

Visual Sensitivity of Dynamic Graphical Displays

by

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Abstract

Advanced display design, such as Ecological Interface Design (EID), makes extensive use of complex graphical objects. Research has shown that by following EID methodologies, supervisory operators have better performance with the EID displays (Pawlak and Vicente, 1996). However, past research does not consider the visual aspects of the graphical objects used in EID. Of particular interest is how different design decisions of graphical objects affect the performance of the objects used within that design. This thesis examines the visual sensitivity of dynamic graphical objects by examining features that make certain graphical objects visually superior for certain monitoring tasks. Previous research into the visual aspects of supervisory control with respect to emergent features, psychophysics and attention were considered in the investigation of the visual sensitivities of the dynamic graphical objects used. Research into static graphical objects, combined with prior work on emergent features has been merged to find emergent features that best show changes in dynamic graphical objects for the monitoring tasks investigated. It was found that for simple dynamic objects such as bars and polygon objects, a line changing in angle was the most noticeable emergent feature to show a departure from “normal” state. For complex graphical objects, those target-indicator displays that mimic a “bull’s eye” when at the target value should be used for displays that show observers when a target value has been reached. Abrupt changes in shape should be used in trend meters to show when variables or processes have changed direction. Finally, “solid objects” that make use of vertical lines and shading should be used for comparison meters that compare two values and keep them in a particular ratio. These findings provide guidance for designers of dynamic advanced graphical displays by encouraging the consideration of visual aspects of graphical objects, as well as prescribing graphical objects that should be used in the types of tasks investigated.

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Chapter 1

Introduction

Complex systems involve several variables and processes changing in status simultaneously, either independently or in collaboration. The user interfaces of these systems attempt to display the real-time status and interactions of these variables. For individuals monitoring these interfaces, it is crucial that the status of key processes is understood at all times. Point data displays, trend displays, and bar charts are common system status displays used in supervisory monitoring environments (Vicente, Roth, and Mumaw, 2001). The ability to discriminate changes in display status depends upon the visual integrity of the dynamic graphical display used to display the information on the interface. This thesis will examine the visual sensitivities of various graphical objects that are used in certain monitoring of complex system tasks.

1.1 Overview

In supervisory monitoring tasks operators are required to scan the display of a complex system consisting of several graphical objects to determine the status of the system. Advanced display design methodologies, such as Ecological Interface Design (EID), make extensive use of complex graphical objects. The combination of complex systems and complex graphical objects leads to questions on whether the integrity of the information being displayed is retained in these graphical displays. Are operators able to discriminate changes in complex system status based on the information provided through the graphical displays?

1.2 Scope and Objectives of Research

Complex systems require constant monitoring and inspection of status to ensure proper and safe functioning. Through the use of a user interface,

operators can monitor the status of systems from a single control room setting (Vicente et al., 2001). However, it is essential that the information portrayed on the user interface clearly shows the status of the system, and that system irregularity is very evident when it occurs.

Graphical objects prescribed through EID have been used to display the status of variables in complex systems (Burns and Hajdukiewicz, 2004). Investigating these graphical objects for their visual sensitivity when used in dynamic supervisory monitoring tasks is the goal of this research. It is important to investigate graphical objects in a dynamic setting for this is representative of the actual tasks involved in complex system monitoring. Thus, this thesis aims to determine the elements of graphical objects that are most visually sensitive, as well as provide guidelines for designers of dynamic graphical objects for complex systems.

The motivation for this study is to identify the visual elements of dynamic graphical objects that are the best to use in certain monitoring tasks. Specifically, this study investigates detecting change by means of object movement, determining when target levels have been attained, and estimating proportions in objects. This study examines both simple and complex graphical objects used in monitoring tasks. The aim of examining simple objects is to determine which emergent features are the most noticeable in a dynamic monitoring task. Studying the monitoring of complex objects provides insight into the visual elements of different types of complex supervisory monitoring tasks.

