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Theoretical Throughput Capacity: Capabilities of Human Information Processing during Multitasking

Aerial N. Camden
Wright State University

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Theoretical Throughput Capacity: Capabilities of Human Information Processing during Multitasking

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy

by

Aerial N. Camden
B.S.B.M.E., Wright State University, 2012
M.S.E., Wright State University, 2012

2015
Wright State University

Chandler A. Phillips, M.D., P.E.
Dissertation Director

Ramana Grandhi, Ph.D.
Director, Ph.D. in Engineering Program

Robert E. W. Fyyfe, Ph.D.
Vice President for Research and Dean of the Graduate School

Committee on Final Examination

Chandler A. Phillips, M.D., P.E.

David B. Reynolds, Ph.D.

Subhashini Ganapathy, Ph.D.

Andy McKinley, Ph.D.

Dana Rogers, Ph.D.

David Kender, M.S.
ABSTRACT

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Technological advancements in automation have allowed humans to collect data at exorbitant rates. As a result, human multitasking as become an integral part of many government, industrial, and routine activities. However, multitasking can be difficult to study, primarily due to the lack of objective metrics. The Human Operator Informatic Model (HOIM) is an information-theory based model that has been recently developed to combat these difficulties. The HOIM is based on Shannon information theory and can provide an objective, meaningful measure to describe system complexity and overall multitasking performance. The main goal of this work was to validate the HOIM as a reliable model and test the effect of multisensory feedback on operator strategy and performance.

Results showed that as input information rate increases, operator output also increases, but not at a proportional rate. As a result, overall information throughput declines with increasing input information rate. Further, multisensory feedback during multitasking was shown to increase performance of the two tasks with feedback. However, this came at a proportional cost in the performance of the two tasks that did not have feedback. Overall performance was not significantly affected by the presence of multisensory feedback. This work proposes that human operators have a throughput capacity: a maximum, finite capacity to process information during multitasking.
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Symbols, Abbreviations, and Acronyms

AF-MATB  Air Force version of the Multiple Attribute Task Battery

\( aoc \)  Number of alternatives of choice for a Hick-Hyman task

\( D \)  Diameter of the cursor of the Targeting component of MATB [pixels]

\( 3D \)  Diameter of the target of the Targeting component of MATB [pixels]

GUI  Graphical User Interface

HOIM  Human Operator Informatic Model

\( ISI_i \)  Interstimulus interval for the \( i^{th} \) MATB component [s]

IT  Information Throughput

MATB  Multiple Attribute Task Battery

\( I_d \)  Fitts’s index of difficulty [bits]

\( I_p \)  Fitts’s index of performance [bits/s]

\( Q_i \)  Spatial information content for the \( i^{th} \) component of MATB [bits]

\( \dot{V} \)  Average cursor drift velocity [pixels/s]

\( V_O \)  Volumetric drain rate of each tank in the Resource component of MATB [L/s]

\( V_{TOT} \)  Total tank volume of each tank in the Resource component of MATB [L]

\( W_i \)  Machine operation weighting coefficient for \( i^{th} \) MATB component

\( \hat{W}_i \)  Human performance weighting coefficient for \( i^{th} \) MATB component

\( \bar{\beta} \)  Information throughput

\( \bar{\beta}_i \)  Component-specific fractional throughput for \( i^{th} \) MATB component

\( \beta_{IN} \)  Total input baud rate [bits/s]

\( \beta_{INi} \)  Input baud rate for the \( i^{th} \) component [bits/s]

\( \beta_O \)  Total output baud rate [bits/s]

\( \beta_{Oi} \)  Output baud rate for the \( i^{th} \) MATB component [bits/s]

\( \rho_i \)  Fractional accuracy of the \( i^{th} \) MATB component
Introduction and Background

1.1 Problem and Research Goals

Human performance of cognitive tasks is a rapidly growing area of research that has interested both psychologists and human factors engineers for over a century. Early work in 1900 investigated the performance effects of mental fatigue in school children [2]. Psychology researchers continued to investigate the idea that mental fatigue affects human performance and can cause mental “blocks” [3]. Cognitive state later became assessed with subjective mental workload scales, such as the NASA-TLX [4]; for a review on subjective workload, see Reference [5]. In today’s age of technology, many automated functions are allocated to machines to allow humans to manage more tasks, making multitasking operations more prevalent than ever. As a result, multitasking effects on human performance is a prime research interest [6]. Recently, divided attention, which occurs during multitasking, has been shown to induce a higher mental workload than sustained attention or selective attention on a single task [7]. In the later half of the twentieth century, researchers investigated the physiological effects of performing mental tasks [8]. Electroencephalography (EEG) has become a tool of keen interest in assessing the physiology of human cognitive
performance [9, 10, 11].

Traditionally, researchers use error rate, response time, and other indicators to describe human performance. While this may be a reasonable approach to singletasking activities, studying multitasking in this manner can quickly become complicated. For each task, the operator has an error rate and a response time, resulting in several measures of performance. Further, this method of analysis does not provide any information on strategy, or how the operator divides their attention between the tasks. To overcome these obstacles, the Human Operator Informatic Model (HOIM) has recently emerged as an efficient and effective method of quantitatively measuring human multitasking performance with a single metric: information throughput [12, 13, 14]. Using this model, the human-machine interaction strategy can be characterized.

The first part of this work focuses on the validation of the HOIM. This study involves human operators performing computer-based multitasking activities with different task combinations and different number of tasks. Although many previous studies have already examined the performance effects of increasing number of tasks, these studies typically increase the total rate of information being presented to the operator. However, by setting a constant difficulty level, i.e., information input rate, the performance effects of different number of tasks and different task combinations can be fairly assessed.

The second part of this work focuses on the effects of multisensorial feedback on multitasking performance. Many previous studies have found sensorial feedback to be useful during singletasking activities. However, there is surprisingly little work that examines the performance effect of feedback in multitasking scenarios. By applying the HOIM, the overall multitasking performance with multisensorial feedback can be fairly compared to a
control. Additionally, the operator strategy can be compared quantitatively.

Finally, this work expands on an idea proposed by Miller nearly 60 years ago. In his original 1956 publication, Miller presents an asymptotic limit to a human’s ability to process information while performing a single task [1]. This asymptotic limit was called the channel capacity. The current work presents evidence that such a limit also exists for information processing while multitasking. The asymptotic limit in information processing while performing multiple tasks is called the throughput capacity.

1.2 Review of Literature

1.2.1 The Neuroanatomical Correlates of Multitasking

The three main cognitive constructs of multitasking are planning, retrospective memory, and prospective memory [15] and are shown in Figure 1.1 (Brain structures involved in multitasking). Planning is important in the prioritization of multiple tasks and can also be related to strategy, or the allocation of attention [16]. Planning has a neuroanatomical basis within the right dorsolateral prefrontal cortex [15, 16]. Retrospective memory involves recalling actions from previous experience and has a neuronal basis in the left anterior and left posterior cingulate regions [15]. In contrast, prospective memory is the ability to perform a task after a delay period of unrelated activity [17]. Recent MRI studies have found evidence that Brodmann Area 10 plays a critical role in prospective memory [17, 18]. With these three cognitive constructs defined, the mechanistic differences in singletasking and multitasking become intuitively clear. As task complexity increases from singletasking to
multitasking, the planning demands of the brain will also increase. Further, the prospective memory, which aids the human operator in “switching” between multiple tasks [19], is not often a critical component of singletasking activities. Indeed, Brodmann Area 10 has been shown to play a critical role in the neural mechanism of task switching [19].

The physiological differences between singletasking and multitasking have also been assessed in performance-related studies. These studies have found notable differences in brain activity while multitasking compared to singletasking. For example, some groups have found that multitasking reduces the power of alpha brain waves and increases the power of theta brain waves [10, 20]. Using EEG, Isreal, et al., found that the amplitude of the P300 component, which is associated with cognitive processing, decreases when a second task is added to a tracking task [21]. The authors reason that divided attention while performing two tasks reduces attentional resources to each task, thus, decreasing the amplitude of the peak. Additional evidence for multiple resources has been shown in working memory systems. For example, Cocchini, et al., show that, when performed simultane-
ously, tasks requiring verbal memory do not greatly interfere with tasks requiring visual memory or perceptuomotor memory; similarly, visual tasks do not greatly interfere with perceptuomotor tasks [22]. Fournier, et al., have shown that in addition to brain activity, multitasking can have other physiological effects [10]. Their experiment shows that multitasking can result in significantly increased heart rate when compared to singletasking.

1.2.2 The Multi-Attribute Task Battery

The Multi-Attribute Task Battery (MATB) was originally developed by NASA to evaluate human multitasking performance [23]. Since its development, MATB has been used in a variety of studies to investigate the performance effects of training [10], task difficulty [10, 24], medications [25, 26, 27], and sleep deprivation [28]. In 2014, the United States Air Force released the latest updated version of MATB [29]. This version includes a section on information throughput (IT) mode. The following discussion refers to MATB operating in this IT mode. MATB presents the human operator with four components to perform simultaneously for a designated length of time in a graphical user interface (GUI) [13] shown in Figure 1.2 (The MATB graphical user interface). These components are Systems Monitoring, Targeting, Communications, and Resource and represent five tasks. Systems Monitoring consists of two tasks, i.e., Lights and Dials. The other components are single task. For the following review, “user” is defined as the person who conducts the MATB study and controls the simulation settings and the “operator” is the person performing multitasking. Each task gives the operator an alert stimulus, to which he or she must respond correctly. The user predetermines the number of stimuli for each task before starting a
1.2.2.1 Systems Monitoring

The Systems Monitoring component consists of two tasks: Lights and Dials, shown in Figure 1.3 (MATB Monitoring component: Lights (top) and Dials (bottom)). For the Lights task, the GUI presents two lights. The human operator must press a key on the keyboard if the green light on the left switches off or if the light on the right switches to red. For the Dials task, MATB presents four dials with gauge pointers that move up and down during the simulation. The operator must press the corresponding key on the keyboard if one of the gauges moves outside of an acceptable region.
1.2.2.2 Communications

The Communications task is shown in Figure 1.4 (MATB Communications component). In this task, the operator is given a call sign: NGT504. MATB then delivers audio messages instructing the operator to identify one of four NAV/COM channels and then change that channel from its current frequency to a specific frequency using the arrow keys. In IT mode, the audio message is always addressed to NGT504, i.e., there are no distractor messages.

1.2.2.3 Resource

The Resource component is shown in Figure 1.5 (MATB Resource component). For the Resource task, MATB uses only two fuel tanks, A and B. Each tank continuously drains at a constant rate during the simulation. The human operator must keep the fuel levels within the designated range, as denoted by two red lines on each of the two tanks. This is accomplished by switching on and off two fill pumps, one for each tank. These fill pumps are numbered “2” and “4” in the GUI. All other pumps in the Resource component are
permanently disabled. Consequently, Tanks C and D are not used for the Resource task.

1.2.2.4 Targeting

The Targeting component, referred to as ‘Tracking’ when not in IT mode, is shown in Figure 1.6 (MATB Targeting component). In this task, MATB presents a white target circle and a green circular cursor. The green cursor randomly drifts during the simulation and represents a perturbation. The human operator must use a joystick to keep the green cursor on target, i.e., within the target circle, and thus, reject the perturbation.

1.2.3 Information Theory

Information theory began in 1948, when Claude Shannon published his groundbreaking work that founded information theory. His method quantified the amount of information in a signal using binary units, or bits [30]. The information content of a signal, \( Q \), can be
Figure 1.5: MATB Resource component.

Figure 1.6: MATB Targeting component.
related to its probability of state occurrence, $p$, as

$$Q = \log_2 \frac{1}{p}$$  \hspace{1cm} (1.1)$$

If all events are equally likely to occur, then $Q$ can be rewritten as

$$Q = \log_2 aoc$$  \hspace{1cm} (1.2)$$

where $aoc$ represents the number of alternatives of choice. As an example, a system with two states with equally likely probabilities has two alternatives of choice.

The birth of information theory led to quantitative modeling of human information processing capabilities. In the 1950s, Hick and Hyman discovered that a human operator’s response time could be linearly related to the amount of information in a stimulus signal. This relationship later became known as the Hick-Hyman law [31, 32]. Similarly, in 1954, Fitts related the human operator’s movement time as a linear function of the index-of-difficulty, which Fitts related to Shannon’s Theorem 17 [33]. The index-of-difficulty, $I_d$, is defined as

$$I_d = \log_2 \frac{A}{W_a/2}$$  \hspace{1cm} (1.3)$$

where $W_a$ is the tolerance range and $A$ is the average amplitude of the movement. Fitts then defines a performance index, $I_p$, as

$$I_p = \frac{1}{t} I_d$$  \hspace{1cm} (1.4)$$
where $t$ is the average time of the movement in seconds. Over the last 60 years, the concepts of information theory have been applied to numerous human-machine systems, often to describe the human operator while performing a single task. For example, the information capacity of the human motor system [34], retinal channel [35], ear [36], and fingertip [37] have been quantified using information theory. Using information theory, Fitts, et al., later showed that stimulus redundancy reduces reaction time [38]. This implies that expectancy of an event increases channel capacity, and thus, could be used in the design of systems. Indeed, one recent review examined the use of Fitts’s law to optimize human-computer interaction of a tracking task [39], while other studies have applied information theory concepts to a joystick tracking task [40, 41]. These studies show that by applying information theory to human-machine systems, human information processing can be quantified in an objective manner. Furthermore, this approach allows for the treatment of human cognition as a “black box” system with an information input and an output, allowing for the application of engineering principles [1].

