, their understanding of the situation, and their ability to predict the future status of the refuelling scenario would be more accurate. The situation awareness questions were divided into three categories based on Endsley's (2003) levels of situation awareness. Level 1 situation awareness questions deal with the participant's perception of the interface, level 2 questions deal with the participant's comprehension of the situation, and level 3 questions are related to the participant's ability to project future states of the system. At pre-specified times during the scenarios, the simulation would be paused and questions about the current state of the aircraft and possible future states were asked. Participants were required to respond to these questions before continuing with the scenarios. Each scenario contained three situation awareness pauses, and each pause contained a question from each SA level. The situation awareness questions are shown below:

SA Level 1:

How fast your plane? (Slow, Moderate, Fast)

How fast was the refuelling plane? (Slow, Moderate, Fast)

In the last 4 seconds was there a refuelling opportunity? (Yes, No)

SA Level 2:

Which of the planes was faster? (Your Plane, Refuelling Plane, Same Speed)

Was your plane increasing, decreasing, or staying at a steady speed? (Increasing, Decreasing, Steady)

Was the refuelling plane increasing, decreasing, or staying at a steady speed? (Increasing, Decreasing, Steady)

SA Level 3:

Were the two planes converging, diverging, or moving in the same direction in terms of speed? (Converging, diverging, Same Direction)

Will the planes be able to refuel soon? (Yes, No)

Which of the planes will probably be faster in 6 seconds? (Your Plane, Refuelling Plane, Same Speed)

After the completion of each experimental block, participants were given a short break where they were required to remove the headphones and tactors. This was done to reduce the adaptation and habituation to the auditory and tactile stimuli. During this break, participants filled out a short questionnaire about their perceived performance, awareness, and the degree of distraction caused by the different stimuli.

5.4 Data Analysis Techniques

Data collection in the second experiment was very similar to the first experiment. Each of the rate units from the scenario were logged with information about the rates of the two streams and if the rates were synchronous. The participant's responses to the refuelling opportunity task (both the accuracy and the response time) and the real-time speed monitoring task were also recorded. Answers to the situation awareness task and the questionnaires were also collected for each block. As in the first experiment, a correction was made to adjust for responses that occurred after the end of a synchronous rate unit. Responses that occurred during the first 0.75 seconds of a rate unit that occurred after a synchrony event were attributed to the synchrony event.

To increase the reliability of the various dependent variables, each of the display conditions (auditory only vs. tactile only vs. multimodal) were repeated. This was important because the situation awareness questions were only presented at three discrete points during each scenario, and performance on these questions may be heavily impacted by a brief lapse in attention. All dependent variables were averaged across the two blocks for each condition and the subsequent analysis used the average values for each display condition.

All post-hoc comparisons were done using a Bonferroni correction and the p-values reported for the post-hoc tests were taken from SPSS's Bonferroni adjusted p-values unless otherwise stated. All error bars in the following graphs represent 95% confidence intervals.

5.5 Results

5.5.1 Refuelling Opportunity Monitoring Task

The refuelling opportunity monitoring task was very similar to the temporal rate synchrony task in experiment 1. Participants were required to monitor both streams for occasions when the rates were synchronous. However, in this experiment the streams could either be within the same modality or in two different modalities. A one-way repeated measures ANOVA was conducted with display type (auditory only vs. tactile only vs. multimodal) as the independent factor. The Mauchly's test indicated that the assumption of sphericity had been violated ($\chi^2 = 9.226$, $p<.05$). Therefore, the degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity (epsilon = 0.624). The results of the ANOVA showed that the different display conditions had an impact on hit rate $F(1.25,13.73) = 39.92$, $p<.001$ (Figure 21).

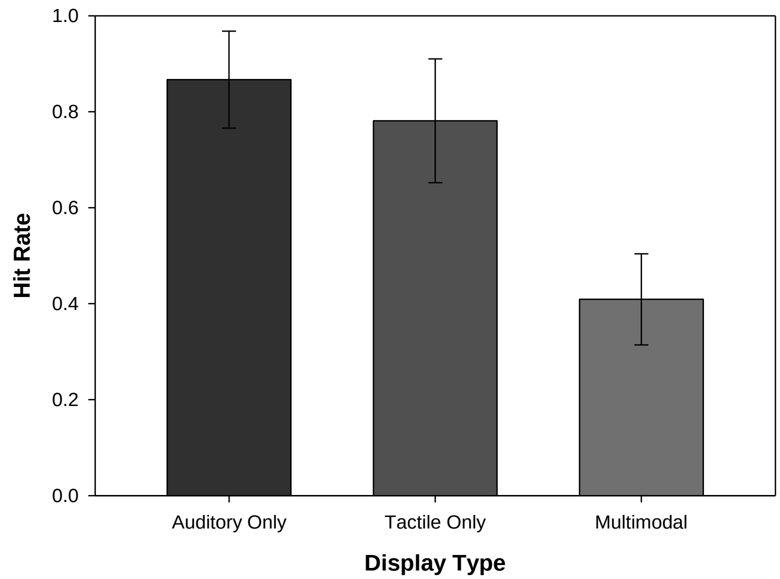


Figure 21: Hit Rate across Display Type Conditions

A post-hoc analysis showed that the multimodal display condition led to significantly lower hit rates than both the auditory only condition (p<.001) and the tactile only condition (p=.001). Hit rate performance for the multimodal display condition (M=0.409, SD=0.149) was very similar to the overall temporal rate synchrony performance in the previous experiment. Hit rate performance in the auditory display (M=0.867, SD=0.159) and tactile display (M=0.781, SD=0.203) condition were much higher and were almost double the hit rate in the multimodal display condition. However, the post-hoc test also revealed that the tactile only condition also produced lower hit rates than the auditory only condition, p<.05.

A similar analysis was for performed for the false alarm rates. A one-way repeated measures ANOVA showed that the false alarm rate was also impacted by the display condition F(2,22)=16.244, p<.001. Post-hoc analysis revealed that the false alarm rates in multimodal condition (M=.055, SD=0.014) were much higher than in the auditory only condition (M=0.031, SD=0.016), p=.003, and the tactile only condition (*M*=0.024, *SD*=0.011), *p*=.001. None of the other comparisons were significant.

Signal detection indices for sensitivity (d') and criterion (c) were calculated for each display condition (auditory only vs. tactile only vs. multimodal) to examine how the participant's ability to detect temporal rate synchrony events and their decision bias differed when the synchrony event was crossmodal and when it was within the same modality. In the refuelling opportunity monitoring task, sensitivity referred to the ability for the participant to discriminate situations when the two planes were travelling at the same speed from situations when they were not at the same speed. In the auditory only condition, this was a comparison of two auditory rates which were presented to different ears (left vs. right) and at different pitches (200 Hz vs. 400 Hz). In the tactile only condition, this was a comparison of two tactile rates, one of which was presented to the left wrist and the other to the right wrist. In the multimodal condition, this was the same crossmodal temporal rate synchrony judgement that was performed in experiment one. Hit rates and false alarm rates of 1 or 0 were adjusted to either 1-1/(2N) or 1/(2N), where N was either the total number of refuelling opportunities or the total number of non-refuelling opportunities (Macmillan & Creelman, 1991).

A one-way ANOVA conducted for sensitivity (d') showed that display type changed participants' ability to detect temporal rate synchrony events, $F(2,22)=42.94$, $p<.001$ (Figure 22). As to be expected, the multimodal display (*M*=1.488, *SD*=0.149) condition resulted in lower sensitivity when compared to both of the unimodal display conditions, $p<.001$. The auditory display (*M*=3.402, *SD*=0.301) did not significantly differ from the tactile display (*M*=3.121, *SD*=0.306) conditions, *p*=.295, *ns*.