1.3 Contributions

The contributions of this thesis can be summarized as follows:

- Examination of simple graphical objects to determine visual sensitivities of emergent features

- Examination of complex graphical objects used in actual complex monitoring systems, through the generation of design alternatives, to determine visual sensitivities of complex graphical objects
- Exploration of what individuals are seeing when examining dynamic graphical objects
- Providing guidelines for designers of graphical objects for complex systems

1.4 Thesis organization

The remainder of this thesis is organized as follows:

- Chapter 2 concentrates on prior research conducted in the areas of supervisory control tasks, emergent features, psychophysics of graphical objects, and visual attention in monitoring tasks.
- Chapters 3-6 introduce, summarize, and discuss each of the four experiments conducted. The experiments investigated graphical objects that made use of emergent features, indicator-target graphics for detection of targets, graphical meters displaying changing directions of process flow, and graphical meters showing the ratio between two values.
- Chapter 7 includes a summary of the findings as well as a discussion of future work to be done in the field of dynamic graphical objects.

Chapter 2

Background Review

2.1 Supervisory Control

Supervisory control tasks for operators involve scanning of a display of a complex system under supervision and the allocation of attention through visual fixations to various objects which provide system information (Wickens and Hollands, 2000). Any complex monitoring system interface, from an aircraft cockpit display to an anesthesiologist's human monitoring display, requires the operator to allocate attention across the entire display. Display and control design is one of the factors that make monitoring complex systems difficult for operators (Vicente et al., 2001). There are several graphical objects on the supervisory control display, with each object providing a piece of information that is necessary to monitor the complex system. These objects need to provide information very clearly because of the complexity of the systems and the number of processes being monitored. This section examines past research that has contributed to supervisory control displays.

2.2 EID in supervisory control

With several objects being monitored simultaneously in supervisory control situations, abnormal states need to be displayed in a manner that allows for operators to quickly and easily notice when the system is not behaving in its normal manner. Ecological Interface Design (EID) is a systematic methodology for designing complex system interfaces. It considers the relationships within the domain in which the system operates. The work environment is reflected in the system interface. Because EID makes use of relationships between information, EID displays integrate information to show these relationships and to exploit anomalies in system status (Burns and

Hajdukiewicz, 2004). Objects displaying different processes, each with individual units of measurement, are often shown on a single, integrated display. In order to show relationships between the information, frequently the information display is visually manipulated. When the system processes are at a “normal” state, the graphical objects take on a “normal” look (Greaney and MacRae, 1997). This can be a symmetrical shape, objects all being the same height or width, or objects all taking on the same appearance. When one or several processes move into an “abnormal” state, the graphical object takes on an “abnormal” look; an asymmetrical shape, a difference in height or width, or objects taking on individual appearances. While this method of display does a very good job of highlighting system issues to the operator, the magnitude of “abnormality” is not easily judged through these displays. Because the graphical objects are visually manipulated, the axis of each process is adjusted. For example, on a multiple axis star display, eight variables or processes may be shown on a single graphical object. Because each axis is showing a different variable or process, it is scaled or manipulated so that when all variables or processes are “normal”, the object takes on a symmetrical star-like shape. One axis may be measuring a variable from a scale of 0-10, where another may be measuring a process on a scale from 0-1000. However, on the graphical object, these axes are manipulated visually so that the axes of the object all appear to be the same length, although they are each measuring processes and variables on different scales. An example of this is shown in Figure 1. Therefore, something that appears to be a small change in a graphical object may in fact be a very large change in the system process. This is an important matter to consider when designing graphical objects used in supervisory control tasks.