### 1.2.4 The Human Operator Informatic Model

While many previous studies have investigated human performance using the Hick-Hyman law and Fitts’s law, these studies have largely focused on the performance of a single task. In 2007, Phillips and colleagues published a mathematical model based on these equations to quantitatively describe information processing of a human operator during a multitasking scenario [12]. This study has since been expanded to produce the Human Operator Informatic Model (HOIM) [13, 14]. The major accomplishment of the HOIM is that it
uses a single, objective, quantitative metric to evaluate human multitasking performance. This performance metric can be considered a measure of information throughput, i.e., the fraction of the total information that the human correctly processes.

### 1.2.4.1 Baud Rate

A baud rate is defined as spatial information content of a stimulus event divided by the temporal information content. Let us define the spatial information content of the $i^{th}$ task as $Q_i$, where $i = L, D, C, R, T$ and denotes the Lights, Dials, Communications, Resource, and Targeting tasks. Let us also define the temporal information content as the average period between stimulus events. For the $i^{th}$ task, the average time between events is the interstimulus interval, or the $ISI_i$. Thus, the MATB machine presents the operator with an information baud rate for each task, $\beta_{INi}$, measured in bits/s:

$$\beta_{INi} = \frac{Q_i}{ISI_i}$$  \hspace{1cm} (1.5)

The overall machine input baud rate, $\beta_{IN}$, can be written as the sum of the input baud rates for each task: Lights, Dials, Resources, Communications, and Targeting.

$$\beta_{IN} = \beta_{INL} + \beta_{IND} + \beta_{INC} + \beta_{INR} + \beta_{INT}$$  \hspace{1cm} (1.6)

The output baud rate can now be defined as that fraction of the input baud rate to which the human operator correctly responded, in bits/s.

$$\beta_{O} = \beta_{OL} + \beta_{OD} + \beta_{OC} + \beta_{OR} + \beta_{OT}$$  \hspace{1cm} (1.7)
The derivations of input baud rates and output baud rates for each task are detailed in Section 2.3. The HOIM is shown schematically in Figure 1.7 and treats the human operator as a black box system with an input, $\beta_{IN}$, and an output, $\beta_{O}$.

### 1.2.4.2 Performance

The Human Operator Informatic Model defines performance, $Pf$, as a measure of information throughput, or the fraction of information that the human operator correctly processes. This measure, $\bar{\beta}$, is the ratio of the human operator information output rate to the machine-generated input rate:

$$Pf = \bar{\beta} = \frac{\beta_{O}}{\beta_{IN}}$$  \hspace{1cm} (1.8)

Substituting Equations 1.6 and 1.7 into Equation 1.8 yields an expanded form of the performance function:

$$\bar{\beta} = \frac{\beta_{OL} + \beta_{OD} + \beta_{OR} + \beta_{OC} + \beta_{OT}}{\beta_{INL} + \beta_{IND} + \beta_{INR} + \beta_{INC} + \beta_{INT}}$$  \hspace{1cm} (1.9)

The development of the HOIM marks a significant accomplishment in the field of
cognitive neuroscience. Previous studies with MATB have often used multiple error rates and response times to describe performance of each task individually; examples of the use of multiple performance metrics can be seen in References [24, 25, 27, 28, 42], to name a few. The HOIM presents a single metric, $\bar{\beta}$, to describe multitasking performance. Further, since the HOIM is based on information theory [12, 30, 31, 32, 33], the calculation of throughput is superior to previous methods, as these methods fail to account for the relative spatial and temporal difficulties of each task. Additionally, this model allows for a quantitative evaluation of operator strategy, discussed in Section 2.1.

1.2.5 Prior Research with the HOIM

1.2.5.1 Phillips, et al., 2007

To date, three studies using the HOIM have been published. The first article, published in 2007, presents the theoretical model [12]. The experiment accompanying the proposed model by Phillips, et al., consists of subjects performing the Lights, Dials, Communications, and Targeting tasks. At the time of publication, the model did not include a quantitative description of the Resource task. The authors prompted the subjects to utilize an implicit strategy by issuing instructions with the following characteristics: “(a) perform the tasks quickly and accurately; (b) all tasks are equally weighted; (c) do not ignore one task at the expense of another; (d) the subject was given a goal to maximize his/her score; and (e) the subject was not provided any feedback (either in real time or after the experiment) regarding his/her performance (or the performance of others)” [12]. With an implicit strategy such as this, one would expect the operator’s response ratios for each task
to be equal. However, the results of the study show that the subjects tended to not equally weight each task; for example, it seems that the Communications task received more attention than the Dials task. Further, the authors found that while utilizing an implicit strategy, the human operators’ information throughput, \( \bar{\beta} \), tended to decrease as \( \beta_{IN} \) increased. Interestingly, the operator output, \( \beta_O \), increased with increasing \( \beta_{IN} \). The authors argue that the traditional measure of operator output, \( \beta_O \), is just that: a human performance parameter [12]. In contrast, information throughput, \( \bar{\beta} \), represents a human-machine interaction (HMI) parameter because it relates operator-generated output to machine-generated input. While human output rate may increase with increasing machine input rate, the increase in output is not a proportional increase to the increase in information input. As a result, the information throughput shows significant decline.

### 1.2.5.2 Craig Walters’s Master’s Thesis, 2012

In 2012, Craig Walters’s thesis provided a deeper insight into the Human Operator Informatic Model [13]. This work led to the inclusion of the Resource Management component in the HOIM. The designed experiment involved prompting subjects to utilize an explicit strategy to perform the MATB simulations. This was done by informing subjects of the relative machine weightings of each task. After performing a series of task combinations at low and high levels, Walters concluded that human operators change their strategy as difficulty, i.e., \( \beta_{IN} \), changes.
1.2.5.3 Phillips, et al., 2013

The most recent publication utilizing the HOIM was published in 2013 [14]. The purpose of this study was to compare the performance of MATB operators using an implicit strategy to that of those using an explicit strategy. At the time the experiments were conducted, the HOIM did not include a term for the Resource task. The authors used the data from the 2007 study for the implicit strategy operator group. To prompt subjects to use an explicit strategy, the authors informed their subjects of the machine weightings for each task. They also placed a placard of the task weightings next to the operator’s computer station to reference during a simulation. As mentioned in Section 1.2.5.1, the subject group using an implicit strategy was unable to match their output weighting to the machine weighting. However, when subjects were informed of the machine weighting, Phillips and colleagues found that they were able to achieve a unity strategy, described in Section 2.2, particularly for lower input baud rates. At higher input baud rates, the response ratios were approximately equal, with a slight tendency to overweight the Lights task. The authors believe this could be due to the relatively low spatial information of each Lights stimulus. At higher $\beta_{IN}$ levels, the Lights task may be perceived easier than the other tasks. Interestingly, the explicit strategy group achieved significantly higher throughput than the implicit strategy group for every $\beta_{IN}$ level tested. The authors note that an effective strategy, such as the unity strategy, allows the operator to “work smarter not harder” [14]. This study demonstrates the importance of an effective strategy with respect to human multitasking performance.
1.2.6  Factors Affecting Human Performance

1.2.6.1  Individual Factors

Many individual factors exist that affect human performance of cognitive tasks. For example, some studies have found scientific evidence supporting the old adage that “practice makes perfect”. Early studies from the late 19th century related repetition and practice to improved performance in a single-task Morse Code activity [43, 44]. These studies concluded that performance “plateaus” and eventually reaches a maximum after sufficient practice. However, about 60 years later, another study showed that this “plateau” in performance could be overcome with different training methods [45]. In 1993, a different study examined the effect of deliberate practice on another single-task activity: playing a musical instrument . The authors define “deliberate practice” as highly structured practice driven by the explicit goal of improving performance [46]. The study concluded that deliberate practice over extended periods of time is related to the mastery of a skill, rather than an individual’s “natural talent”. These conclusions are intriguing, as they suggest that an individual’s maximum performance is not strictly governed by innate limits, but rather of variables capable of being controlled, such as training methods and amounts of practice. More recently, a study found that single-task training has limited effect on multiple task performance, finding evidence that multiple task performance is significantly improved with multiple-task training [47].

While it is fairly intuitive that practice affects performance, it may be surprising that practice produces significant changes in brain activity. In 2009, a Chinese study evaluated the long-term effects of practice on brain activity using positron emission tomography
PET) [48]. The study compared the PET scans of two groups as they performed mental calculations by visualizing an abacus. One group of subjects was new to abacus-based calculations, while the second group consisted of experts recommended by the Abacus Calculation Promoting Association. As expected, the abacus experts performed calculations faster and more accurately than the non-experts. However, the PET scans showed notable differences in metabolic brain activity. The non-expert group showed significantly more activation in the superior frontal and left frontal areas than the expert group, while the expert group showed greater activation in the parietal lobe than the non-experts. The authors reason that the non-experts are spending more time planning and coordinating the calculation, while the more practiced expert group is immediately proceeding with the visualizations and calculations. Although this study examined a single-task activity, research shows that training also improves multitasking performance; however, the neurophysiological mechanism remains uncertain [49].

In addition to practice, there is evidence that working memory capacity affects multitasking performance. A 2005 publication examined attention, working memory, and intelligence as factors that affect multitasking performance and found that of these, working memory capacity was the best indicator of performance [50]. More specifically, the authors later found that working memory is a predictor of multitasking speed and error rate [51]. Another investigation found that while intelligence and working memory capacity are correlated, working memory capacity is the best indicator of multitasking performance [52]. Similar results have been reported by Cowan, et al. [53]. Understanding working memory capacity’s role in task performance could help to account for differences between individuals [54].
Biochemical factors have also been shown to affect cognitive function and performance between individuals. Numerous studies have investigated the effects of serotonin on cognitive performance for singletasking activities. Riedel, et al. evaluated cognitive task performance in subjects who were given an amino acid mixture with or without tryptophan, the precursor to serotonin [55]. The group that was given the mixture without tryptophan experienced reduced performance and long-term memory, compared to the group that was given the tryptophan mixture; short-term memory was not significantly impaired. Another study by Riedel, et al. found that certain serotonergic reuptake inhibitors impairs vigilance when compared to placebo [56]. Schmitt, et al. report that low serotonin levels impair cognitive performance, but normalizing serotonin levels could have a positive impact on cognition and memory [57]. Another chemical affecting human performance of both single- [58] and multi-tasking [59] is caffeine. Reference [59] shows that moderate amounts of caffeine improves performance of MATB tasks. Other chemical factors that have been shown to affect human cognitive performance include amphetamines [26, 60], alcohol [60], diazepam [60], cannibis drugs [60, 61], ecstasy (MDMA) [61], and certain antihistamines [25, 62].

1.2.6.2 Task Difficulty

In addition to individual factors, studies have shown that the task itself can affect performance. In particular, many psychologists have long examined workload as a factor controlling performance. Mental workload has been defined as the mental effort exerted by a human operator while performing a cognitive task [4]. In 1908, Yerkes and Dodson proposed that very low workload causes the operator to be understimulated and very high
workload causes the operator to be overstimulated [63]. Either scenario can have negative effects on performance. According to the Yerkes-Dodson law, there is an optimal workload level that results in a maximum performance. Although this hypothesis was originally developed to describe singletasking, a recent published study suggests the same inverted-U relationship between performance and multitasking difficulty [64].