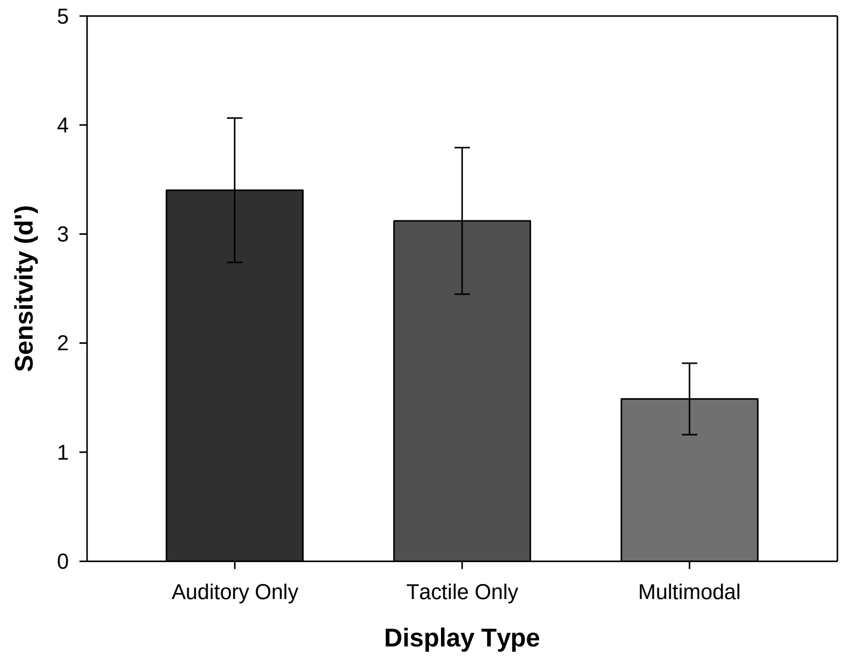


Figure 22: Sensitivity (d') across Display Type

The criterion (c) was also compared using a one-way ANOVA. In the refuelling opportunity monitoring task, criterion referred to the decision bias a participant may have with regards to indicating that a refuelling opportunity was present. A participant with a conservative decision bias would be much more likely to indicate that the two planes were travelling at different speeds while a participant with a risky decision bias would be much more likely to indicate that a refuelling opportunity was possible. Mauchly's test of Sphericity revealed that the sphericity assumption was violated (χ^2 = 9.137, p<.05), and degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity (*epsilon* = 0.625). The ANOVA showed that the display type manipulation had an effect on the participants' decision biases, F(1.25,13.76)=22.783), p<.001 (Figure 23).

Participants' criterion (c) in the multimodal condition (M=-1.003, SD=0.328) was more risky than in the auditory only condition (M=-0.453, SD=0.171), p<.001, and the tactile only condition (M=-0.624, SD=0.221), p=.016. The decision biases in the two unimodal conditions also differed from each other: the auditory only condition resulted in more conservative judgements of temporal rate synchrony than the tactile only condition, *p*=.019.

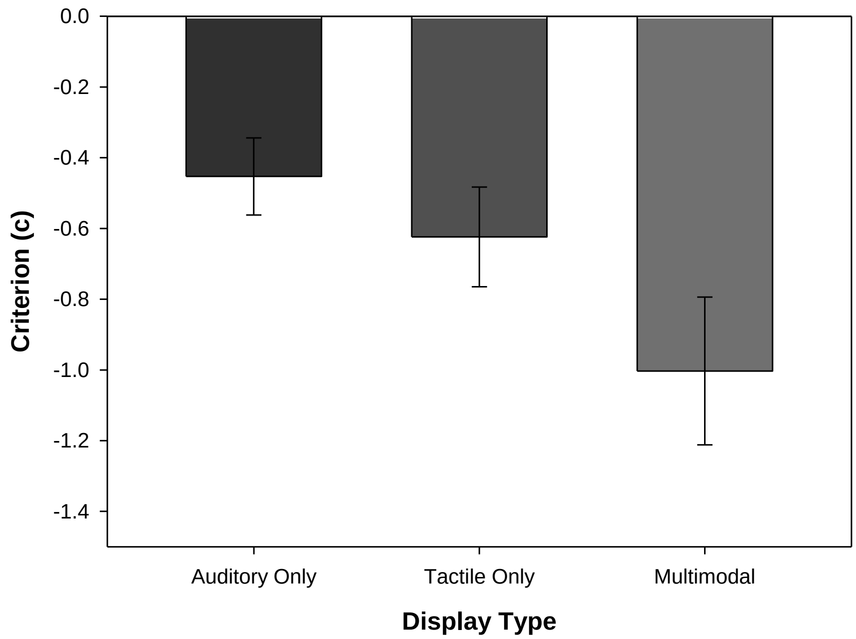


Figure 23: Criterion (c) across Display Conditions

5.5.2 Real-time Speed Monitoring Task

During the experimental task, participants were asked to monitor the speed of both their own plane and the refuelling plane. In addition to monitoring for refuelling opportunities when the velocities of both planes were the same, participants were also asked to indicate whether their own plane should speed up or slow down to match the speed of the refuelling plane. Participants responded by using the up-arrow key to indicate that their plane should speed up and the down-arrow key to indicate that their plane should slow down. The indicated direction of speed change remained constant until the participant responded with a different input. The goal of the real-time speed monitoring task was to assess the participant’s ability to monitor the two independent velocities and their ability to make judgements about the speed over long monitoring situations.

Accuracy in the speed monitoring task was calculated by determining the number of rate units that participants had correctly indicated the direction of speed change required by their plane and dividing by the total number of rate units in the entire scenario. The percentage of correct rate units was calculated for each of the conditions and shown in Figure 24. A one-way ANOVA was performed comparing the accuracy across the three different display conditions (auditory only vs. tactile only vs. multimodal). Mauchly's test indicated that the sphericity assumption was violated (χ^2 = 11.770, *p*=.003) and the degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity (*epsilon* = 0.591). The result of the ANOVA did not reveal any significant differences in the accuracy of the real-time speed monitoring task across the three display conditions, *F*(1.18, 13.00)=0.750, *p*=.424, *ns*.

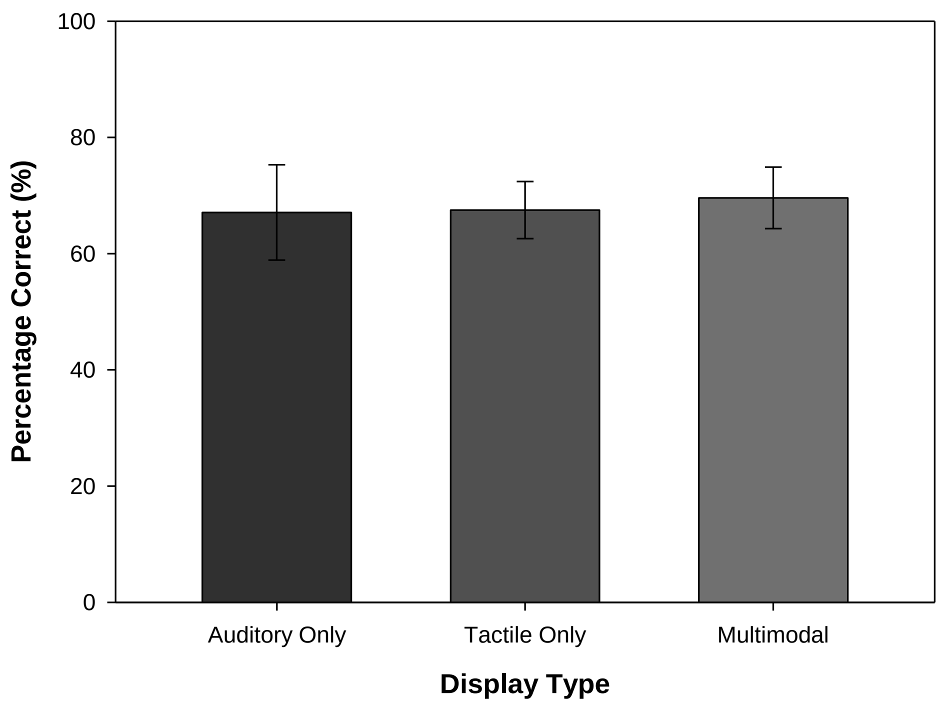


Figure 24: Accuracy on the Speed Monitoring Task across Display Conditions

5.5.3 Situation Awareness Task

Similarly to the real-time speed measurement test, the goal of the situation awareness task was to gauge the participant's ability to monitor the two streams of information, one representing the speed of the participant's plane and the other representing the speed of the refuelling plane. While the speed monitoring task allowed for real-time responses to changes in the speed and a constant monitoring of the speed of both planes, the situation awareness task used discrete probes to determine the degree to which the participants were monitoring and understanding the behaviour of the two planes. The technique used to gauge situation awareness was based on a popular situation awareness technique, the Situation Awareness Global Assessment Technique (SAGAT) (Endsley, Bolte, & Jones, 2003).