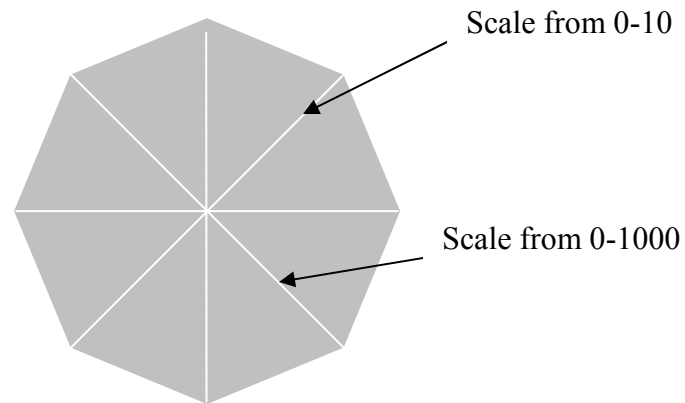


Figure 1: Example of a graphical object with adjusted scales

The issue of scale transformations is discussed by Petersen and May (2003). The authors present arguments for why designers must consider scale transformations with respect to the information presented to the observer from a cognitive perspective. They consider the presentation of information and transformation of scale on a cognitive level and argue that information is presented on a continuum of relationships that ranges from strongly inter-related information presentation (e.g. ratios) to weaker inter-related information presentation (e.g. nominal forms). When scales are transformed, the information presented moves along this continuum since “scale transformations change the information contained in data” (p. 76). When scales are transformed, the information presented moves from a stronger to a weaker relationship, thus “data on different scales have different information content with respect to the property it characterizes” (p. 79). However, this only appears to be one part of the discussion. In addition to the cognitive interpretation of the scale transformation, the visual interpretation must be considered as well. While data may be displayed on a certain scale and interpreted as having a strong or weak relation to the information presented, the visual perception aspect of detecting the display value and value changes must also be considered. Therefore, in addition to the cognitive interpretation of scale transformations, the visual perception aspects of scale transformations must also be considered for graphical objects used in display design.

Through examining the alignment, scaling, and size effects of discriminating static graphical objects, Hollands (1992) examined the mental operations of observers in discrimination tasks. As discussed previously, the relationships between processes are often shown by inter-related graphical objects. Hollands explains that often proportional data is shown as a function of another variable. When data is shown in this inter-related manner, alignment, scale and size of the objects change, and the information that can be drawn from these objects correspondingly changes. Therefore it is important to consider these display techniques in designing graphical objects for monitoring tasks to ensure that the information conveyed from the objects is correctly interpreted by observers.

2.3 Emergent features in supervisory control

The issue of the visual aspects of scale transformations can be addressed by making use of graphical object attributes that immediately show when a process is changing, so that the change is very evident and can be addressed in a timely manner. Emergent features are attributes of integrated graphical objects that make changes in process relationships visually salient, so that they are very noticeable (Wickens and Hollands, 2000). Thus, when one or several variables begin to move into an “abnormal” state, their changes are noticed immediately through the use of emergent features. Greaney and MacRae (1997) link emergent features to visual search tasks and explain that emergent features are sufficiently salient so that once they are encountered, the target of the operator’s visual search has been found. Therefore, the emergent feature becomes the target of the search task. The effective use of emergent features in dynamic environments to highlight system failures has been demonstrated by Buttigieg and Sanderson (1991). The researchers examined object displays as well as a separated display to determine if emergent features made the detection of failures more noticeable. Subjects were presented with two types of emergent features in each type of display: well mapped emergent features, and displays without well mapped emergent features. Features in the well

mapped category included emphasizing linearity, deviating angles (leading to transforming shapes), and detection of equality of slopes. Through a multiple-day experiment, it was found that there were significantly positive effects for reaction times in detecting failures for displays that made use of mapped emergent features. A key conclusion from this work is that “features can be made to emerge over time just as much as over space, and that this fact can be exploited to represent important changes in a dynamic process” (p. 647). As discussed, supervisory monitoring involves the monitoring of complex dynamic processes. Buttigieg and Sanderson (1991) enforce the use of emergent features in process monitoring tasks to reduce the reaction time to detect system changes. While the researchers recommend that emergent features show a direct mapping of system states, they do not provide recommendations on the types of emergent features that best show the changes in system state. However, this work is considered important for it examines dynamic displays for monitoring tasks and confirms that emergent features are beneficial in graphical objects used for dynamic process monitoring.

Further experiments by Bennett, Toms, and Woods (1993) investigated emergent features in both separable and configural displays. By investigating the task time of participants using a feed-water flow system interface, the researchers found that both low-level displays that show single variables, as well as complex displays that show the interactions of various processes benefit from the use of emergent features. Their results indicate that graphical objects that show relationships between variables should configure to produce emergent features that highlight the critical data relationships. In doing so, observers have a significantly reduced reaction time to critical changes in variables or processes. By examining dynamic graphical objects, the researchers recommend the consideration of emergent features for objects used in dynamic monitoring tasks.

We can conclude that emergent features are effective in indicating system states to operators. However, the types of emergent features that best convey this information in dynamic monitoring tasks have not yet been identified. Thus research into the integrity of specific emergent features for supervisory monitoring is necessary to form guidelines on designing graphical objects for monitoring tasks.

2.4 Psychophysics of graphical objects

Graphical objects are used to display quantitative information in a visual manner. This visual method of display makes the task of integrating information simpler for an operator in supervisory control. Spence (1990) explains that graphical objects are powerful tools for they have the ability to display relationships among information. The advantage of graphical objects is that information can be inherently deduced without the need to compute and compare the exact quantitative values presented. For example, with two bar graphs, the observer can tell which is of a smaller value based on the relationship between the two bars. The exact magnitude of each of the bars does not have to be calculated and compared.