### 1.2.6.3 Task Design: Multiple Resource Theory

Task design has also been shown to affect performance. Multiple resource theory (MRT) seeks to describe human performance with respect to the design of multitasking activities. Originally developed in 1980 [65], MRT was updated in 2000 [66] and 2002 [67]. The model proposes that the human has multiple, albeit limited, independent resource systems to allocate during multitasking. There are four dimensions of resources: processing stages, perceptual modalities, visual channels, and processing codes. Tasks that use the same level of any dimension may interfere with each other, resulting in decreased performance. The distinct “stages” of a task are the perceptual/cognitive processing and the selection/execution of a response. Interference may occur if two tasks are highly dependent on the resources of one stage (e.g., two tasks are processing-intensive or two tasks are response-intensive). Similarly, if tasks use the same sensory modalities, human performance is expected to decline. Examples of sensory modalities include the visual, auditory, or tactile systems. Nested within the visual modality are the visual channels, which can be either focal or ambient. Focal vision refers to fine detail and pattern recognition; tasks involving focal vision may include reading text or identifying small objects. Ambient vision, on the other hand, relies on peripheral vision. An everyday task requiring ambient vision is keep-
ing a car in the center of a lane while driving. Many tasks take advantage of the parallel processing of these two visions. Wickens gives the example of a person reading a book while walking down a hallway [67]. However, like the other dimensions, task interference and performance degradation may occur if multiple tasks are heavily dependent on any one visual channel. Lastly, processing codes describe the operator output and are categorized as either spatial or verbal. Spatial codes may involve the operator responding to a task by moving a mouse, joystick, or steering wheel. Verbal codes involve a spoken response from the human operator. Multiple resource theory offers a well-supported and intuitive model to relate task design to human operator performance. It also provides an explanation of why some tasks are performed easily together (e.g., driving and talking), while some are not (e.g., driving and texting).

1.2.7 Strategy

In general, strategy is the way that a human operator divides his/her time and attention. Operators use strategies to prevent or manage information overload while performing an information processing task [68]. However, strategies may also result in decreased efficiency of information transmission. According to Schaeken, et al., there are two types of strategy: implicit and explicit [69]. Implicit strategy is characterized by task performance without a specified goal, without pertinent strategy information, and without performance feedback. In contrast, an explicit strategy is one in which the operator works towards a specified goal after being provided with important strategy information. Further, the operator is provided with feedback on their performance, either during or after the task. Strategy
has long been considered a side effect of multitasking, rather than a variable capable of being controlled. For instance, multiple resource theory indirectly suggests altering strategy [67]. The model states that multitasking performance can be improved by redesigning the task so that the operator may better perform both tasks simultaneously. In this scenario, it seems that changing the design of the task has the side effect of changing operator strategy. Similarly, increasing the number of sensory modalities has been shown to improve multitasking performance, presumably by shifting the operator’s attention. As an example, Seagull, et al., evaluated eye movement data during simultaneous performance of a tracking task and monitoring task [70]. The monitoring task used a visual, auditory, or combined display to present information. The group found that performance of the tracking task was best when the monitoring task used the auditory display, reasoning that this could be because subjects were spending more time visually fixating on the tracking task. This would indirectly imply that the multimodal display alters operator strategy of the dual-task performance. In another paper, the use of tactile cues on a gauge task while performing a monitoring task was investigated [71]. The authors found that the tactile cues improved accuracy and response time of the gauge task, which they hypothesize is due to shifting the operator’s attention. However, these studies lack a reliable method to measure operator attention and strategy. The measurement of operator strategy in objective and quantifiable terms is a notable achievement of the HOIM.
1.2.8 Auditory and Haptic Feedback Effects on Information Processing

Somatosensory feedback is often used to enhance human performance. A visual-based task, for example, might allow for improved performance by assisting the human operator with auditory signals or alerts. Task enhancement using auditory feedback has been shown to improve operator performance in a variety of technologies, such as computer programming interfaces [72, 73], automobile navigation systems [74, 75], and computer-based monitoring systems [76, 77]. Additionally, much research has been conducted to identify effective auditory tones for attentional cueing applications. In general, effective auditory signals are audible and distinct from the sound environment [78]. Once signals have been established, they should become standardized in the work environment; a signal used for one situation should not be used for another situation. In 1997, the Department of Defense (DoD) released updated military standards for aircrew station alerting systems [79]. Specifically, the auditory alerting requirements must follow those established in the DoD standards for Human Engineering [80]. By these standards, auditory alerts must have a distinct meaning, be differentiable by human ear, and not interfere with other sound sources. The standardization also holds that “when used in conjunction with visual displays, audio warning devices shall be supplementary or supportive and shall be used to alert and direct user attention to the appropriate visual display” [80]. Additionally, the alert’s loudness, duration, period, and persistence are dependent on the work environment setting.

Another sensory modality used to increase human performance is the sense of touch. Haptic feedback applies vibration or force to the operator and has shown promise in many
human factors applications, such as manufacturing, telerobotics, teleoperation, education and training, and rehabilitation [81]. In the 1990s, haptic feedback proved to enhance a joystick tracking task. With the addition of force-feedback on the joystick, individuals with spastic disorders were better able to keep a cursor’s position on target in a tracking task [82, 83]. Later research showed similar results of haptic feedback aiding in perturbation rejection. In a study of normal individuals performing a joystick tracking task subject to random noise, force-reflection was shown to help subjects reduce root mean squared error of distance from the cursor to the target [84]. In addition to tracking tasks, haptic feedback has been used as an alerting mechanism to the human operator. A recent study found that vibrotactile cues can be used to direct visual attention in drivers to rapidly approaching cars [85]. The study found that drivers’ response times were significantly faster with the presence of haptic feedback than with no feedback. Other driving applications have investigated the use of haptic feedback in the steering wheel for perturbation rejection [86]. Further, studies have shown that haptic feedback assists operators in target identification on computer interfaces. For example, the use of vibrotactile feedback from a computer mouse has been shown to improve operators’ time to identify targets [87]. Another study found that vibrotactile feedback from a computer mouse improved response time when visibility was reduced [88]. Haptic feedback may also play a role in human-machine interactions in military applications. For example, Chen, et al. found that tactile feedback improved response time on gunnery, communications, and robotics tasks when compared to control conditions without tactile feedback [89]. Haptic feedback has even been shown to improve performance of blind computer operators in target identification tasks [90]. While these studies show great promise for haptic technology in human performance applications, very
few studies have examined the effect of haptic feedback in multitasking environments. Enriquez, et al. [91] performed an experiment involving multitasking; participants read text from a screen while monitoring gauges. If a gauge went out of bounds, a haptic alert would be applied to the participants’ hands via a steering wheel device. The study found that haptic feedback was successful in alerting the participants to a potential problem by rapidly diverting their attention from one task to another. Since haptic technology is still relatively new, few military standards currently exist; however, the DoD mandates that any haptic alert be “unambiguous” [80].

1.2.9 Concluding Remarks

A large effort in the field of cognitive neuroscience is focused on enhancing human performance. However, surprisingly little work has been conducted on multitasking performance. Even with the increased role of machine automation, human operators remain critical in decision making and execution of multiple tasks [92]. A better understanding of human multitasking performance and strategy could have potential applications in virtually all sectors of society, ranging from everyday life to industrial and military applications.
Mathematical Methods

2.1 Relationship between Strategy and Information Throughput

The mathematical relationship between strategy and information throughput is given below.

Define \( W_i \), the machine operation weighting coefficient, as

\[
W_i = \frac{\beta_{IN_i}}{\beta_{IN}} \tag{2.1}
\]

where \( i = L, D, C, R, T \). Similarly, \( \widehat{W}_i \), the operator weighting coefficient can be defined for each task as

\[
\widehat{W}_i = \frac{\beta_{Oi}}{\beta_O} \tag{2.2}
\]

The operator weightings, \( \widehat{W}_i \), represent the strategy. They provide information on how the operator is allocating their information output amongst the four components.

Also define a component-specific fractional throughput as:

\[
\bar{\beta}_i = \frac{\beta_{Oi}}{\beta_{IN}} \tag{2.3}
\]
This quantity denotes the fraction of component-specific operator output rate to the total input information rate. The sum of the component-specific fractional throughputs is equal to the total information throughput, $\bar{\beta}$. First, apply Equation 2.3 to obtain the sum of the component-specific fractional throughputs:

$$\Sigma \bar{\beta}_i = \frac{\beta_{OM}}{\beta_{IN}} + \frac{\beta_{OC}}{\beta_{IN}} + \frac{\beta_{OR}}{\beta_{IN}} + \frac{\beta_{OT}}{\beta_{IN}}$$

(2.4)

Adding the fractions and substituting Equations 1.7 and 1.8 into Equation 2.4 gives:

$$\Sigma \bar{\beta}_i = \frac{\beta_O}{\beta_{IN}} = \bar{\beta}$$

(2.5)

The mathematical relationship between strategy and information throughput performance can be derived. Rearranging Equation 2.2 gives:

$$\beta_{O_i} = \hat{W}_i \beta_O$$

(2.6)

Next, divide both sides of Equation 2.6 by $\beta_{IN}$

$$\frac{\beta_{O_i}}{\beta_{IN}} = \hat{W}_i \frac{\beta_O}{\beta_{IN}}$$

(2.7)

Finally, substitution of Equations 1.8 and 2.3 into Equation 2.7 yields the mathematical relationships between operator strategy and performance:

$$\bar{\beta}_i = \hat{W}_i \bar{\beta}$$

(2.8)
2.2 Definition of Unity Model Paradigm

Phillips, et al. present an interesting idea in their 2007 paper which they call the “unity model paradigm” [12]. For such a paradigm to occur, the operator’s output weighting matches in machine’s input weighting. Let \( f_i \) represent the ratio of operator task weighting to machine task weighting:

\[
f_i = \frac{\widehat{W}_i}{W_i}
\]  

(2.9)

Thus, in a unity model paradigm, the operator’s output matches the machine’s information input for each task.

\[
f_L = f_D = f_C = f_R = f_T = 1
\]  

(2.10)

2.3 HOIM Applied to MATB

2.3.1 Systems Monitoring

Lights

When a Light event occurs, the machine presents the human operator with two alternatives of choice: press the F5 key or the F6 key. By applying Equation 1.2, the spatial information content of the Light events, \( Q_L \), can be calculating as

\[
Q_L = \log_2 2 = 1 \text{ bit}
\]  

(2.11)
Further, since the user sets the number of light events and sets the length of the simulation, the average time between light events, $ISI_L$, can be calculated as

$$ISI_L = \frac{\text{Simulation length}}{\text{Number of light events}}$$  \hspace{1cm} (2.12)

where “Simulation length” and $ISI_L$ have units of seconds. The resulting input baud rate for Lights is then found.

$$\beta_{INL} = \frac{Q_L}{ISI_L} = \frac{1}{ISI_L} \text{ bits/s}$$  \hspace{1cm} (2.13)

The rate of information to which the human operator correctly responds for the Lights task, can now be calculated as $\beta_{OL}$. Define $\rho_L$ as the fraction of Light events to which the operator correctly responds. For example, if a MATB simulation has 10 light events and the human operator correctly responds to 7 of these events, $\rho_L$ would be equal to 0.7. The output baud rate can be computed.

$$\beta_{OL} = \rho_L \beta_{INL}$$  \hspace{1cm} (2.14)

**Dials**

For each Dials event, the machine presents four alternatives of choice: the human operator may press the F1, F2, F3, or F4 key. Thus, the spatial information input content for each Dials event can be computed from Equation 1.2 as

$$Q_D = \log_2 4 = 2 \text{ bits}$$  \hspace{1cm} (2.15)
Similar to the Lights task, the user sets the number of Dials events per simulation, resulting in an average time between Dials events, $ISI_D$, per Equation 2.12. Thus, the input baud rate for Dials is

$$\beta_{IN_D} = \frac{Q_D}{ISI_D} = \frac{2}{ISI_D} \text{ bits/s}$$  \hspace{1cm} (2.16)$$

Defining $\rho_D$ as the fractional accuracy of the Dials task, the output baud rate for Dials can then be found.

$$\beta_{OD} = \rho_D \beta_{IN_D}$$  \hspace{1cm} (2.17)$$

### 2.3.2 Communications

Each Communications task consists of two parts: first the operator must select the specified channel, then he/she must select the specified frequency. Thus, the total spatial information for a Communications task, $Q_C$ is the sum of the information from the two parts.

$$Q_C = Q_{ch} + Q_{freq}$$  \hspace{1cm} (2.18)$$

The channel selection consists of four alternatives of choice. The frequency selection consists of 13 alternatives of choice, or the average number of key clicks required by the operator to change frequency. Therefore,

$$Q_{ch} = \log_2 4 = 2 \text{ bits}$$  \hspace{1cm} (2.19)$$

$$Q_{freq} = \log_2 13 = 3.7 \text{ bits}$$  \hspace{1cm} (2.20)$$
Substituting these values into Equation 2.18,

\[ Q_C = 2 + 3.7 = 5.7 \text{ bits} \]  \hspace{1cm} (2.21)

Since the user specifies the number of Communications events per simulation, the inter-stimulus interval for the Communications task, \( ISI_C \), is the average time between events. Thus, the input baud rate for Communications is

\[ \beta_{INC} = \frac{Q_C}{ISI_C} = \frac{5.7}{ISI_C} \text{ bits/s} \]  \hspace{1cm} (2.22)

Similar to the Lights and Dials, Communications is a discrete task. The fractional accuracy for Communications, \( \rho_C \), is therefore, the fraction of events to which the operator correctly responded. The operator output baud rate for communications can then be found.

\[ \beta_{OC} = \rho_C \beta_{INC} \]  \hspace{1cm} (2.23)

### 2.3.3 Resource Management

For the Resource Management task, the human operator controls the tanks by pressing the “2” and “4” keys. Thus, the machine presents two alternatives of choice and the spatial information content per stimulus is

\[ Q_R = \log_2 2 = 1 \text{ bit} \]  \hspace{1cm} (2.24)
The calculation for the Resource interstimulus interval, is slightly different from the discrete Lights, Dials, and Communications tasks. For the discrete tasks, the user sets the number of stimulus events. However, the Resource task is continuous in nature. The user sets the volumetric drain rate of the tank, $\dot{V}_0$. The tanks will each drain at this constant rate while the pump is “OFF”. When the pump is “ON”, the tank will fill at a rate of $2\dot{V}_0$ while continuing to drain at $\dot{V}_0$. Consequently, the tank will either drain at a rate of $\dot{V}_0$ when the pump is ON or fill at a net rate of $\dot{V}_0$ when the pump is OFF. During IT mode, the drain rate is set to $\dot{V}_0 = 100$ units per second, while the fill rate is set to $2\dot{V}_0 = 200$ units per second. The time between events can then be computed as the time for the liquid to move from the midpoint of the tolerance region to either boundary. The tolerance region is set at 15% of the total tank volume, $V_{TOT}$. Since the volumetric rate of change is also known, the time between Resource events can now be expressed as

$$ISI_R = \frac{0.075V_{TOT}}{\dot{V}_0}$$

(2.25)

Finally, the input baud rate for Resource Management is

$$\beta_{INR} = \frac{Q_R}{ISI_R} = \frac{1}{0.075V_{TOT}/\dot{V}_0} \text{ bits/s}$$

(2.26)

It should be noted that for the Resource task, the user controls $\beta_{INR}$ by adjusting $V_{TOT}$, the total volume of each tank.