While the participant was monitoring the speed of the aircraft, the experiment would pause at pre-set intervals and situation awareness questions were presented to the participants. Three types of situation awareness questions were used during each of the pauses, one for each of the situation awareness levels. Level 1 questions dealt with the participant's ability to detect changes in the perceptual characteristics of the signals (e.g., whether a synchrony event had occurred or not). Level 2 questions dealt with the participant's ability to comprehend the perceptual information that they perceived in level 1 and to relate it to understanding the current situation (e.g., whether the planes were increasing or decreasing in speed). Finally, level 3 questions dealt with the participant's ability to predict future states of the system based on their understanding of the current situation (e.g., whether the planes were converging or diverging in terms of speed).

Each scenario contained three situation awareness questions, for a total of 9 questions per scenario (3 x Level 1, 3 x Level 2, and 3 x Level 3). The percentage of correct answers was calculated for each situation awareness level across all three display conditions and are listed in Table 9. While accuracy in the situation awareness task was relatively low across all conditions, performance was still above chance performance (33.3% for the questions with three answers and 50% for the questions with two answers). Accuracy was also lower than those found in the real-time speed monitoring task.

Table 9: Response Accuracy for Situation Awareness Questions

Situation Awareness Level	Display Type	Mean	Standard Deviation
Level 1	Auditory Only	51.39%	20.67%
	Tactile Only	54.17%	30.26%
	Multimodal	54.17%	16.10%
Level 2	Auditory Only	45.83%	16.10%
	Tactile Only	48.61%	19.41%
	Multimodal	55.56%	20.52%
Level 3	Auditory Only	51.39%	22.98%
	Tactile Only	47.22%	9.62%
	Multimodal	55.56%	22.84%

The percentage of correct answers was subjected to a two-way repeated measures ANOVA with situation awareness question level (1 vs. 2 vs. 3) and display type (auditory only vs. tactile only vs. multimodal) as the independent factors. Mauchly's test of sphericity indicated that the sphericity assumption had been violated (χ^2 = 10.147, p=.006) and degrees of freedom were adjusted using Greenhouse-Geisser estimates of sphericity (*epsilon*=0.611). No significant interactions were found between display type and situation awareness level, $F(2.86,31.42)=0.306$, $p>.05$, *ns*. In addition, no significant main effects for situation awareness level, $F(1.22,13.44)=0.185$, $p>.05$, *ns*, and display type, $F(1.30,14.26)=0.859$, $p>.05$, *ns*, were found.

5.5.4 Questionnaire

A questionnaire was provided to participants at the end of each block which contained questions on:

1. their perceived performance on the refuelling opportunity monitoring task,
2. the difficulty of the refuelling opportunity monitoring task,
3. confidence in their ability to monitor the two planes, and
4. how distracting they found each of the streams of information.

Each question was answered using a 7-point scale, and answers were coded from 0 to 6. In addition, each participant provided some feedback on their strategies for completing the different monitoring tasks, and any thoughts they had on the experiment. The anchoring points for each scale are provided in the following sections. The questionnaire can be found in Appendix B. As was done for the other analyses, participants' responses for each condition were averaged across both blocks for that display condition.

5.5.4.1 Perceived Performance

Each participant was asked to gauge how well they believe that they performed on the refuelling opportunity monitoring task. This was done on a scale between "Extremely Well", which was coded as 0, and "Extremely Poorly", which was coded as 6. Table 10 shows the results of the ratings in each of the different conditions. Overall, participants did not find the refuelling opportunity monitoring task overly difficult. The lowest (best perceived performance) reported perceived performance was 0 in the auditory only condition, and the highest (worst perceived performance) was 4.5 in the tactile only condition.

Table 10: Perceived Performance in Refuelling Opportunity Monitoring Task

	Mean	Std. Deviation	Percentiles		
			25th	50th	75th
Auditory Only	2.000	1.148	1.125	2.5	3
Tactile Only	2.875	1.090	2	3	3.875
Multimodal	2.708	0.782	2.125	2.5	3

The participants' ratings were compared across all three display conditions (auditory only vs. tactile only vs. multimodal) using the Friedman's test. This revealed that the participants' perceived performance in the refuelling opportunity monitoring task was only marginally affected by the display type, $\chi^2(2)=5.318$, $p=.070$. While the Friedman's test only revealed a marginally significant difference between the display types, given the small sample size of experiment 2, the difference may still be indicative of a difference between the display conditions. Further investigation was carried out with a post-hoc analysis using Wilcoxon signed-ranked tests conducted with a Bonferroni correction applied with an adjusted significance level of $\alpha=.05/3=.017$. The results of these post-hoc tests are shown in Table 11.

Table 11: Post-hoc Comparisons of Perceived Performance

	Auditory Only vs. Tactile Only	Auditory Only vs. Multimodal	Tactile Only vs. Multimodal
Z	-1.842	-2.070	-0.309
Asymp. Sig. (2-tailed)	0.065	0.038	0.757

None of the comparisons reached significance but the data showed an interesting trend. Participants believed their performance was much better in the auditory only display than in the other two conditions and that participants believed that they performed similarly in the tactile only and the multimodal display conditions. However, their actual performance showed that performance in the multimodal display condition was much lower than in the two unimodal conditions. Participants also performed better in the auditory only condition than in the tactile only condition, but their own perceived performance ratings seemed to suggest that the tactile display was actually much more difficult that the auditory display.

5.5.4.2 Difficulty

Each participant was also asked to report how difficult the refuelling opportunity monitoring task was in each of the display conditions. Participants rated this on a scale between "Extremely Easy", which was coded as 0, and "Extremely Difficult", which was coded as 6. The results were very similar to the ratings from the perceived performance questions, and are shown in Table 12.

Table 12: Difficulty of Refuelling Opportunity Monitoring Task

	Mean	Std. Deviation	Percentiles		
			25^{th}	50^{th}	75^{th}
Auditory Only	2.000	1.148	1.625	2.5	3
Tactile Only	2.875	1.090	2.5	3.5	4.375
Multimodal	3.417	1.019	2.5	3.5	4.375

The participant's ratings of the difficult of the refuelling opportunity monitoring task were compared across the three display conditions using a Friedman's test. This revealed that display type did affect the ratings of difficulty, χ^2 (2)=6.488, p=.039. Post-hoc tests using the Wilcoxon signed-ranks tests with a Bonferroni correction applied with an adjusted significance level of α=.05/3=.017

were conducted (Table 13). None of the comparisons were significant, but they showed very similar trends to those found for the ratings of perceived performance. Participants felt that the auditory only display condition was much less difficult than both the tactile only and multimodal display conditions. The reported difficulty levels between the tactile and multimodal display conditions were very similar. These results differed from the actual performance data, where performance in the tactile only display condition were much better than the multimodal display condition.