Hollands and Spence (2001) indicate that there are several properties used by observers in discriminating graphical objects. Among them, perceptual cues or features such as angle, area, slope, position, and height are cues used to discriminate between graphical objects. In their Incremental Estimation Model, the researchers explain how these properties are used by observers in the discrimination of proportions. Through experimentation, this model was tested on pie charts and divided bar graphs to examine the discrimination of aligned segments, non-aligned segments, and overall size. On a computer screen, participants were shown pairs of static graphs, and were asked to indicate which graph had the larger proportion. Results of this work indicate that the properties identified in the Incremental Estimation Model are the features used by observers when judging proportions. The researchers suggest

that making use of a single feature consistently in proportion discrimination tasks does not capitalize on the number of features used by observers in judging proportions. By using this model, it is suggested that several perceptual features may be used in proportion judging tasks; observers will make use of the features that to them best indicate the proportions. This work has several practical implications in static comparison tasks. The authors mention comparison of sales and marketing data as an area where this research is applicable. The conclusions provide insight into graph discrimination for computer displays, but do not address dynamic displays that are used for proportion discrimination. Hollands and Spence's (2001) work provides a foundation for graphical comparisons, but this work needs to be taken a step further if it is to be applied to dynamic graphical displays.

Different graphical objects allow observers to perform better on judging changes in the objects. In particular, considering the time to determine a change and accuracy of determining a change are important determinants when designing graphical objects for supervisory monitoring. Hollands and Spence (1992) investigated these determinants with different types of graphical objects. They looked at line graphs, bar graphs, pie charts, and tiered bar graphs for judging change and proportion. As discussed, graphical objects display information in a manner that makes integration and comparison simpler for the observer. Hollands and Spence (1992) indicate that the judgment of change involves the comparison of different quantities, and then integrating the information acquired from this comparison. Thus, finding the graphical objects that best indicate changes serve the purposes of information integration and comparison for the observer. Participants in the experiments conducted by Hollands and Spence were shown four graphs of varying degree of change, on each of the pages printed in a booklet. Participants were instructed to indicate how each proportion depicted changed in time by stating whether it increased, decreased, or did not change. Line and bar graphs were found to be quicker and more accurate than pie charts and

tiered bar graphs for the judgment of change in the object. They theorize that perception of change with the line and bar graphs requires fewer mental operations and therefore suggest that in judging perception of change, graphical objects that require fewer mental operations to detect the change should be used. The researchers provide recommendations for graph design and indicate that the type of judgment task dictates the performance of observers with a particular type of graph. Therefore the task must be closely examined to determine the type of graphical object that should be used to best convey the information presented by the graph to the observer.

These works by Hollands and Spence (Spence 1990; Hollands and Spence 1992, 2001) provide a basis for the graphical object design that can be used in dynamic supervisory monitoring. In the studies discussed, the researchers were looking solely at static graphical objects. Much can be learned about the perception of graphical objects from these studies of static objects. However, in order to comprehend the dynamic graphical objects that should be used in supervisory monitoring tasks, research into the perception of dynamic graphical objects must be done.

2.5 Visual attention in supervisory control

In supervisory control, the operator is monitoring the status of an entire complex system. The interface being used to monitor the system shows the status of several processes and variables through different graphical forms. The forms begin to move or change shape to reflect the changes in system variables or processes. Yantis and Jonides (1984) explain that in scenes with moving objects, before an object begins to move, it “can seem completely invisible; at movement onset, the object’s location is immediately and compellingly manifest, almost without effort on the part of the observer” (p. 601). This guides the notion that movement in complex displays will capture observer attention without great effort on the part of the graphical designer due to the nature of moving objects grabbing observer attention. When there

are several objects to monitor, the detection of the change is limited to the time it takes to search the entire display. However, detection of the target does not suffer from this visual search (Yantis and Jonides, 1984). In further experiments, Hillstrom and Yantis (1994) investigate the notion of elements in motion forming “new objects”. New objects are formed through motion not previously attended to by an observer. These new objects are extremely salient to the observer and draw the observer’s attention involuntarily. For example, when on a safari, the presence of a leopard may or may not be the target of a visual search. A leopard when stationary is difficult to detect in its natural setting. When the leopard begins to move, its spots move in a pattern that is new to the observer. This pattern of movement forms a “new object” and draws the observer’s attention. A visual search may be facilitated if the safari guide indicates that leopards may be seen. A search for a yet to be identified target may be initiated if the guide indicates that wildlife (not necessarily leopards) may be seen. Hillstrom and Yantis claim that this new object draws observer attention, however once the object becomes known to the observer, its salience diminishes. These ideas of movement drawing attention are integral in supervisory control, for observers must be drawn to the portion of the display that is moving in order to attend to the changes in the system. Movement drawing attention is fundamental in designing displays that are used in dynamic system monitoring. Dynamic graphical objects move when a process is changing; this is when a process needs to be attended to.