For the Resource Management component, $\rho_R$ is a delay-adjusted percent of time that the operator maintains the fuel level within or towards the specified range. Define $dT_{ON}$ as
the time in seconds that the fuel level is within the specified range, i.e., the time that the operator keeps the fuel level on target. Define \( dT_{TO} \) as the time in seconds that the fuel level is outside of the specified range but is moving towards the target range due to the operator performing the correct pump-toggle action. Also define the total MATB simulation time in seconds as \( \Delta T \). The fractional accuracy for the Resource Management component is then calculated as:

\[
\rho_R = \frac{dT_{ON} + 0.5dT_{TO}}{\Delta T} \tag{2.27}
\]

Note that the \( dT_{ON} \) quantity gives credit to the operator for keeping the fuel in the target range while the \( 0.5dT_{TO} \) quantity gives half-credit to the operator for taking the corrective action after the fuel level went outside of the target range. The output baud rate for Resource can be computed.

\[
\beta_{OR} = \rho_R \beta_{INR} \tag{2.28}
\]

### 2.3.4 Targeting

For the Targeting task, let us define the cursor diameter as \( D \), equal to 33 pixels. The target diameter is then equal to \( 3D \), or 99 pixels. Consider a scenario in which the cursor has drifted \( 3D \) pixels from the target. The amplitude of movement, \( A \), is equal to \( 3D \). The tolerance range, \( W_a \), is equal to the effective width of the target, \( 3D - D = 2D \). Substituting into Fitts index of difficulty equation, Equation 1.3, the spatial information content of the Targeting task, \( Q_T \), is then computed.

\[
Q_T = \log_2 \frac{3D}{2D/2} \tag{2.29}
\]
\[ Q_T = \log_2 3 = 1.58 \text{ bits} \]  

(2.30)

The interstimulus interval is the time elapsed for the cursor to drift 3D pixels from the target. Since time is distance divided by velocity, \( ISI_T \) can be computed as

\[ ISI_T = \frac{3D}{V} \]  

(2.31)

where \( V \) is the user-defined average cursor drift velocity in pixels/s. The input baud rate for Targeting is then

\[ \beta_{INT} = \frac{1.58}{3D/V} \text{ bits/s} \]  

(2.32)

Note that \( \beta_{INT} \) is controlled by adjusting \( V \) while \( D \) remains constant at 33 pixels.

Targeting is a time-on-target task. Thus, the fractional accuracy, \( \rho_T \), is the fraction of seconds during the MATB simulation that the operator keeps the cursor on target. The information output rate for Targeting is then

\[ \beta_{OT} = \rho_T \beta_{INT} \]  

(2.33)
Experiment 1: Evaluation and Validation of HOIM Throughput Components

3.1 Objectives

3.1.1 Objective A

First, this experiment sought to evaluate various task combinations at a constant input baud rate. Although prior literature has studied human multitasking performance of different task combinations, the total information rate is not typically maintained at a controlled value, due to a lack of objective metrics.

3.1.2 Objective B

Second, this experiment sought to validate the Human Operator Informatics Model independent throughput components.
3.2 Experimental Methods

3.2.1 Participants

Thirty-one volunteers (mean age=25.6, SD=6.1) from Wright State University signed a consent form approved by the Wright State University Institutional Review Board. Participants were screened to ensure that they were able to operate a mouse and joystick, able to hear audio signals, have normal or corrected to normal vision, and were not colorblind. All participants had no prior experience with MATB.

3.2.2 Equipment

3.2.2.1 Hardware

All MATB simulations were performed on an HP Compaq 8200 Elite desktop computer with a 3.10 GHz, quad-core Intel i5 processor and the Windows 7 (x64) operating system. Simulations were displayed on a 24-inch HP EliteDisplay E221 monitor. Participants interacted with MATB using an HP mouse, and a CH Products Fighterstick USB joystick.

3.2.2.2 Software

The 2014 version of Air Force MATB in Information Throughput mode was utilized for data collection [29]. Data analysis was performed using JMP statistical software [93].
Table 3.1: List of MATB information input rates.

<table>
<thead>
<tr>
<th>Task Combination</th>
<th>$\beta_{INM}$</th>
<th>$\beta_{INC}$</th>
<th>$\beta_{INR}$</th>
<th>$\beta_{INT}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCR</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>MCT</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>MRT</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>CRT</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>MCRT</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
</tr>
</tbody>
</table>

3.2.3 Procedures

First, each participant was introduced to the MATB software with a verbal description of each task. Each participant then received a four-minute practice session to familiarize themselves with the MATB controls. Participants were observed to ensure that they correctly understood the instructions.

After the practice session, participants began the trial runs. Each participant completed five four-minute MATB simulations. Each of the five simulations had a unique task combination defined as follows: MCR (Monitoring, Communications, and Resource present; no Targeting), MCT (Monitoring, Communications, and Targeting present; no Resource), MRT (Monitoring, Resource, and Targeting present; no Communications), CRT (Communications, Resource, and Targeting present; no Monitoring), and MCRT (Monitoring, Communications, Resource, and Targeting present). Trial order was randomized to control for order effects. The total session time for each participant was less than an hour to avoid fatigue-related performance effects. Each of the five unique task combinations had an information input rate, $\beta_{IN}$, of 1.2 bits/s. Machine weightings, $W_i$, were equal: for the task combinations with three tasks, each $W_i$ equaled $\frac{1}{3}$ of the total input information; for the task combination with four tasks, each $W_i$ equaled $\frac{1}{4}$ of the total input information.
Table 3.2: ANOVA results to evaluate the effect of number of tasks on information throughput performance.

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>SS</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Tasks</td>
<td>1</td>
<td>0.0214</td>
<td>1.5867</td>
<td>0.2097</td>
</tr>
<tr>
<td>Error</td>
<td>153</td>
<td>2.0646</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>154</td>
<td>2.0860</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Component-specific input information rates are listed in Table 3.1.

### 3.2.4 Experimental Hypothesis

It was hypothesized that different task combinations would result in different information throughput performance results. It was also hypothesized that the four-task combination, MCRT, would have a lower performance compared to the three-task combinations.

### 3.3 Experimental Results

After completion of all experimental runs, results were analyzed using JMP Statistical Software [93]. First, an ANOVA was conducted to compare the performance of the three-task combinations to the performance of the four-task combination. No significant difference in performance was detected based on the number of tasks ($p = 0.2097$, shown in Table 3.2).

A second ANOVA was conducted to compare the performance across all five different task combinations; no significant differences were detected ($p = 0.5253$, shown in Table 3.3). Throughput results are listed in Table 3.4.

Operator strategy was also assessed as $\widehat{W}_i$ using the HOIM. These results are given in Table 3.5. For any component, M, C, R, or T, $\widehat{W}_i$ was the lowest during the MCRT task.
Table 3.3: ANOVA results to evaluate the effect of task combination on information throughput performance.

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>SS</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Task Combination</td>
<td>4</td>
<td>0.0437</td>
<td>0.8026</td>
<td>0.5253</td>
</tr>
<tr>
<td>Error</td>
<td>150</td>
<td>2.0423</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>154</td>
<td>2.0860</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.4: Average information throughput results for different task combinations. Standard deviations shown in parentheses.

<table>
<thead>
<tr>
<th>Number of Tasks</th>
<th>Task Combination</th>
<th>Combination Throughput</th>
<th>Average Throughput</th>
</tr>
</thead>
<tbody>
<tr>
<td>Four</td>
<td>MCRT</td>
<td>0.6477</td>
<td>0.6477 (0.1087)</td>
</tr>
<tr>
<td></td>
<td>MCR</td>
<td>0.6625</td>
<td></td>
</tr>
<tr>
<td></td>
<td>MCT</td>
<td>0.6713</td>
<td>0.6770 (0.1179)</td>
</tr>
<tr>
<td></td>
<td>MRT</td>
<td>0.6755</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CRT</td>
<td>0.6988</td>
<td></td>
</tr>
<tr>
<td>Three</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

combination compared to the other three-component combinations. Additionally, Table 3.5 shows that operators had the tendency to place the highest weighting on the Communications component and the lowest weighting on the Resource component. Average fractional throughput results, $\bar{\beta}_i$, are listed in Table 3.6.

Table 3.5: Average operator strategy results.

<table>
<thead>
<tr>
<th>Combination</th>
<th>$\bar{W}_M$</th>
<th>$\bar{W}_C$</th>
<th>$\bar{W}_R$</th>
<th>$\bar{W}_T$</th>
<th>Average $\bar{\beta}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCRT</td>
<td>0.2251</td>
<td>0.3303</td>
<td>0.2060</td>
<td>0.2386</td>
<td>0.6477</td>
</tr>
<tr>
<td>MCR</td>
<td>0.3283</td>
<td>0.4106</td>
<td>0.2611</td>
<td>—</td>
<td>0.6625</td>
</tr>
<tr>
<td>MCT</td>
<td>0.3083</td>
<td>0.4052</td>
<td>—</td>
<td>0.2865</td>
<td>0.6713</td>
</tr>
<tr>
<td>MRT</td>
<td>0.4052</td>
<td>—</td>
<td>0.2698</td>
<td>0.3250</td>
<td>0.6755</td>
</tr>
<tr>
<td>CRT</td>
<td>—</td>
<td>0.4084</td>
<td>0.2676</td>
<td>0.3240</td>
<td>0.6988</td>
</tr>
</tbody>
</table>
3.4 Discussion

3.4.1 Objective A

3.4.1.1 Number of Tasks and Performance

The results above indicate that the number of tasks does not significantly affect performance. Although numerous studies have shown that an increasing number of tasks has a negative effect on performance [10, 15, 20, 21, 22], these studies do not maintain a constant difficulty level. Thus, by increasing the number of tasks, the total information input rate presented to the human operator also increases. In contrast, this study maintained a constant difficulty rate of 1.2 bits/s. When difficulty was held constant, number of tasks was not found to affect performance.

3.4.1.2 Strategy and Performance

The HOIM is also useful in quantitatively assessing the relationship between strategy and performance. During the MCRT combination, operators allocated 22.51% of their total information output to Monitoring, 33.03% to Communications, 20.60% to Resource, and 23.86% to Targeting. However, when one component was removed and the operator per-
formed a three-task combination, the operator was able to reallocate that portion of their output across the remaining components. For example, when Monitoring was removed during CRT, the operator had 22.51% of their output to redistribute across the Communications, Resource, and Targeting components. The increase in operator weighting to each component accompanied an increase of component-specific fractional throughput when compared to MCRT. This can be seen in Table 3.6. The fractional throughput for Communications, $\bar{\beta}_C$, rose from 0.2116 in MCRT to 0.2824 in CRT. Similarly, $\bar{\beta}_R$ rose from 0.1326 in MCRT to 0.1870 in CRT while $\bar{\beta}_T$ rose from 0.1570 in MCRT to 0.2294 in CRT.