Table 13: Post-Hoc Comparisons for Difficulty

	Auditory Only vs. Tactile Only	**Auditory Only vs. Multimodal**	**Tactile Only vs. Multimodal**
Z	-1.990	-1.944	-0.268
Asymp. Sig. (2-tailed)	0.047	0.052	0.789

5.5.4.3 Confidence in Monitoring of Plane Velocities

In addition to the questions about the participant's ability to monitor for refuelling opportunities, participants were also asked to report on their confidence in the monitoring of the velocities of their own plane and the refuelling plane. This was done on a scale between "Extremely Confidence", coded as 0, and "Not at all Confident", coded as 6. The results of this question are shown in Table 14 and in Figure 25. The PP columns represent ratings about the participant's plane and RP represents ratings about the refuelling plane. Lower numbers correspond to higher ratings of confidence.

Table 14: Confident in Plane Velocity Monitoring

	Mean		Std. Deviation		Percentiles					
					25th		50th		75th	
	PP	RP	PP	RP	PP	RP	PP	RP	PP	RP
Auditory Only	2.042	2.250	1.233	1.034	1.50	1.50	1.75	2.00	2.50	3.00
Tactile Only	2.208	2.542	1.233	1.304	1.00	1.50	2.50	2.75	3.00	3.50
Multimodal	2.417	3.125	0.875	0.882	2.00	2.50	2.00	3.00	3.00	3.875

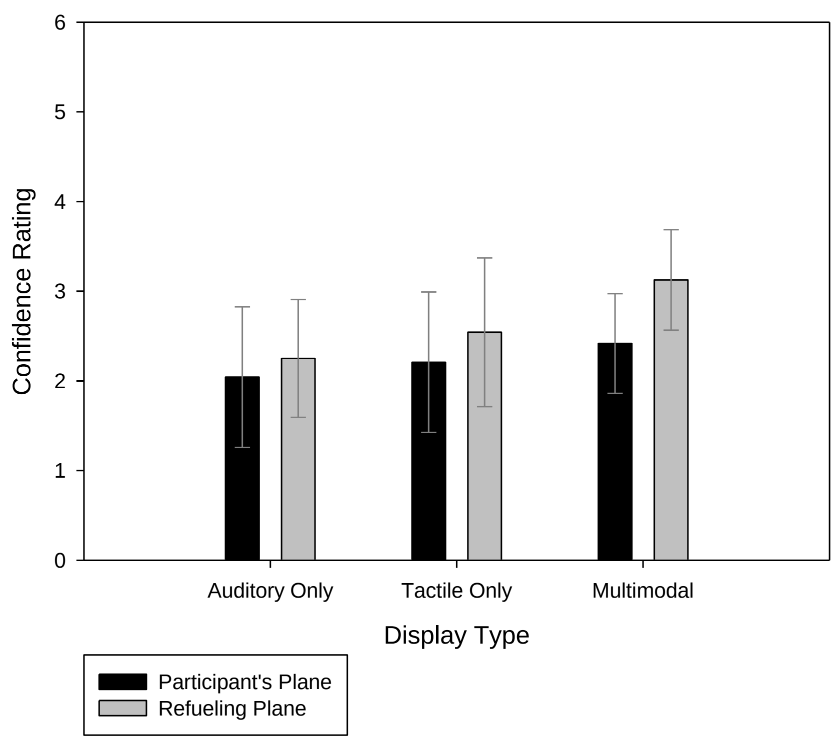


Figure 25: Confidence Ratings across different Display Types and Plane

A two-way repeated measures ANOVA was used to test the differences between both the plane being monitored and the display type. ANOVA's are typically conducted on continuous data, but in the questionnaire participants were asked to respond on a discrete ordinal scale and, as such, the previous analyses were conducted using non-parametric tests such as Friedman’s and Wilcoxon signed-ranked tests. However, the confidence scale could also be interpreted by the participant’s as a continuous variable that varied from being extremely confident to being not at all confident. Therefore, the parametric two-way repeated measures ANOVA was used because there was no non-parametric equivalent to this test and because the ratings were done on a relatively large scale (7-point scale). Non-parametric tests are more robust but also have less power than parametric tests and the results of the ANOVA were interpreted with this change in power in mind.

The two-way repeated measures ANOVA revealed that there was no significant interaction between the plane being monitored and the display type, $F(2,22)=1.98$, $p>.05$, *ns*, or a main effect of display type, $F(2,22)=2.982$, $p=.071$, *ns*. There was a significant main effect of the plane being monitored, $F(1,11)=7.174$, $p=.021$. Participants reported that they were more confident in the monitoring of their own plane than in the monitoring of the refuelling plane.

5.5.4.4 Distraction

The questionnaire also asked participants to rate how distracting they found the monitoring of the two streams of information in the different display conditions. Participants rated the amount of distraction on a scale between “Not Distracting”, coded as 0, and “Extremely Distracting”, coded as 6. The results are shown in Table 15. The PP columns represent ratings about the participant’s plane and RP represents ratings about the refuelling plane.

Table 15: Distraction Ratings

	Mean		Std. Deviation		Percentiles					
					25th		50th		75th	
	PP	RP	PP	RP	PP	RP	PP	RP	PP	RP
Auditory Only	2.000	2.625	1.581	1.170	0.62	1.50	2.00	2.75	3.38	3.50
Tactile Only	2.167	3.083	1.572	1.203	0.38	1.75	2.25	3.25	3.50	3.88
Multimodal	2.583	3.458	1.145	1.373	1.62	2.50	2.50	3.50	3.50	4.50

Similar to the analysis of confidence, a two-way repeated measures ANOVA was conducted with plane and display type as the independent factors. This analysis revealed a marginally significant main effect of plane type, $F(1,11)=4.619$, $p=.055$. Participants reported that the refuelling plane was more distracting than their own plane.

5.5.4.5 Additional Feedback

Many participants also provided additional verbal feedback during the questionnaire period of the experiment. One of the most common comments was about alternative strategies that the participant's used in the multimodal display condition to help with making the crossmodal temporal rate synchrony judgement. Instead of directly comparing the stimuli in the auditory and tactile modalities, some participants reported that they tried to simplify the task by either tapping their feet/fingers to the beat of the auditory stimuli or by listening to the sound that the tactors made. Both of these strategies suggested that participants were reducing the difficulty of the task by changing the crossmodal judgement into one that was unimodal. One of the participants also remarked that musicians may have an easier time at the experimental tasks due to their familiarity with detecting temporal rhythms.

The participant, who was also a drummer, felt that the task was much easier when he imagined it in a drumming context and tapped his feet to help match the rhythms.

5.6 Discussion

5.6.1 Temporal Synchrony Judgements: Unimodal and Crossmodal

In this experiment, three different types of temporal rate synchrony judgements were required. In the auditory only condition, participants needed to compare the rate of two auditory streams of information. The hypothesis was that temporal rate synchrony judgements would be easier in the unimodal display conditions when compared to the multimodal display condition, and the results supported this hypothesis. Hit rate, false alarm rate, and sensitivity were all better in the two unimodal display conditions than in the multimodal display condition, and this difference was quite large. Participants' accuracy in the multimodal display condition were very similar to the accuracy values found in experiment 1, and these results reinforce the finding that crossmodal temporal rate synchrony was a difficult and not intuitive perceptual judgement for the participants.

However, there were a few interesting differences between the two unimodal conditions which were apparent in both the performance data and in the self-reported questionnaire responses. Participants had slightly higher hit rates in the auditory only display condition than in the tactile only display condition, while false alarm rates and sensitivity were not different. However, even though the auditory only condition produced slightly better performance than the tactile only condition, performance in the tactile only condition was still much higher than in the multimodal condition. Yet, participants felt that there were large differences between the auditory and tactile interfaces and reported these in the questionnaire answers. The auditory display condition was perceived to be easier and the participant's perceived performance was also higher than in the tactile condition. In fact, participants felt that their perceived performance and the difficulty of the tactile display condition were similar to those of the multimodal condition even though the performance data painted a different picture.

The disconnect between the self-reported data and the actual performance data suggests that there may exist some characteristic in the auditory rate synchrony judgements that is different than the tactile rate synchrony judgements even though participants were able to do both tasks to roughly the same degree of accuracy. Participants also changed their decision biases between the two unimodal conditions: participants adopted riskier decision biases in the tactile only display condition. One possible explanation for this difference was that the judgements of auditory temporal rate synchrony were much more salient than judgements of tactile temporal rate synchrony. Almost all of the participants reported that the auditory synchrony events seemed to “pop-out” and emerge as a new perceptual object even if they were not focused on detecting the synchrony events. The same effect was not as evident in the tactile and crossmodal synchrony judgements.

The perceptual “pop-out’ effect was one of the hypothesized benefits of using crossmodal temporal rate synchrony, but this characteristic of the perceptual judgement did not appear in either of the experiments. The auditory temporal rate synchrony judgement demonstrates that the “pop-out” effect does exist. However, it is interesting to note that the same emergent effect was not as visible in the tactile only condition even though performance was similar. This suggests that performance, by itself, is not a great indicator of a stimulus’s ability to be perceived as a single perceptual object, at least in a task similar to the one used in experiment 2. In more complex situations (e.g., additional tasks and workload), the performance benefits of the “pop-out” effect may be more pronounced.

5.6.2 Stream Awareness

The other main hypothesis for this experiment was that the participant’s ability to monitor the two streams of information would be better in the multimodal condition when compared to the unimodal condition. Stream awareness was measured using two tasks in the experiment: the real-time speed monitoring task and the situation awareness task. The results of both these tasks do not support the original hypothesis. Instead, there is evidence that participants were able to monitor the two streams at roughly the same levels of awareness in all three display conditions.

Each of the display types used different methods for segregating the two different streams. The streams differed in terms of the pitch (200 Hz vs. 400 Hz) and the ear of presentation (left vs. right). In the tactile only display condition, participants needed to compare the rate of two tactile streams of information, with each stream being presented at the same frequency but to different wrists (left vs. right). Finally, in the multimodal display condition, the modality of presentation was used to create two different streams. Thus, there were a large variety of different perceptual properties that differentiated the two streams. However, these different methods for segregating the streams did not seem to impact the participant's ability to monitor the streams.

The responses to the situation awareness task suggested that there were no differences in awareness between the different display types. However, the large standard deviations in the responses show that the situation awareness task was not a very reliable method for evaluating awareness. The situation awareness task was made of three discrete probes in each scenario each containing 3 situation awareness questions (one for each level). Thus, each participant only provided 6 responses per block for each situation awareness level x display type condition. While the limited number of responses coupled with the small sample size is a cause for concern, it is important to note that performance in the situation awareness questions was all above chance performance (which varied between 33% and 50% depending on the question) and that a second measure of stream awareness also did not find evidence for differences due to display type. In the real-time speed monitoring task, participant performance across all three display types had a mean accuracy of 68%. The real-time speed monitoring task required that participants make constant comparisons between the rates of the two streams of information, which is a very different method for assessing awareness than the discrete SAGAT style questions used in the situation awareness task. The fact that these two complimentary measures of stream awareness both found that performance was the same across all three display conditions reinforces the claim that there were no benefits for stream monitoring when the streams were displayed in two different modalities.

There are several limitations of the second experiment which should also be considered when interpreting the results. The largest limitation was the small sample size of the second experiment. There was a large amount of variability in the responses of participants, especially for the situation awareness task. A second limitation of the study was that the experiment used a very simple simulation of the plane refuelling scenario which participants may not have made use of when dealing with the experimental tasks. The context of the experiment was explained through text instructions, and all the questions and terminology used in the experiment referenced the plane refuelling scenario. However, there was some evidence that participants were not monitoring the two streams as the velocities of two planes. For example in the real-time monitoring situation, had participants correctly understood the plane refuelling scenario they may have uncovered a simpler strategy for accomplishing the task. The optimal method would be to monitor for the refuelling opportunities, occasions when the rates/velocities of both streams were the same, and then to make a judgement about the relative rate/velocities of the planes in the next rate unit. This strategy is optimal because the direction of speed change would only require adjustment after a refuelling event since the rate units would only change at a rate of one beat every rate unit. However, very few participants realized this fact which suggests that participants were not building a mental model of the relative velocities of the planes. Instead, they may have been treating the real-time speed monitoring task as purely a perceptual comparison between the speeds of the two streams of information. This may have reduced some of the benefits of using multiple modalities to reduce inter-modality interference.

Another possible explanation for the lack of differences in awareness between the display conditions was that the difficulty of the refuelling opportunity monitoring task in the multimodal condition actually counteracted the awareness benefits of presenting information to different modalities. In experiment 1, participants found the crossmodal temporal rate synchrony judgements very difficult and they reported that it required sustained attention. The refuelling opportunity monitoring task used the same crossmodal temporal rate synchrony as in experiment 1. The performance data supports the fact that participants found the judgements very difficult. Participants also reported that the refuelling opportunity monitoring task was very difficult and their perceived performance was much lower in the multimodal display condition. Due to the difficulty of the crossmodal temporal rate synchrony judgements, participants may have diverted attention away from monitoring of the two streams to focus on detecting the refuelling opportunities. Since the refuelling opportunity monitoring task was required throughout the entire duration of the experiment, this effect would impact both the real-time monitoring task and situation awareness task.

5.7 Summary

Experiment 2 examined benefits for presenting different streams of information in different modalities when compared to presenting information within the same modality. The current results do not show any evidence that there is a benefit for presenting information in different modalities. Instead, performance in the auditory only display condition, the tactile only display condition, and the multimodal display condition were all very similar. In the unimodal display conditions, special care was taken to design two streams that differed along a variety of important dimensions, and it may be that good signal design is able to overcome many of the interference effects that would be detrimental to stream monitoring within a single modality. However, the task used in this experiment was still relatively simple, and in more complex environments the additional benefits of separating information into different modalities may be more evident and warrants further investigation.

Chapter 6
Discussion and Conclusion

6.1 Summary

In this thesis, the use of crossmodal temporal rate synchrony as a method for linking data across sensory modalities was evaluated. Crossmodal relationships may prove to be useful methods for perceptually representing relationships between data variables that are displayed in different modalities. By presenting these relationships perceptually, operators of complex systems are able to recognize the underlying data relationships without using cognitively demanding analytical processing of the low-level variables. Crossmodal temporal rate synchrony was evaluated using two proposed metrics: resistance to workload changes and awareness in stream monitoring.

The first metric, resistance to workload, was tested in Experiment 1. It was hypothesized that a crossmodal relationship should be easy for an operator to process and understand, and the participant's ability to recognize the relationship should be resistant to changes in operator workload. There was no evidence that crossmodal temporal rate synchrony was resistant to changes in workload. As the workload of the secondary tasks increased, performance in the temporal rate synchrony task decreased as well. The results suggest that the temporal rate synchrony task was not automatic and required conscious effort and mental resources to accomplish. In fact, the monitoring of temporal rate synchrony was one that required constant sustained attention and most participants found it to be very demanding and fatiguing. Experiment 1 also showed that performance in the temporal rate synchrony task was poor even when participants had no additional tasks.

The second metric, awareness in stream monitoring, was tested in Experiment 2. It was hypothesized that good candidate crossmodal relationships should not impede the participant's ability to monitor the individual data streams that are being related. In a multimodal interface, with data streams being presented in different modalities, the participant should actually experience better stream monitoring awareness when compared to unimodal interfaces where intra-modal interference effects may be present. Experiment 2 found no evidence for better stream monitoring performance in the multimodal display when compared to the unimodal displays. Participants exhibited similar levels of stream awareness in the multimodal interface, the auditory only interface, and the tactile only interface. However, there was a large difference in performance in terms of the three synchrony judgements used in the different interfaces. The auditory temporal rate synchrony judgement had the highest number of detections and participants reported that it was the easiest to detect. The tactile temporal rate synchrony judgement also had high rates of detection, but participants felt that their performance was much lower and that the task was much more difficult. The crossmodal temporal rate synchrony judgement was perceived to be the most difficult and the participants' performance reflected the perceived difficulty.