### 3.4.2 Objective B

#### 3.4.2.1 Multiple-Task Interference

Psychologists and other researchers of human performance have long studied the effects of divided attention across multiple tasks. A 1927 study found that the response time for a task increases when subjects were required to shift attention between alternating tasks [94]. This phenomenon is called multiple-task interference (or dual-task interference for multitasking of two simultaneous tasks). Multiple-task interference refers to the cost of performing additional tasks on the performance of the first task. In this study, multiple-task interference can be seen. For example, during the three-task combination of MCR, the average fractional throughput for the Monitoring component was 0.2218. However, when an additional task (Targeting) was added for the MCRT combination, the average fractional throughput for the Monitoring component fell to 0.1465. It is also important to note that since the *overall* performance did not significantly change, the overall operator output also
did not significantly change. Instead, it appears that the output was simply redistributed across the tasks.

### 3.4.2.2 Linear Independence of Throughput Channels

The lack of difference in performance across the different task combinations also suggests that there is no task interaction effect. For example, if the Resource task interacted negatively with the Monitoring task, one would expect to see an increase in operator output for MCT or CRT compared to MCRT. However, no such increase occurred. This observation helps to support the approximation of the HOIM that the throughput channels for each task are independent. Future studies should focus on regression modeling of multiple task performance and task interaction to further evaluate this hypothesis.

### 3.4.3 Reliability of the HOIM

These results highlight the reliability of using information theory to model human multi-tasking performance and strategy. The lack of performance differences amongst the different task combinations indicates the reliability of $\beta_{IN}$ as a measure of total system complexity. Further, these results suggest that individual component difficulty is appropriately described by its component-specific input information rate, $\beta_{IN_i}$. Although other studies make qualitative observations about strategy, the HOIM is unique by objectively quantifying operator strategy.
Experiment 2: Shifting Multitasking

Strategy Using Multisensorial Feedback

4.1 Experimental Methods

4.1.1 Participants

Forty volunteers (25 male, 15 female, mean age=23.3, SD=5.5) from Wright State University signed a consent form approved by the Wright State University Institutional Review Board. Participants were screened to ensure that they were able to operate a mouse and joystick, able to hear audio signals, have normal or corrected to normal vision, and were not colorblind. All participants had no prior experience with MATB.

4.1.2 Equipment

4.1.2.1 Hardware

All MATB simulations were performed on an HP Compaq 8200 Elite desktop computer with a 3.10 GHz, quad-core Intel i5 processor and the Windows 7 (x64) operating system.
Simulations were displayed on a 24-inch HP EliteDisplay E221 monitor. Participants interacted with MATB using an HP mouse, a CH Products Fighterstick USB joystick, and an Immersion Corporation haptic joystick.

4.1.2.2 Software

The 2014 version of Air Force MATB in Information Throughput mode was utilized for data collection [29]. This version of MATB was augmented using port triggering. Port triggering enabled the MATB software to interact with the haptic joystick so that it vibrated when the operator was out of bounds on the Targeting component. Data analysis was performed using JMP statistical software [93].

4.1.3 Procedures

The purpose of this study was to evaluate the effects of multisensorial feedback on MATB multitasking performance. When multisensorial feedback was present, auditory tones alerted the operators whenever a light or dial required a response. Six different auditory tones were used to uniquely correspond to the two lights and the four dials. Haptic feedback was also used as an alerting mechanism for the Targeting task; whenever the operator was out of bounds on the Targeting task, the joystick generated a vibration.

Similar to the previous experiment, each participant was introduced to the MATB software with a verbal description of each task. Each participant then received a four-minute practice session to familiarize themselves with the MATB controls. Participants were observed to ensure that they correctly understood the instructions.

After the initial practice session, each participant performed six four-minute MATB
Table 4.1: List of MATB information input rates in bits/s.

<table>
<thead>
<tr>
<th>$\beta_{IN}$</th>
<th>$\beta_{INM}$</th>
<th>$\beta_{INC}$</th>
<th>$\beta_{INR}$</th>
<th>$\beta_{INT}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8</td>
<td>0.27</td>
<td>0.18</td>
<td>0.09</td>
<td>0.27</td>
</tr>
<tr>
<td>1.2</td>
<td>0.40</td>
<td>0.27</td>
<td>0.13</td>
<td>0.40</td>
</tr>
<tr>
<td>1.6</td>
<td>0.53</td>
<td>0.36</td>
<td>0.18</td>
<td>0.53</td>
</tr>
</tbody>
</table>

runs. Three levels of $\beta_{IN}$ were examined: 0.8, 1.2, and 1.6 bits/s. At each value of $\beta_{IN}$ MATB was either augmented with the multisensorial feedback or it was not. Machine weighting ratios were equal across the different levels of $\beta_{IN}$ with $W_M = \frac{3}{5}$, $W_C = \frac{2}{9}$, $W_R = \frac{1}{9}$, $W_T = \frac{3}{9}$. Component-specific $\beta_{IN}$ at each $\beta_{IN}$ are shown in Table 4.1. Trial order was randomized to control for order effects. The total session time for each participant was less than an hour to avoid fatigue-related performance effects.

### 4.1.4 Experimental Hypothesis

It was hypothesized that the application of multisensorial feedback to the Monitoring and Targeting components of MATB would result in improved throughput performance. It was also hypothesized that an interaction effect of difficulty level and presence of feedback would affect throughput performance; although multisensorial feedback was expected to improve throughput performance, it was hypothesized that feedback would be particularly helpful at higher difficulty levels. Further, it was hypothesized that multisensorial feedback would result in a change of strategy. Operator weightings for Monitoring and Targeting were expected to increase; operator weightings for Communications and Resource were expected to decrease.
Table 4.2: ANOVA results to evaluate the effect of multisensorial feedback and task difficulty (information input rate) on information throughput performance.

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>SS</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feedback</td>
<td>1</td>
<td>0.0398</td>
<td>2.1847</td>
<td>0.1407</td>
</tr>
<tr>
<td>Difficulty</td>
<td>2</td>
<td>1.6077</td>
<td>44.1125</td>
<td>&lt;0.0001*</td>
</tr>
<tr>
<td>Difficulty*Feedback</td>
<td>2</td>
<td>0.0203</td>
<td>0.5562</td>
<td>0.5742</td>
</tr>
<tr>
<td>Error</td>
<td>234</td>
<td>4.2640</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>239</td>
<td>5.9318</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.2 Experimental Results

First, to evaluate the effect of multisensorial feedback on information throughput, an ANOVA was performed using JMP Statistical Software [93]. This two-way ANOVA used the factors of feedback, difficulty, and their interaction as inputs to predict information throughput and is shown in Table 4.2. Interestingly, multisensorial feedback was not found to improve performance at the $\alpha = 0.05$ level ($p = 0.1407$). There is evidence that difficulty significantly affects performance ($p < 0.0001$). No interaction effect between difficulty and the presence of feedback was observed ($p = 0.5742$).

One-way ANOVAs were performed at each $\beta_{IN}$ level to compare the information throughputs with and without multisensorial feedback. The results of these statistical tests are shown in Table 4.3. At each $\beta_{IN}$ level, information throughput was not significantly affected by the presence of feedback. However, as $\beta_{IN}$ increased, information throughput, $\bar{\beta}$, decreased.

One-way ANOVAs were also performed at each $\beta_{IN}$ level to compare the total information output rates, $\beta_O$, with and without multisensorial feedback. These results are listed
Table 4.3: Information throughput results with and without multisensorial feedback. Standard deviations shown in parenthesis.

<table>
<thead>
<tr>
<th>$\beta_{IN}$</th>
<th>$\bar{\beta}$ (without feedback)</th>
<th>$\bar{\beta}$ (with feedback)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8</td>
<td>0.76 (0.14)</td>
<td>0.78 (0.13)</td>
<td>0.5378</td>
</tr>
<tr>
<td>1.2</td>
<td>0.67 (0.13)</td>
<td>0.68 (0.15)</td>
<td>0.8092</td>
</tr>
<tr>
<td>1.6</td>
<td>0.55 (0.14)</td>
<td>0.60 (0.12)</td>
<td>0.0824</td>
</tr>
</tbody>
</table>

Table 4.4: Operator output results with and without multisensorial feedback. Standard deviations shown in parenthesis.

<table>
<thead>
<tr>
<th>$\beta_{IN}$</th>
<th>$\bar{\beta}_O$ (without feedback)</th>
<th>$\bar{\beta}_O$ (with feedback)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8</td>
<td>0.61 (0.11)</td>
<td>0.62 (0.11)</td>
<td>0.4699</td>
</tr>
<tr>
<td>1.2</td>
<td>0.80 (0.16)</td>
<td>0.81 (0.18)</td>
<td>0.7445</td>
</tr>
<tr>
<td>1.6</td>
<td>0.88 (0.22)</td>
<td>0.97 (0.20)</td>
<td>0.0642</td>
</tr>
</tbody>
</table>

in Table 4.4. Similar to the throughput results, the presence of feedback was not found to significantly affect operator output at any level of $\beta_{IN}$. However, as $\beta_{IN}$ increased, $\bar{\beta}_O$ also increased.

By performing one-way ANOVAs on each operator strategy component, $\hat{W}_i$, the affect of multisensorial feedback on operator strategy was assessed. These results are listed in Table 4.5. Multisensorial feedback significantly increased the operator weightings for the Monitoring and Targeting components and decreased the operator weighting for the Communications component. The presence of feedback also decreased the operator weighting for the Resource component; however, this change was not statistically significant at the $\alpha = 0.05$ level.
Table 4.5: Average operator weighting (i.e., strategy) results. Asterisk denotes a significant difference in operator weighting for $\alpha = 0.05$.

<table>
<thead>
<tr>
<th>Component</th>
<th>Without feedback</th>
<th>With feedback</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\hat{W}_M$</td>
<td>0.2938</td>
<td>0.3119</td>
<td>0.0472*</td>
</tr>
<tr>
<td>$\hat{W}_C$</td>
<td>0.2482</td>
<td>0.1975</td>
<td>&lt;0.0001*</td>
</tr>
<tr>
<td>$\hat{W}_R$</td>
<td>0.1023</td>
<td>0.0975</td>
<td>0.0986</td>
</tr>
<tr>
<td>$\hat{W}_T$</td>
<td>0.3556</td>
<td>0.3932</td>
<td>&lt;0.0001*</td>
</tr>
</tbody>
</table>

4.3 Discussion

4.3.1 Shifting Strategy with Multisensorial Feedback

Originally, it was hypothesized that multisensorial feedback would improve the overall information throughput performance. Multiple resource theory proposes that humans take in information through independent modalities [67]. Thus, it was expected that by adding additional sensory feedback, the operators would be able to use more “mental resources” to complete the tasks instead of overloading the visual modality. However, that was not observed in this study. This is particularly interesting given the large sample size of 240 experimental trials. Closer inspection of the data reveal that $\beta$ did not increase with feedback because operator output $\beta_O$ did not significantly increase with feedback.

Although multisensorial feedback did not increase overall operator output, Table 4.5 suggests a shift in operator strategy. The presence of multisensorial feedback had the effect of increasing $\hat{W}_M$ and $\hat{W}_T$ while decreasing $\hat{W}_C$ and $\hat{W}_R$. In other words, the feedback diverted the operator’s attention away from the Communications and Resource components and redirected it towards the Monitoring and Targeting components. Since this occurred as a proportional tradeoff, the total operator output did not change. As a result, no change in
performance was observed.

### 4.3.2 Effect of $\beta_{IN}$ on Performance

In their 2007 publications, Phillips et al. found that as $\beta_{IN}$ increases, $\beta_O$ also increases, but not at a proportional rate [12]. Since the $\beta_O$ does not increase as fast as $\beta_{IN}$ increases, the overall performance, $\bar{\beta}$, declines. The results presented in the current study agree with those from the 2007 study: as $\beta_{IN}$ increases, $\beta_O$ also increases but $\bar{\beta}$ decreases. This trend can be seen in Tables 4.3 and 4.4.
Nearly sixty years ago, George A. Miller presented a theoretical limitation on human information processing while performing a task, proposing that

If the human observer is a reasonable kind of communication system, then when we increase the amount of input information the transmitted information will increase at first and will eventually level off at some asymptotic value [1].

Miller applies this idea to a variety of activities by studying how transmitted information, i.e., operator output, is affected by increasing input information. For example, Miller examined data that involved having listeners determine auditory pitch. Figure 5.1 shows that as the input information increases, the transmitted information also increases, but then levels off. In this case, the operator output may asymptotically be approaching 2.5 bits. Miller refers to this maximum information output from the operator as the “channel capacity”. In another example, Miller graphed the transmitted operator output against information input for a task involving the determination of auditory loudness. Figure 5.2 shows that for this task, the operator channel capacity is 2.3 bits.
Figure 5.1: Channel capacity of the determination of auditory pitch [1].