6.2 Temporal Rate Synchrony

Temporal rate synchrony was selected as a candidate crossmodal perceptual relationship because time was an amodal characteristic that occurred across multiple modalities (Hoggan & Brewster, 2006). It was also one of the factors that heavily influenced multisensory integration (Stein & Meredith, 1993), a process that automatically integrates information from multiple modalities into one perceptual event. Finally, crossmodal temporal synchrony matching was a task that humans are able to accomplish from a very early age (Lewkowicz, 2000). These factors contribute to a crossmodal perceptual relationship that was hoped to be easily recognized and able to link relevant data relationships between concurrently presented streams of information in different modalities.

For multimodal interface design, the proposed role of the crossmodal temporal rate synchrony relationship is much like the role of the high-level constraints information that is presented in configural displays. Configural displays reflect high-level constraints of a system by showing the relationships between low-level data variables in the system (Bennett, Toms, & Woods, 1993). In configural displays, the low-level variables are arranged such that the relationships that exist between the variables appear as an emergent feature of the display. In terms of the objects in the experiments within this thesis, the low-level data variables are the individual streams of information, such as the velocity of the planes in Experiment 2, and the high-level constraints were attempted to be shown using the temporal rate synchrony events, which represented times when the speeds matches and refuelling was possible. Emergent features help with the monitoring of system because they are often treated as a new feature or object that integrates the underlying data and is easily accessible.

Therefore, one of the goals of using temporal rate synchrony was to invoke a new emergent feature using stimuli in different sensory modalities. What the two experiments showed, however, was that judgements of temporal rate synchrony did not seem to produce this effect. Instead, it was a crossmodal matching task that was laborious and difficult for the participants to accomplish. One possible reason for this was the reliance on working memory because of the 2-second duration of the temporal rate units. Participants may have been forced to make use of working memory instead of just their perceptual resources to make the matches between rate information in the two different modalities. However, the results from the second experiment suggest that even with the 2-second rate units, the synchrony events in the auditory only display did emerge as an emergent feature. In Experiment 2, participants reported that the auditory rate synchrony events were very easily to detect and their performance in detecting these events was also very high. In post-experiment feedback, participants stated that the synchronous auditory rates seemed to “pop-out” and appear as a new object, which is an example of an emergent feature of the rate information. This result leads to the conclusion that it may not have been a reliance on working memory that made the crossmodal comparisons more difficult, because the same rate units were used in the auditory-only display, it may have to do with the perceptual comparisons themselves.

The results of the tactile-only temporal rate synchrony judgements also provide some insight into this problem. While participants reported the emergence of a new perceptual object in the auditory-only condition, the same was not found in the tactile-only condition. While performance in the tactile condition was still relatively high, participants reported that their perceived performance was low (almost the same as performance in the crossmodal temporal rate synchrony judgement) and the task difficulty was high. Thus, the tactile temporal rate synchrony judgement was an example of a judgement where there was no apparent emergent feature, but individuals were able to make the comparisons relatively well, even if their perceptions of their own performance were much lower. These results suggest that the emergent feature effect of rate synchrony isn't solely based on whether the two streams were unimodal or crossmodal, and also high performance isn't necessarily tied to the conciousdetection of an emergent feature. Without the emergent feature present to help with the synchrony monitoring task, participants were forced to use sustained attention to monitor the streams, leading to a increase sense of difficulty and more uncertainty about their own performance.

Finally, in the crossmodal judgements of temporal rate synchrony, participants had a difficult time making the judgements of synchrony and they also reported that the task was very difficult. One possible explanation is that there is a cognitive cost for making arbitrary comparisons of synchrony across different modalities. The detection of crossmodal synchrony may require a large amount of attentional resources because participants are still perceptually processing the two modalities separately before converting the temporal information into some common reference-frame for comparison, as suggested by some theories of crossmodal matching (Stein & Meredith, 1993). There are two reasons why this conversion stage would be causing lower performance. Firstly, participants may be having a lot of trouble converting between different modalities which results in loss of information during the conversion process. A second possibility is that the additional cognitive cost of converting the stimuli added to the already taxing sustain attention task of monitoring the streams may be beyond human information processing limitations. In either of these cases, crossmodal temporal rate synchrony would not function well as a method for perceptually linking information across modalities because individuals are using some cognitive demanding process to converting information from one modality to another modality. In fact, many of the participants were observed using strategies to simplify this conversion process. For example, some people tapped their feet to the sound of the auditory stimuli which changed both streams into information that could be processed by the somatosensory system.

However, it is interesting to note that there are many times where people are able to integrate information across two different modalities. Even in the case of temporal synchrony, people are able to detect synchrony between auditory and visual events during speech, and any asynchrony during this process is very noticeable. So, while there was no evidence that people were detecting an emergent feature arising out of the two modalities in the two experiments, people are able to integrate multiple modalities together to understand the world. This begs the question of whether emergent features actually do exist between separate modalities. When emergent features are discussed within a modality, they typically refer to new features or objects that seem to arise out of the information that was present, and these features or objects are detected a very low-level perceptual level. However, in multisensory integration, the integration occurs to support higher-level concepts about the world. For example, an individual may integrate incomplete information from each sensory modality to build a better understanding of some event in the world. So, instead of building a new perceptual object, the role of integration is to build a better picture of the world to facilitate action or comprehension. One simple analogy using the situation awareness literature is that emergent features tend to be perceived at the first level of situation awareness, perception. However, the results of multisensory integration support the second level of situation awareness, comprehension. Because of this difference, it becomes much more difficult for interface designers to make use of multisensory integration in the design of interfaces because semantic mappings may already be present.

6.3 Implications for Multimodal Interfaces

These findings suggest a number of implications for the use of crossmodal relationships in multimodal interfaces:

- Even when information is presented in different modalities, operators may use strategies to bring everything into a single modality.
- Stream monitoring performance is dependent on the design of the display: with well-designed stream characteristics, interference between streams is kept at a minimum.
- Temporal rate synchrony is a difficult and resource demanding task for operators to use in human supervisory control situations.
- Crossmodal relationships are difficult to build into interfaces and require special care to ensure that the semantic mappings are appropriate and are not in conflict with the crossmodal relationship.

6.4 Future Work

The results of the two experiments described in this thesis are only a preliminary step in the investigation of perceptual methods for linking information across different sensory modalities. It has been demonstrated that there are good reasons for providing perceptually accessible methods for understanding relationships between variables that are monitored in different sensory modalities. However, the results presented have shown that temporal rate synchrony was not an example of one such relationship. A number of future steps can be taken in the search for other perceptual relationships that facilitate this process.

Firstly, in this thesis, two methods for evaluating the appropriateness of crossmodal relationships were proposed and used for the examination of crossmodal temporal synchrony. Further validation of the two criteria used should be pursued in future work to determine the generalizability of the evaluation criteria to other crossmodal relationships. This can be done by first making use of these metrics in evaluating whether current perceptual methods for displaying relationships in unimodal displays are appropriate. While this thesis has presented evidence that these metrics are appropriate, further validation of these metrics will assist with the search for new crossmodal relationships.

Secondly, further investigation of the presence of emergent features in crossmodal relationships should be investigated by drawing from findings in the current multisensory perception literature. Up until this point, no one has examined the use of multisensory integration as a display tool for interface designers. The suitability to this perceptual process and its ability to represent abstract data variables is still unclear. The results of these studies may prove that multisensory integration and crossmodal matching are both inappropriate for showing data relationships. If this is true, other methods for linking information across modalities will need to be investigated.

Finally, methods for determining which modality different variables should be presented in should be further investigated. The current work by Burns, Ho, and Arrabito (2011) provides some initial thoughts about how this problem can be solved using EID, however no examples of the use of this method for determining perceptual fit have yet been published. One possible outcome of future research in crossmodal perceptual relationships is that it is not possible to perceptually link information presented in different modalities. In that case, interface designers must be very careful about which modality they chose to represent information so that they can avoid having important data relationships that are presented in different modalities.

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regards,

Rob

--

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> From: Wayne Giang [mailto:wcwgiang@gmail.com]

> Sent: January-09-12 10:25 AM

>

>

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>

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> Sincerely,

> Wayne Giang

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Appendix A

Experiment I – Experimental Materials

Questionnaire

Participant Number:____________

<u>Performance</u>

How *well* do you feel you performed on the visual task?

|-------------|-------------|-------------|-------------|-------------|-------------|

Extremely Well Extremely Poorly

How *well* do you feel you performed on the synchrony task?

|-------------|-------------|-------------|-------------|-------------|-------------|

Extremely Well Extremely Poorly

How *well* do you feel you did overall?

|-------------|-------------|-------------|-------------|-------------|-------------|

Extremely Well Extremely Poorly

<u>Workload</u>

How *difficult* did you find the visual task?

|-------------|-------------|-------------|-------------|-------------|-------------|

Extremely Easy Extremely Difficult

How *distracting* did you feel the visual task was?

|-------------|-------------|-------------|-------------|-------------|-------------|

Not Distracting Extremely Distracting

How *difficult* did you find synchrony task?

|-------------|-------------|-------------|-------------|-------------|-------------|

Extremely Easy Extremely Difficult

How *distracting* did you feel the synchrony task was?

|-------------|-------------|-------------|-------------|-------------|-------------|

Not Distracting Extremely Distracting

How much *effort* did you apply to the different tasks?

|--------------|--------------|--------------|--------------|--------------|--------------|

Exclusively focused on Visual Task — Exclusively focused on Synchrony Task

<u>Integration</u>

These questions refer to the Synchrony Task.

How discrete or separate did you find the auditory and tactile stimuli overall?

|--------------|--------------|--------------|--------------|--------------|--------------|

Extremely Discrete — Extremely Together

How much did the synchronous auditory and tactile stimuli feel like a single “perceptual event”?

|--------------|--------------|--------------|--------------|--------------|--------------|

Completely — Not at all

Participant Run Schedule

Participant ID	Session 1	Session 2	Session 3
ID01	1,NA	2,1	3,2
ID02	2,NA	3,1	1,2
ID03	3,NA	1,1	2,2
ID04	1,NA	2,2	3,1
ID05	2,NA	3,2	1,1
ID06	3,NA	1,2	2,1
ID07	1,NA	3,1	2,2
ID08	2,NA	1,1	3,2
ID09	3,NA	2,1	1,2
ID10	1,NA	3,2	2,1
ID11	2,NA	1,2	3,1
ID12	3,NA	2,2	1,1
ID13	1,NA	2,1	3,2
ID14	2,NA	3,1	1,2
ID15	3,NA	1,1	2,2
ID16	1,NA	2,2	3,1
ID17	2,NA	3,2	1,1
ID18	3,NA	1,2	2,1
ID19	1,NA	3,1	2,2
ID20	2,NA	1,1	3,2
ID21	3,NA	2,1	1,2
ID22	1,NA	3,2	2,1
ID23	2,NA	1,2	3,1
ID24	3,NA	2,2	1,1

First # is PT

Second # is ST

Appendix B

Experiment II – Experimental Materials

Questionnaire

Participant Number:___________ Cond:_________ Scenario:___________ Session:_____________

Tracking Task

How *well* do you feel you performed on the tracking task?

|-------------|-------------|-------------|-------------|-------------|-------------|

Extremely Well Extremely Poorly

How *difficult* did you find the tracking task?

|-------------|-------------|-------------|-------------|-------------|-------------|

Extremely Easy Extremely Difficult

Awareness

How *confident* were you in your monitoring of the speed of the refueling plane?

|-------------|-------------|-------------|-------------|-------------|-------------|

Extremely Confident Not at all Confident

How *confident* were you in your monitoring of the speed your own plane?

|-------------|-------------|-------------|-------------|-------------|-------------|

Extremely Confident Not at all Confident

Distraction

How *distracting* did you find the monitoring of the refueling plane?

|-------------|-------------|-------------|-------------|-------------|-------------|

Not Distracting Extremely Distracting

How *distracting* did you find the monitoring of your own plane?

|-------------|-------------|-------------|-------------|-------------|-------------|

Not Distracting Extremely Distracting

Participant Run Schedule

Participant ID	Session	Scenario	Condition
ID01	1	4	1
ID01	2	2	2
ID01	3	6	3
ID01	4	5	1
ID01	5	1	2
ID01	6	3	3
ID02	1	2	2
ID02	2	4	3
ID02	3	3	1
ID02	4	1	2
ID02	5	6	3
ID02	6	5	1
ID03	1	6	3
ID03	2	2	1
ID03	3	1	2
ID03	4	4	3
ID03	5	5	1
ID03	6	3	2
ID04	1	4	3
ID04	2	6	2
ID04	3	3	1
ID04	4	5	3
ID04	5	2	2
ID04	6	1	1
ID05	1	3	2
ID05	2	4	1
ID05	3	5	3
ID05	4	6	2
ID05	5	1	1
ID05	6	2	3
ID06	1	6	1
ID06	2	1	3
ID06	3	5	2
ID06	4	3	1
ID06	5	4	3
ID06	6	2	2
ID07	1	4	1

ID07	2	1	2
ID07	3	6	3
ID07	4	3	1
ID07	5	2	2
ID07	6	5	3
ID08	1	5	2
ID08	2	3	3
ID08	3	1	1
ID08	4	6	2
ID08	5	2	3
ID08	6	4	1
ID09	1	4	3
ID09	2	1	1
ID09	3	3	2
ID09	4	5	3
ID09	5	6	1
ID09	6	2	2
ID10	1	2	3
ID10	2	5	2
ID10	3	6	1
ID10	4	1	3
ID10	5	3	2
ID10	6	4	1
ID11	1	6	2
ID11	2	5	1
ID11	3	4	3
ID11	4	2	2
ID11	5	3	1
ID11	6	1	3
ID12	1	5	1
ID12	2	4	3
ID12	3	2	2
ID12	4	1	1
ID12	5	6	3
ID12	6	3	2

Situation Awareness Questions for Each Scenario

Participant ID ______________ **Session** ______________

Scenario ______1________ **Condition** ______________

Please circle your answer. If you are unsure, please put down your best guess.

1. How fast was your plane?
    a. Slow
    b. Moderate
    c. Fast

2. Was the refueling plane increasing, decreasing, or staying at a steady speed?
    a. Increasing
    b. Decreasing
    c. Steady

3. Were the two planes converging, diverging, or moving in the same direction in terms of speed?
    a. Converging
    b. Diverging
    c. Same Direction

Participant ID _______________ **Session** _______________

Scenario ______1________ **Condition** _______________

Please circle your answer. If you are unsure, please put down your best guess.

4. How fast was the refueling plane?
    a. Slow
    b. Moderate
    c. Fast

5. Which of the planes was faster?
    a. Your Plane
    b. Refueling Plane
    c. Same Speed

6. Will the planes be able to refuel soon?
    a. Yes
    b. No

Participant ID ______________ **Session** ______________

Scenario ______1________ **Condition** ______________

Please circle your answer. If you are unsure, please put down your best guess.

7. In the last 4 seconds was there a refueling opportunity?
    a. Yes
    b. No

8. Was your plane increasing, decreasing, or staying at a steady speed?
    a. Increasing
    b. Decreasing
    c. Steady

9. Which of the planes will probably be faster in 6 seconds?
    a. Your Plane
    b. Refueling Plane
    c. Same Speed

Participant ID _______________ **Session** _______________

Scenario _____2__________ **Condition** _______________

Please circle your answer. If you are unsure, please put down your best guess.

1. How fast was the refueling plane?
    a. Slow
    b. Moderate
    c. Fast

2. Which of the planes was faster?
    a. Your Plane
    b. Refueling Plane
    c. Same Speed

3. Will the planes be able to refuel soon?
    a. Yes
    b. No

Participant ID _______________ **Session** _______________

Scenario ______2_________ **Condition** _______________

Please circle your answer. If you are unsure, please put down your best guess.