Figure 5.2: Channel capacity of the determination of auditory loudness [1].
Although Miller’s work only examined limits on human capacity for processing information while performing a single task, his theory can be extended to multitasking. Both studies in this work showed that under similar levels of information input rate, different strategies produce similar performances. This may suggest that information output rate is an asymptotic function of information input rate. From this observation, it seems reasonable that each operator has a maximum possible output he or she can achieve while multitasking. Experiment 2 assessed operator output during multitasking at three different rates of information input. This is displayed graphically in Figure 5.3. As information input increases, the operator output also increases but disproportionately so that it appears to be leveling off. This trend is observed for the both the trials that included multisensorial feedback and those that did not. Examination of multitasking performance at higher input information rates may reveal the asymptotic limit. Using the Human Operator Informatic Model, the multitasking limitation, or the throughput capacity, might be determined.
Figure 5.3: Multitasking throughput capacity during MATB activity. Error bars show 95% confidence intervals and may be smaller than marker size.
Implications of Research and Future Work

6.1 Task Interaction Effects

Experiment 1 of this work examined different three- and four-task combinations within the Multiple-Attribute Task Battery. Since the different task combinations yielded similar performances, it can be deduced that the tasks are independent. However, a more rigorous study could evaluate this hypothesis by examining one, two, three, and four task combinations. A regression model would be appropriate to determine if any higher-order interactions exist.

6.2 Multitasking Throughput Capacity

This work presented the idea that an asymptotic limit, called the multitasking throughput capacity, exists to operator output while multitasking. Although Figure 5.3 shows that operator output appears to be leveling off, future research should examine operator output at higher levels of information input to determine the location of the asymptote. Additionally,
this work only considered the average throughput of a group. One would expect there to be
differences in multitasking throughput capacity between individuals. Future research may
investigate various factors that affect individual throughput capacity. Training effects and
methods to improve throughput capacity should also be explored. Further, this research
study involved performance in a benign environment. The military may benefit from future
studies of throughput capacity in a high-stakes, threat environment.

6.3 Application of Information Theory to Other Systems

This work evaluated the use of information theory applied within MATB. However, exten-
sion of information theory to other multitasking environments would further enhance the
utility of information theory.
Conclusions

7.1 A Case for Information-Theory Based Modeling of Human Multitasking Performance

As the technology industry produces more advances in automation, humans become heavily reliant on multitasking in many sectors in society. Although this raises a plethora of resource questions, the field of human factors has little work that objectively assesses human multitasking performance and strategy, primarily due to the difficulty of creating objective metrics. However, the Human Operator Informatic Model (HOIM) is based on Shannon’s information theory and can be applied to multitasking conditions, such as those presented in the Multiple-Attribute Task Battery (MATB) computer software. This model objectively quantifies both the overall system complexity and the overall operator multitasking performance. The work presented here found this model to reliably calculate task difficulty and overall system difficulty. Objective performance metrics revealed that task interference occurs. However, no task interaction was observed. These results highlights the utility and reliability of information theory in the modeling of human multitasking performance.
7.2 Shifting Strategy with Multisensorial Feedback

Multisensorial feedback has been shown to be useful in enhancing human performance in a wide range of tasks. However, many of these studies only examine the performance of a single task. Very little work has been conducted on how multisensorial feedback affects overall multitasking performance, presumably due to a lack of objective metrics. This work applied haptic and auditory feedback to the Targeting and Monitoring components of MATB, respectively. Compared to control, the addition of multisensorial feedback did not affect throughput performance. Analysis of operator strategy revealed that multisensorial feedback shifted operator attention away from the Communications and Resource components (which had no additional feedback) and towards the Targeting and Monitoring components. The shift in strategy also resulted in a shift in operator output. However, the increase in operator Monitoring and Targeting output was accompanied with a proportional decrease in the operator Communications and Resource output.

7.3 Theoretical Limitations of Multitasking Throughput Capacity

The two experiments in this study both suggest that each operator has some maximum, finite possible output: the multitasking throughput capacity. The multitasking throughput capacity is analogous to the singletasking channel capacity first proposed by Miller in 1956. Although it appears that interventions, such as multisensorial feedback, may shift the operator strategy, these interventions may not increase this theoretical limit. Additional re-
search may identify methods to improve an individual’s multitasking throughput capacity, thereby enhancing the capabilities of a human operator.
Appendix A

List of Publications Resulting from Dissertation

Journal Publications


Peer-Reviewed Journal Abstracts


**Conference Presentations**

Appendix B

AF-MATB-IT User Guide

Prepared by

Chandler A. Phillips, M.D., P.E.

Craig M. Walters, M.S.E.

Aerial N. Camden, M.S.E

Department of Biomedical, Industrial, and Human Factors Engineering

Wright State University

Dayton, OH 45435

27 July 2014
For a general introduction to the Air Force Adaptation of the Multiple-Attribute-Task-Battery (AF-MATB) refer to:


Contact information (below) is provided for anyone who would like the latest software release (which includes the IT implementation and build). Justin R. Estepp (JRE) maintains the repository for the AF-MATB software and will add any and all interested parties to the mailing list.

JRE is pleased to release the current software build, along with a draft of the new user’s manual, to interested individuals on a by-request basis. Once the new manuscript (cited above) is approved for publication, JRE will post it to the repository and notify the entire mailing list.
Contact:

Justin R. Estepp, DR-II
Research Biomedical Engineer
Air Force Research Laboratory

711 HPW/RHCPA
BLDG 840, W200
2510 Fifth Street
Wright-Patterson AFB, OH 45433-7951

Phone: (937) 938-3602 / DSN: 798-3602
Fax: (937) 656-6894

e-mail: justin.estepp@us.af.mil


**Introduction**

This information throughput version of MATB is based on the Human Operator Informatic Model (HOIM) of the Human-MATB Interaction (HMI) as previously reported [12, 13, 14, 95].

The mathematical formulation of the HOIM is based upon the definition of a baud rate $\beta$ as the ratio of spatial information content $Q$ (in bits) to temporal information content $[ISI]$ (in secs).

$$\beta = \frac{Q}{ISI} \quad \tag{B.1}$$

There is a specific spatial information content $Q$ to each of the four MATB components: Monitoring (M), Communication (C), Targeting (T), Resource (R). $Q$ is predefined as either Hick-Hymen [H] bits or Fitts [I.D.] bits [12, 13, 14, 95].

The Inter-Stimulus-Interval $[ISI]$ is the elapsed time during which the user must make a response in order to process the $Q$ [bits] of information.

The temporal information content $[ISI]$ for the four MATB components (M, C, T, R) is user selectable depending upon the users desired baud rates. This process is outlined in the steps that follow.
Steps

**Step 1**: User requires a total MATB generated baud rate ($\beta_{IN}$) and task duration (TD).

**Step 1A**: User requires a total MATB generated baud rate ($\beta_{IN}$).

With respect to information throughput, the $\beta_{IN}$ relationship to difficulty level may be approximated as follows:

<table>
<thead>
<tr>
<th>$\beta_{IN}$</th>
<th>Difficulty Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>up to 0.5</td>
<td>Very low</td>
</tr>
<tr>
<td>0.6-0.9</td>
<td>Low</td>
</tr>
<tr>
<td>1.0-1.3</td>
<td>Medium</td>
</tr>
<tr>
<td>1.4-1.7</td>
<td>High</td>
</tr>
<tr>
<td>1.8-2.1</td>
<td>Very high</td>
</tr>
<tr>
<td>2.2 and above</td>
<td>Ultra-High</td>
</tr>
</tbody>
</table>

Enter that value on the worksheet (baud rate section) shown in Figure B.3.

**Step 1B**: User requires MATB task duration (TD).

Enter that value on the worksheet (task duration section) shown in Figure B.3.

**Step 2**: For this step (component weighting), the total sum of the component weighting must equal 100 (percent-weightings) or 1.0 (fractional-weighting). However, the user may weight any component or combination of components as zero. In this case the zero weighted components may be hidden and will then appear as a black space on the AF-MATB screen.

Also, when using any AF-MATB screen display, the two far-right-side vertical display bars may also be hidden and will appear as black spaces on the AF-MATB screen display.

**Step 2A**: The user requests a MATB weighting for each of the four components as a percent.
weighting of the total baud rate ($W_M, W_C, W_T, W_R$): where the sum of $W_i$'s must equal 100.

Enter the $W_i$ values on the worksheet (component weighting section) shown in Figure B.3.

Continuing Step 2A, the user then calculates the various component-specific MATB generated baud rates as follows (where $W_M, W_C, W_T, W_R$ are now divided by 100): :

$$\beta_{INM} = W_M\beta_{IN}$$  \hspace{1cm} (B.2)
$$\beta_{INC} = W_C\beta_{IN}$$  \hspace{1cm} (B.3)
$$\beta_{INT} = W_T\beta_{IN}$$  \hspace{1cm} (B.4)
$$\beta_{INR} = W_R\beta_{IN}$$  \hspace{1cm} (B.5)

Enter the $\beta_{INM}, \beta_{INC}, \beta_{INT}$ and $\beta_{INR}$ on the worksheet (baud rate section) of Figure B.3.

**Step 3:** The Monitoring component (M) of MATB machine generated baud rate is composed of two separate sub-component baud rates: a Lights task (L) baud rate and a Dials task (D) baud rate:

$$\beta_{INM} = \beta_{INL} + \beta_{IND}$$  \hspace{1cm} (B.6)

**Step 3A:** From the $\beta_{INM}$ (from Step 2A) calculate $\beta_{INL}$ and $\beta_{IND}$. By convention, Lights is weighted as 1/3 of the Monitoring and Dials is 2/3:
Enter these two values in the worksheet shown in Figure B.4 (Monitoring section).

**Step 3B:** Referring to Table B.2, proceeding down the “$\beta_{INL}$” column, identify the baud value closest to the $\beta_{INL}$ (from step 3A).

Proceeding across that $\beta_{INL}$ row, identify the value in the “ISI” column. Enter that value into the worksheet shown in Figure B.4 ($ISI_{ML}$ of the Monitoring section).

**Step 3C:** Also identify the value in the “Events Per 4 Minutes” column. Scale that “Events (4 mins)” value to the specific duration of your MATB run (TD of Step 1B) using the events scaling the equation:

$$Events(TD) = \frac{Events(4 min)}{4}(\frac{TD}{60})$$

**Step 3D:** Enter the value from 3C into the worksheet shown in Figure B.4 ($N_{ML}$ Monitoring section).

**Step 3E:** Referring to Table B.3, proceeding down the “$\beta_{IND}$” column, identify the baud value closest to the $\beta_{IND}$ (from step 3A).

Proceeding across that $\beta_{IND}$ row, identify the value in the “ISI” column. Enter the value into the worksheet shown in Figure B.4 ($ISI_{MD}$ of the Monitoring section).
Step 3F: Also identify the value “Events Per 4 Minutes” column.

Step 3G: Using the events scaling equation (Step 3C) calculate the number of events for the specific duration (TD) of your MATB run.

Step 3H: Enter the value from the step 3G into the worksheet shown in Figure B.4 ($N_{MD}$ of the Monitoring section).

Step 4: The communications component specific MATB generated baud rate [$\beta_{INC}$] is calculated (Step 2A).

Step 4A: Referring to Table B.4, proceeding down the “$\beta_{INC}$” column, identify the baud value closest to the $\beta_{INC}$.

Proceeding across that $\beta_{INC}$ row, identify the value in the “ISI” column. Enter that value into the worksheet shown in Figure B.4 ($ISI_C$ of the Communications section).

Step 4B: Also identify the value in the “Events Per 4 Minutes” column. Using the events scaling the equation (Step 3C) calculate the number of events for the specific duration of your MATB run.

Step 4C: Enter the value from step 4B into the worksheet shown in Figure B.4 ($N_C$ of the Communications section).

Step 5: The targeting component specific MATB generated baud rate [$\beta_{INT}$] is calculated (step 2A).

Step 5A: Calculate the Cursor Velocity (V) in pixels per cycle using the $\beta_{INT}$:

$$ V = (6.2)(\beta_{INT}) $$  \hspace{1cm} (B.10)

Alternatively, use Table B.5 to find the necessary velocity in pixels per cycle to obtain
your $\beta_{INT}$.

**Step 5B**: Enter the value from Step 5A into the worksheet shown in Figure B.4 (Cursor Velocity in the Targeting section).

**Step 5C**: Calculate the Target Speed Lower Limit ($V_{TL}$) and the Target Speed Upper Limit ($V_{TU}$).

\[
V_{TL} = 6.2\beta_{INT} - 0.1 \quad \text{(B.11)}
\]

\[
V_{TU} = 6.2\beta_{INT} + 0.1 \quad \text{(B.12)}
\]

**Step 5D**: Enter the results from Step 5C into the worksheet shown in Figure B.4 ($V_{TL}$ and $V_{TU}$ of the Targeting section).

**Step 6**: The resource component specific MATB generated baud rate [$\beta_{INR}$] is calculated (Step 2A). Resource Management parameters for desired $\beta_{INR}$ are shown in Table B.6.

To calculate the MATB parameters for the Resource component, use the following steps (6A through 6F).