4. In the last 4 seconds was there a refueling opportunity?

    a. Yes

    b. No

5. Was your plane increasing, decreasing, or staying at a steady speed?

    a. Increasing

    b. Decreasing

    c. Steady

6. Which of the planes will probably be faster in 6 seconds?

    a. Your Plane

    b. Refueling Plane

    c. Same Speed

Participant ID ______________ **Session** ______________

Scenario ______2________ **Condition** ______________

Please circle your answer. If you are unsure, please put down your best guess.

7. How fast was your plane?
    a. Slow
    b. Moderate
    c. Fast

8. Was the refueling plane increasing, decreasing, or staying at a steady speed?
    a. Increasing
    b. Decreasing
    c. Steady

9. Were the two planes converging, diverging, or moving in the same direction in terms of speed?
    a. Converging
    b. Diverging
    c. Same Direction

Participant ID ______________ **Session** ______________

Scenario ______3________ **Condition** ______________

Please circle your answer. If you are unsure, please put down your best guess.

1. In the last 4 seconds was there a refueling opportunity?
   a. Yes
   b. No

2. Was your plane increasing, decreasing, or staying at a steady speed?
   a. Increasing
   b. Decreasing
   c. Steady

3. Which of the planes will probably be faster in 6 seconds?
   a. Your Plane
   b. Refueling Plane
   c. Same Speed

Participant ID _______________ **Session** _______________

Scenario ______3________ **Condition** _______________

Please circle your answer. If you are unsure, please put down your best guess.

4. How fast was the refueling plane?

    a. Slow

    b. Moderate

    c. Fast

5. Which of the planes was faster?

    a. Your Plane

    b. Refueling Plane

    c. Same Speed

6. Will the planes be able to refuel soon?

    a. Yes

    b. No

Participant ID ______________ **Session** ______________

Scenario ______3________ **Condition** ______________

Please circle your answer. If you are unsure, please put down your best guess.

7. How fast was your plane?
    a. Slow
    b. Moderate
    c. Fast

8. Was the refueling plane increasing, decreasing, or staying at a steady speed?
    a. Increasing
    b. Decreasing
    c. Steady

9. Were the two planes converging, diverging, or moving in the same direction in terms of speed?
    a. Converging
    b. Diverging
    c. Same Direction

Participant ID ______________ **Session** ______________

Scenario ______4________ **Condition** ______________

Please circle your answer. If you are unsure, please put down your best guess.

1. How fast was your plane?

    a. Slow

    b. Moderate

    c. Fast

2. Was the refueling plane increasing, decreasing, or staying at a steady speed?

    a. Increasing

    b. Decreasing

    c. Steady

3. Were the two planes converging, diverging, or moving in the same direction in terms of speed?

    a. Converging

    b. Diverging

    c. Same Direction

Participant ID ______________ **Session** ______________

Scenario ______4________ **Condition** ______________

Please circle your answer. If you are unsure, please put down your best guess.

4. In the last 4 seconds was there a refueling opportunity?
    a. Yes
    b. No

5. Was your plane increasing, decreasing, or staying at a steady speed?
    a. Increasing
    b. Decreasing
    c. Steady

6. Which of the planes will probably be faster in 6 seconds?
    a. Your Plane
    b. Refueling Plane
    c. Same Speed

Participant ID ______________ **Session** ______________

Scenario ______4________ **Condition** ______________

Please circle your answer. If you are unsure, please put down your best guess.

7. How fast was the refueling plane?
    a. Slow
    b. Moderate
    c. Fast

8. Which of the planes was faster?
    a. Your Plane
    b. Refueling Plane
    c. Same Speed

9. Will the planes be able to refuel soon?
    a. Yes
    b. No

Participant ID ______________ **Session** ______________

Scenario ______5________ **Condition** ______________

Please circle your answer. If you are unsure, please put down your best guess.

1. How fast was the refueling plane?
    a. Slow
    b. Moderate
    c. Fast

2. Which of the planes was faster?
    a. Your Plane
    b. Refueling Plane
    c. Same Speed

3. Will the planes be able to refuel soon?
    a. Yes
    b. No

Participant ID ______________ **Session** ______________

Scenario _____5_________ **Condition** ______________

Please circle your answer. If you are unsure, please put down your best guess.

4. How fast was your plane?
    a. Slow
    b. Moderate
    c. Fast

5. Was the refueling plane increasing, decreasing, or staying at a steady speed?
    a. Increasing
    b. Decreasing
    c. Steady

6. Were the two planes converging, diverging, or moving in the same direction in terms of speed?
    a. Converging
    b. Diverging
    c. Same Direction

Participant ID ______________ **Session** ______________

Scenario ________5______ **Condition** ______________

Please circle your answer. If you are unsure, please put down your best guess.

7. In the last 4 seconds was there a refueling opportunity?
    a. Yes
    b. No

8. Was your plane increasing, decreasing, or staying at a steady speed?
    a. Increasing
    b. Decreasing
    c. Steady

9. Which of the planes will probably be faster in 6 seconds?
    a. Your Plane
    b. Refueling Plane
    c. Same Speed

Participant ID ______________ **Session** ______________

Scenario _______6_______ **Condition** ______________

Please circle your answer. If you are unsure, please put down your best guess.

1. In the last 4 seconds was there a refueling opportunity?
    a. Yes
    b. No

2. Was your plane increasing, decreasing, or staying at a steady speed?
    a. Increasing
    b. Decreasing
    c. Steady

3. Which of the planes will probably be faster in 6 seconds?
    a. Your Plane
    b. Refueling Plane
    c. Same Speed

Participant ID ______________ **Session** ______________

Scenario _____6_________ **Condition** ______________

Please circle your answer. If you are unsure, please put down your best guess.

4. How fast was your plane?
   a. Slow
   b. Moderate
   c. Fast

5. Was the refueling plane increasing, decreasing, or staying at a steady speed?
   a. Increasing
   b. Decreasing
   c. Steady

6. Were the two planes converging, diverging, or moving in the same direction in terms of speed?
   a. Converging
   b. Diverging
   c. Same Direction

Participant ID ______________ Session ______________

Scenario _____6_________ Condition ______________

Please circle your answer. If you are unsure, please put down your best guess.

7. How fast was the refueling plane?
    a. Slow
    b. Moderate
    c. Fast

8. Which of the planes was faster?
    a. Your Plane
    b. Refueling Plane
    c. Same Speed

9. Will the planes be able to refuel soon?
    a. Yes
    b. No

Participant ID _______________ **Session** _______________

Scenario ______7_________ **Condition** _______________

Please circle your answer. If you are unsure, please put down your best guess.

1. In the last 4 seconds was there a refueling opportunity?
    a. Yes
    b. No

2. Was your plane increasing, decreasing, or staying at a steady speed?
    a. Increasing
    b. Decreasing
    c. Steady

3. Which of the planes will probably be faster in 6 seconds?
    a. Your Plane
    b. Refueling Plane
    c. Same Speed

Participant ID _______________ **Session** _______________

Scenario ______7________ **Condition** _______________

Please circle your answer. If you are unsure, please put down your best guess.

4. How fast was your plane?
    a. Slow
    b. Moderate
    c. Fast

5. Was the refueling plane increasing, decreasing, or staying at a steady speed?
    a. Increasing
    b. Decreasing
    c. Steady

6. Were the two planes converging, diverging, or moving in the same direction in terms of speed?
    a. Converging
    b. Diverging
    c. Same Direction

Participant ID _______________ **Session** _______________

Scenario _____7_________ **Condition** _______________

Please circle your answer. If you are unsure, please put down your best guess.

7. How fast was the refueling plane?

    a. Slow

    b. Moderate

    c. Fast

8. Which of the planes was faster?

    a. Your Plane

    b. Refueling Plane

    c. Same Speed

9. Will the planes be able to refuel soon?

    a. Yes

    b. No