**NOTE**: Steps 6A through 6F apply to a single tank volume.

**Step 6A**: Calculate the Total Tank Volume using the $V_{TTot}$ equation using the $\beta_{INR}$:

\[
V_{TTot} = \frac{1333}{\beta_{INR}} \quad \text{(B.13)}
\]

Enter that value into the worksheet shown in Figure B.4 (Total Tank Volume of the Resource section).
Step 6B: Calculate the Starting Tank Volume \( (V_{TMid}) \) using the result from Step 6A:

\[
V_{TMid} = \frac{V_{TTot}}{2}
\]  

(B.14)

Enter that value into the worksheet shown in Figure B.4 (Starting Tank Volume of the Resource section).

Step 6C: Calculate the Upper Limit Tank Volume \( (V_{TUL}) \) and the Lower Limit Tank Volume \( (V_{TLL}) \) using the results from Step 6A and 6B:

\[
V_{MUL} = V_{TMid} + (0.075)V_{TTot}
\]

(B.15)

\[
V_{MLL} = V_{TMid} - (0.075)V_{TTot}
\]

(B.16)

Step 6D: Enter the \( V_{MUL} \) value from Step 6C into the worksheet shown in Figure B.4 (Target Range Upper Limit of the Resource Section). Enter the \( V_{MLL} \) value from Step 6C into the worksheet shown in Figure B.4 (Target Range Lower Limit of the Resource Section).

Step 7: After completion of step 6, the “Trial Design Worksheet” should be completed and the user can now begin to generate their script using the AF_MATB Configuration Utility.

Step 7A: Ensure that the following files are present in the directory from which you will be running the AF_MATB program: AF_MATB_ConfigurationUtility.exe, AF_MATB_ScriptGenerator.exe, AF_MATB.exe, and the AF_MATB System Files folder. Before the first use of the AF_MATB, the user will also need to install the MATLAB Compiler Runtime (MCRInstaller.exe). Then begin by opening the AF_MATB Configura-
tion Utility (pictured in Figure B.1). There is a drop-down menu in the top left corner which allows the user to select the desired set of AF_MATB parameters they wish to modify.

**Step 7B**: Select the “AF_MATB System Parameters” option from the drop-down menu and disable “Scheduling”. Enable “Information Throughput Mode”.

**Step 7C**: Select the “Communications Subtask Parameters” option from the drop-down menu. Change the value for “Slot 1 & 2 Frequency Increments” and “Slot 3 & 4 Frequency Increments” to “0.1”.

**Step 7D**: Select the “Tracking Subtask Difficulty Parameters” option from the drop-down menu. Referring to the Trial Design Worksheet, enter the value for “$V_{TL}$” into the “Moderate Difficulty Target Speed Lower Limit” textbox. Enter the value for “$V_{TU}$” in the “Moderate Difficulty Target Speed Upper Limit” textbox.

**Step 7E**: Select the “Resource Management Subtask Basic Parameters” option from the drop-down menu. Set the value for “Pump 2 & 4 Flow Rates” to “12000” and the value for
“Tank A & B Drop Rates” to “6000”. Referring to the Trial Design Worksheet, enter the value for “Total Tank Volume” into the “Tank A & Tank B Maximum” textbox. Next, enter the value from “Starting Tank Volume” into the “Tank A Starting Volume” textbox. Enter this same value into the “Tank B Starting Volume” textbox.

**Step 7F**: Select “Resource Management Subtask Automation Parameters” from the drop-down menu. Enter tank lower limit and upper limit under “Main Tank Automation Lower Limit” and “Main Tank Automation Upper Limit”. Enter the value for one-“Starting Tank Volume” into the “RMS Target Value” textbox.

**Step 7G**: Select the “Save and Continue to Script Generator” button in the lower right corner of the parameters utility. A SaveAs box will appear and allow you to select a name for the output file for the parameters you have just set. The file will be saved with your chosen file name as well as with a timestamp appended to the name. By clicking “Save”, the parameters utility will close and the Script Generator utility will open automatically (pictured in Figure B.2).

**Step 8**: The script generator utility that opens will appear as pictured in Figure B.2.

**Step 8A**: In the bottom right corner of the screen, click the “Load Config or Script File” button, and load the parameters file you just created.

**Step 8B**: In the “Script Parameters” section at the top of the screen, enter a condition name of your choice into the “Condition Name” textbox. Next, enter your desired trial length (in seconds) into the “Sequence Length” textbox. This should be the same value that you entered into the “Task Duration” box in the Trial Design Worksheet. Referring to the Trial Design Worksheet, enter the value for “$N_C$” into the “True Comms” textbox under the
“Communications Subtask” heading and enter a “0” in the “False Comms” textbox. Next, select “Tracking Moderate” in the “Difficulty” drop-down menu under the “Tracking Task” heading. Referring to the Trial Design Worksheet, enter the values for “$N_{ML}$” and “$N_{MD}$” into the “Lights” and “Gauges” textboxes under the “System Monitoring Task” heading. If there are any MATB components that will not be used for your experiment, set them to be invisible under the “Task Component Visibility” heading.

**Step 8C:** In the “Conditions that Will Comprise this Script” section, click the “Schedule Current Condition” button and ensure that no errors are reported in the “Script Parameter Errors” box and the name you have chosen for the current condition appears in the list. Next, click the “Generate Script” button.

**Step 8D:** Click the “Save Script” button to save your custom AF_MATB script file and parameters settings.

**Step 9:** After your desired parameters settings have been saved and your events script has
been written, you may open the MATB to run your customized script.

**Step 9A:** If you would like to load your customized script immediately after writing it in the AF_MATB Script Generator, click the “Save & Continue to AF_MATB” button in the lower right hand corner of the Script Generator display. From here you will be prompted to enter a file name a location to save your script file in. After saving, the AF_MATB program will open automatically and load your script.

**Step 9B:** It is very common to use the same script multiple times. In this case, it is not necessary to load a script file into MATB through the Script Generator utility. After generating your custom script in the Script Generator, click the “Save Script” button to save a copy of your custom script. From here the Script Generator utility will close. To run any saved script from outside the Script Generator, simply run the AF_MATB_V300.exe file. After entering a Valid Subject Identifier in the textbox, click “Yes” to load a Config or Script file. Then click the “Script File” button. After this, locate your desired script file and open it. From here, the AF_MATB program will open using your custom script file.

**AFTER RUNNING AF-MATB:**

**Step 10:** Once your script has finished running in AF_MATB, data from the trial will be exported to several output files. These files will be written to a single folder which is located in the folder from which you are running AF_MATB. The output files folder name will contain your subject identifier followed by a timestamp. After you have located and opened your output files folder, you will find another folder inside called “Condition_1”. There will be additional “Condition” folders if you ran multiple conditions in one AF_MATB script. Inside the “Condition_1” folder is a file with a name contains the words “Information_Throughput_Summary”. After opening this file, near the bottom of
the spreadsheet you will find a table titled “Throughput Numbers”. The input baud rates are listed for each MATB component in the “Machine Input Baud Rate” column. Similarly, the fractional accuracy is listed for each MATB component in the “Accuracy” column. Copy and Paste “Machine Input Baud Rate” and “Accuracy” columns of data into the AF_MATB_IT Summary Spreadsheet provided separately. From there, the spreadsheet will calculate all other values relevant to the Human Operator Informatic Model (HOIM).

For a more detailed description of the operation of the AF_MATB Parameters Utility and Script Generator, please consult the AF-MATB User’s Manual (see page 62).

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1To obtain an electronic copy of the AF-MATB-IT Summary Spreadsheet, contact Chandler A. Phillips (chandler.phillips@wright.edu) or Justin R. Estepp (see page 63).
Figure B.3: Trial Design Worksheet: part 1.
Figure B.4: Trial Design Worksheet: part 2.
Table B.2: Number of Light events for a four-minute MATB run at a desired $\beta_{INL}$.

<table>
<thead>
<tr>
<th>$\beta_{INL}$ (bits/s)</th>
<th>ISI (s)</th>
<th># Events Per 4 Minutes</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.004</td>
<td>240.000</td>
<td>1</td>
</tr>
<tr>
<td>0.008</td>
<td>120.000</td>
<td>2</td>
</tr>
<tr>
<td>0.013</td>
<td>80.000</td>
<td>3</td>
</tr>
<tr>
<td>0.017</td>
<td>60.000</td>
<td>4</td>
</tr>
<tr>
<td>0.021</td>
<td>48.000</td>
<td>5</td>
</tr>
<tr>
<td>0.025</td>
<td>40.000</td>
<td>6</td>
</tr>
<tr>
<td>0.029</td>
<td>34.286</td>
<td>7</td>
</tr>
<tr>
<td>0.033</td>
<td>30.000</td>
<td>8</td>
</tr>
<tr>
<td>0.038</td>
<td>26.667</td>
<td>9</td>
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<tr>
<td>0.042</td>
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</tr>
<tr>
<td>0.046</td>
<td>21.818</td>
<td>11</td>
</tr>
<tr>
<td>0.050</td>
<td>20.000</td>
<td>12</td>
</tr>
<tr>
<td>0.054</td>
<td>18.462</td>
<td>13</td>
</tr>
<tr>
<td>0.058</td>
<td>17.143</td>
<td>14</td>
</tr>
<tr>
<td>0.063</td>
<td>16.000</td>
<td>15</td>
</tr>
<tr>
<td>0.067</td>
<td>15.000</td>
<td>16</td>
</tr>
<tr>
<td>0.071</td>
<td>14.118</td>
<td>17</td>
</tr>
<tr>
<td>0.075</td>
<td>13.333</td>
<td>18</td>
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<tr>
<td>0.079</td>
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<tr>
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</tr>
<tr>
<td>0.088</td>
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<tr>
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<tr>
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<td>10.000</td>
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<td>0.104</td>
<td>9.600</td>
<td>25</td>
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<tr>
<td>0.108</td>
<td>9.231</td>
<td>26</td>
</tr>
<tr>
<td>0.113</td>
<td>8.889</td>
<td>27</td>
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<tr>
<td>0.117</td>
<td>8.571</td>
<td>28</td>
</tr>
<tr>
<td>0.121</td>
<td>8.276</td>
<td>29</td>
</tr>
<tr>
<td>0.125</td>
<td>8.000</td>
<td>30</td>
</tr>
<tr>
<td>$\beta_{INL}$ (bits/s)</td>
<td>ISI (s)</td>
<td># Events Per 4 Minutes</td>
</tr>
<tr>
<td>------------------------</td>
<td>---------</td>
<td>------------------------</td>
</tr>
<tr>
<td>0.129</td>
<td>7.742</td>
<td>31</td>
</tr>
<tr>
<td>0.133</td>
<td>7.500</td>
<td>32</td>
</tr>
<tr>
<td>0.138</td>
<td>7.273</td>
<td>33</td>
</tr>
<tr>
<td>0.142</td>
<td>7.059</td>
<td>34</td>
</tr>
<tr>
<td>0.146</td>
<td>6.857</td>
<td>35</td>
</tr>
<tr>
<td>0.150</td>
<td>6.667</td>
<td>36</td>
</tr>
<tr>
<td>0.154</td>
<td>6.486</td>
<td>37</td>
</tr>
<tr>
<td>0.158</td>
<td>6.316</td>
<td>38</td>
</tr>
<tr>
<td>0.163</td>
<td>6.154</td>
<td>39</td>
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</tr>
<tr>
<td>0.171</td>
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</tr>
<tr>
<td>0.175</td>
<td>5.714</td>
<td>42</td>
</tr>
<tr>
<td>0.179</td>
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<td>43</td>
</tr>
<tr>
<td>0.183</td>
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<td>44</td>
</tr>
<tr>
<td>0.188</td>
<td>5.333</td>
<td>45</td>
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<tr>
<td>0.192</td>
<td>5.217</td>
<td>46</td>
</tr>
</tbody>
</table>
Table B.3: Number of Dials events for a four-minute MATB run at a desired $\beta_{ind}$.

<table>
<thead>
<tr>
<th>$\beta_{ind}$ (bits/s)</th>
<th>ISI (s)</th>
<th># Events Per 4 Minutes</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.008</td>
<td>240.000</td>
<td>1</td>
</tr>
<tr>
<td>0.017</td>
<td>120.000</td>
<td>2</td>
</tr>
<tr>
<td>0.025</td>
<td>80.000</td>
<td>3</td>
</tr>
<tr>
<td>0.033</td>
<td>60.000</td>
<td>4</td>
</tr>
<tr>
<td>0.042</td>
<td>48.000</td>
<td>5</td>
</tr>
<tr>
<td>0.050</td>
<td>40.000</td>
<td>6</td>
</tr>
<tr>
<td>0.058</td>
<td>34.286</td>
<td>7</td>
</tr>
<tr>
<td>0.067</td>
<td>30.000</td>
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<tr>
<td>0.075</td>
<td>26.667</td>
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</tr>
<tr>
<td>0.083</td>
<td>24.000</td>
<td>10</td>
</tr>
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<td>11</td>
</tr>
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<td>0.100</td>
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</tr>
<tr>
<td>0.108</td>
<td>18.462</td>
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</tr>
<tr>
<td>0.117</td>
<td>17.143</td>
<td>14</td>
</tr>
<tr>
<td>0.125</td>
<td>16.000</td>
<td>15</td>
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<tr>
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<td>0.208</td>
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<tr>
<td>0.225</td>
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<td>27</td>
</tr>
<tr>
<td>0.233</td>
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<td>28</td>
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<tr>
<td>0.250</td>
<td>8.000</td>
<td>30</td>
</tr>
</tbody>
</table>
Table B.3: Number of Dials events for a four-minute MATB run at a desired $\beta_{IN}$.  

<table>
<thead>
<tr>
<th>$\beta_{IN}$ (bits/s)</th>
<th>ISI (s)</th>
<th># Events Per 4 Minutes</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.258</td>
<td>7.742</td>
<td>31</td>
</tr>
<tr>
<td>0.267</td>
<td>7.500</td>
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<td>0.275</td>
<td>7.273</td>
<td>33</td>
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<tr>
<td>0.283</td>
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<td>0.292</td>
<td>6.857</td>
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<tr>
<td>0.300</td>
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</tr>
<tr>
<td>0.308</td>
<td>6.486</td>
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</tr>
<tr>
<td>0.317</td>
<td>6.316</td>
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<td>0.333</td>
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<tr>
<td>0.342</td>
<td>5.854</td>
<td>41</td>
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<tr>
<td>0.350</td>
<td>5.714</td>
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</tr>
<tr>
<td>0.358</td>
<td>5.581</td>
<td>43</td>
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<td>5.455</td>
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<td>45</td>
</tr>
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<tr>
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<td>5.000</td>
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<td>4.800</td>
<td>50</td>
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<tr>
<td>0.425</td>
<td>4.706</td>
<td>51</td>
</tr>
<tr>
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<td>4.615</td>
<td>52</td>
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<tr>
<td>0.442</td>
<td>4.528</td>
<td>53</td>
</tr>
<tr>
<td>0.450</td>
<td>4.444</td>
<td>54</td>
</tr>
<tr>
<td>0.458</td>
<td>4.364</td>
<td>55</td>
</tr>
<tr>
<td>0.467</td>
<td>4.286</td>
<td>56</td>
</tr>
</tbody>
</table>
Table B.4: Number of Communications events for a four-minute MATB run at a desired \( \beta_{INC} \).

<table>
<thead>
<tr>
<th>( \beta_{INC} ) (bits/s)</th>
<th>ISI (s)</th>
<th># Events Per 4 Minutes</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.024</td>
<td>240.000</td>
<td>1</td>
</tr>
<tr>
<td>0.048</td>
<td>120.000</td>
<td>2</td>
</tr>
<tr>
<td>0.071</td>
<td>80.000</td>
<td>3</td>
</tr>
<tr>
<td>0.095</td>
<td>60.000</td>
<td>4</td>
</tr>
<tr>
<td>0.119</td>
<td>48.000</td>
<td>5</td>
</tr>
<tr>
<td>0.143</td>
<td>40.000</td>
<td>6</td>
</tr>
<tr>
<td>0.166</td>
<td>34.286</td>
<td>7</td>
</tr>
<tr>
<td>0.190</td>
<td>30.000</td>
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</tr>
<tr>
<td>0.214</td>
<td>26.667</td>
<td>9</td>
</tr>
<tr>
<td>0.238</td>
<td>24.000</td>
<td>10</td>
</tr>
<tr>
<td>0.261</td>
<td>21.818</td>
<td>11</td>
</tr>
<tr>
<td>0.285</td>
<td>20.000</td>
<td>12</td>
</tr>
<tr>
<td>0.309</td>
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Table B.5: Average cursor velocity for a desired $\beta_{INT}$.

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Table B.5: Average cursor velocity for a desired $\beta_{INT}$.

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<th>Velocity (pix/cycle)</th>
<th>ISI (s)</th>
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Table B.5: Average cursor velocity for a desired $\beta_{INT}$.

<table>
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<th>$\beta_{INT}$ (bits/s)</th>
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<th>ISI (s)</th>
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Table B.5: Average cursor velocity for a desired $\beta_{\text{INT}}$.

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<th>$\beta_{\text{INT}}$ (bits/s)</th>
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Table B.6: Resource Management tank settings for a desired $\beta_{\text{INR}}$.

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Table B.6: Resource Management tank settings for a desired $\beta_{INR}$.

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Appendix C

Haptic and Auditory Feedback in

AF-MATB Guide

The following Appendix presents a guide to using haptic and audio feedback in the 2014 version of AF-MATB. In the Bioengineering Laboratory, where this research was conducted, AF-MATB was installed on a computer with the Windows 7 operating system. The haptic and auditory feedback was controlled via port-triggering through a Windows 98 machine.

Steps

Step 1: Follow Steps 1-6D from the User Guide of Appendix B to determine component baud rates.

Step 2A: Follow Steps 7-7F to input parameters into a Config file.

Step 2B: Select the “Port Triggering Parameters” option from the drop-down menu. Under “Enable Port Triggering?” select “Yes”.

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**Step 3:** Follow Steps 7G-8D to save the Config file and create a Script file.

**Step 4:** Make sure that the Fighterstick is NOT plugged into the Windows 7 computer that will run MATB. Make sure the Immersion Stick is plugged into the Windows 7 machine. Turn the Immersion Stick on.

**Step 5:** Run the `AF_MATB` executable to launch the MATB program. After entering a Valid Subject Identifier in the textbox, click “Yes” to load a Config or Script file. Then click the “Script File” button. After this, locate your desired script file and open it. From here, the `AF_MATB` program will open using your custom script file. You should see a box that says “File Sucessfully Loaded!” Click OK. You should then see a box that reads “Serial port-triggering connection enabled.” Click OK.

**Step 6:** On the Windows 7 machine- In the directory from where MATB was launched, click on the participant’s created test folder (ex. `ParticipantID_TimeStamp`). Select the condition folder for the current run. Drag the `ParticipantID_Tracking_Log_1` to the TrakData Program (jeb) on the desktop (see Figure C.1). A message will appear with the Tracking Log’s path. Click OK. A message will appear that reads “Track Error LogFile Open”. Click OK. Note: If this message does not appear, please review the Troubleshooting section of this Guide.

**Step 7:** On the Windows 98 machine- Drag the trak.txt file on the desktop to the win98 program on the desktop (see Figure C.2). Hold the Immersion Stick in the center position and press OK.

**Step 8:** On the Windows 7 machine- Open the MATB window and press the space bar to begin. Audio tones will accompany the Monitoring component and haptic feedback will
Figure C.1: Step 6.

Figure C.2: Step 7.
occur when the Targeting cursor drifts outside of the target.

**Troubleshooting**

The cursor does not move when I move the Immersion Stick.

Check to make sure that the Immersion Stick is plugged in and the Fighterstick is not plugged in and restart MATB.

I did not see the “Track Error LogFile Open” message. Instead, I received the message “Remote File Failed”.

The TrakData program cannot read the Tracking Log file that you provided. Make sure that in the complete file path of the Tracking Log, that no directories have spaces, periods, or special characters.

The cursor drifts away when I let go of the Immersion Stick.

You will need to calibrate the joysticks. To calibrate:

Step 1: On the Windows 7 machine, open the start menu and click on “Devices and Printers”.

Step 2: Right Click on the “Logitech Extreme 3D” icon. Select “Game Controller Settings” from the drop down menu.

Step 3: Click on the “Properties” box. Then select the “Settings” tab. Click on “Calibrate”.

Step 4: Click “Next”. Center the handle of the black and silver Logitech Joystick and click “Next”. (Not the Immersion Stick. The Immersion stick receives information from the Logitech joystick.)
Step 5: Move the handle of the Immersion stick in complete circles and click “Next”.

(MATB gets X,Y information from the Immersion stick)

Step 6: Move the slider on the Logitech joystick up and down and click “Next”.

Step 7: Twist the Logitech joystick to the left and right and click “Next”.

Step 8: Click “Finish”. The joysticks should now be calibrated.
Appendix D

MATLAB Script to Calculate Resource Accuracy

%Aerial Camden
%Resource Correction Script
%March 2015

%This MATLAB script uses the Resource Management Log generated by MATB to calculate the Resource accuracy, adjusted for delay.

%INPUT: a set of excel files that contain only the resource data (no words).
%OUTPUT: creates an excel file that lists corrected resource accuracy for each subject.
%BE SURE TO CHANGE THE UPPER AND LOWER TANK LIMITS
%BE SURE THAT FILES ARE READ IN NUMERICAL ORDER
clear all
close all
clc

%Input these limits to match those used during the MATB run:
UL=8516;
LL=6295;

%Input file locations
cd('E:\DissExpt\Data Analysis\B\B1_Cleaned\Bin08')
Files=dir('E:\DissExpt\Data Analysis\B\B1_Cleaned\Bin08\resource*.xlsx')

for j=1:length(Files)
    data = xlsread(Files(j).name);
    [T,nCol]=size(data);
    %This "data" array contains
    % Col 1=EventTime
    % Col 2=Tank A Value
    % Col 3=Tank B Value
    % Col 4=Tank A Difference (from the center)
    % Col 5=Tank B Difference (from the center)
    % Col 6=Tank A Deviation
    % Col 7=Tank B Deviation
    % Col 8=Euclidian Distance
    % Col 9=Tank A in target
% Col 10=Tank B in target
% Col 11=Both in range?

% I'm going to add
% Col 12=A Direction (-1 for down; +1 for up; 0 for unchanged (i.e, the
% tank stays empty))
% Col 13=B Direction
% Col 14=Is A direction correct
% If A is "on target" = 1
% If A is too high and direction is -1 = 1
% If A is too low and direction is +1 = 1
% If A is too high and direction is +1 = 0
% If A is too low and direction is NOT +1 = 0
% Col 15=Is B direction correct?
data(1,12)=-1;  % The tanks always DRAIN at the beginning of MATB
data(1,13)=-1;

% This for loop populates col 12 and 13:
for i=2:T
    testAdir=data(i,2)-data(i-1,2);  % checks the direction of A
    if testAdir<0                      % Assigns value to Col 12
        data(i,12)=-1;
    elseif testAdir>0
        data(i,12)=1;
    else
        data(i,12)=0;
end
testBdir=data(i,3)-data(i-1,3); %checks direction of B
if testBdir<0 %Assigns value to Col 13
    data(i,13)=-1;
elseif testBdir>0
    data(i,13)=1;
else
    data(i,13)=0;
end
end

%This for loop populates col 14 and 15
data(1,14)=1; %The tanks always start "on target"
data(1,15)=1;
for i=2:T
    %Assign a "1" for correct direction if one of these conditions is met:
    %A is on target
    %A is too high and direction is -1
    %or A is too low and direction is +1
    if data(i,2)<UL && data(i,2)>LL
        data(i,14)=1;
    elseif data(i,2)>UL && data(i,12)==-1
        data(i,14)=1;
    elseif data(i,2)<LL && data(i,12)==1
        data(i,14)=1;
    else
        data(i,14)=0;
    end
%Same for tank B:

if data(i,3)<UL && data(i,3)>LL
    data(i,15)=1;
elseif data(i,3)>UL && data(i,13)==-1
    data(i,15)=1;
elseif data(i,3)<LL && data(i,13)==1
    data(i,15)=1;
else
    data(i,15)=0;
end
end

%Calculate the accuracy for resource:

naON=0;
bON=0;
aOFF=0;
bOFF=0;
aTO=0;
bTO=0;
aAWAY=0;
bAWAY=0;
for i=1:T
    if data(i,9)==1
        naON=naON+1;
    else
        naOFF=naOFF+1;
    end
if data(i,9)==0 && data(i,14)==1
    naTO=naTO+1;
end

if data(i,9)==0 && data(i,14)~=1
    naAWAY=naAWAY+1;
end

if data(i,10)==1
    nbON=nbON+1;
else
    nbOFF=nbOFF+1;
end

if data(i,10)==0 && data(i,15)==1
    nbTO=nbTO+1;
end

if data(i,10)==0 && data(i,15)~=1
    nbAWAY=nbAWAY+1;
end

end

rhoR(j) = ((naON+nbON)+0.5*(naTO+nbTO))/(2*T);
end
subj=1:length(Files);

RESULTS=cat(2,subj',rhoR')

xlswrite('accuracies.xlsx',RESULTS)
Bibliography


[77] Szalma, J. L., Warm, J. S., Matthews, G., Dember, W. N., Weiler, E. M., Meier, A., and Eggemeier, F. T. Effects of sensory modality and task duration on performance,