2.6 Summary and motivation

In this chapter, the motivation behind the current research was introduced and discussed. Previous research into the visual aspects of supervisory control with respect to emergent features, psychophysics and attention are considered in investigating the visual sensitivities of dynamic graphical objects used in supervisory control. This research considers that object movement directs attention. Therefore, it is taken that the observer is attending the graphical objects being investigated because the movement has captured the operator’s

attention. The research into static graphical objects, combined with the prior work on emergent features has been merged to form the foundation of determining emergent features that best show changes in dynamic graphical objects for the monitoring tasks investigated. Previous research and their limitations suggest reasons why the investigation of the visual aspects of dynamic graphical displays in supervisory control is necessary. The following chapters discuss experiments conducted for four separate monitoring tasks. The designs under investigation, experimental setup, and results are presented for each experiment. This research attempts to examine the supervisory control tasks through investigation of various graphical objects. Its aim is to provide design recommendations for the graphical objects used in those types of monitoring tasks.

Chapter 3

Enhancement of Emergent Features in Dynamic Monitoring Tasks

In complex monitoring tasks, often a number of variables and processes are being monitored at the same time. When the status of a variable or process changes, the change is reflected in the representing graphical object on the user interface. When there are several variables being displayed on the same interface, it becomes necessary to make changes in status salient so that they can be noticed by operators. Emergent features are attributes of graphical objects that provide the necessary salience when displaying multiple variables. Wickens and Hollands (2000) define emergent features as “a global property of a set of stimuli (or displays) not evident as each is seen in isolation” (p. 89). Buttigieg and Sanderson (1991) advise that emergent features help to draw attention to abnormal conditions in dynamic displays. Thus, the investigation of enhancements to emergent features for simple graphical objects is necessary to determine which types of emergent features are the most noticeable in dynamic monitoring tasks.

Vertical bar objects, horizontal bar objects and polygon objects are commonly prescribed graphical objects for complex monitoring tasks (Burns and Hajdukiewicz, 2004). These objects move upward/downward or inward/outward when the variable or process represented is increasing or decreasing. When displayed on their own, these objects do not make use of any emergent features. Attributes added to the graphical objects are considered to provide emergent features to the object. Therefore, adding indicators, shading, and reference bars between the graphical objects are considered to provide emergent features.

Typically, the departure from the prescribed “normal” state is mentally calculated by operators to determine the status of the variable or process being displayed by the graphical object. The emergent features used in this experiment help to emphasize the departure from the normal state. Buttigieg and Sanderson (1991) comment that “the more the emergent feature carrying the information pops out, the more effectively system states will be discriminated” (p. 634). Thus, the best emergent features for discriminating departure from normal system states are desired.

Rectangle bars were chosen for the vertical bar and horizontal bar objects. These types of graphical objects mimic the look of analogue status meters used in monitoring tasks. The three bars were of the same width, and were spaced one bar-width apart. These bars are used to display the status of a variable and the current value and the direction of movement. Enhancements to the emergent features used were indicator shapes (in this case a triangle), connecting bars, and no indicators. For the indicator shapes, the emergent feature would be the movement of the indicator as the meter moved upward or downward. The connecting bar would change in angle and length as the meter moved. This change in angle and length of the connecting line is the emergent feature. For displays without indicators, the discrepancy between the moving bar height and the heights of the static bars is the emergent feature. Thus for the bar objects in this experiment, an examination of the emergent feature that best showed changing status of meters was performed among the following emergent features: moving object, changing angles and length, and using reference bars.

An eight-axis polygon was chosen for the polygon object. Polygon objects have an adjusted scale so that all variables displayed in the polygon that give the polygon a symmetric look at the prescribed normal state. When a variable or process changes in value, its corresponding polygon axis changes in length. In this experiment the emergent features being assessed were a solid block of

shading and an outline shape. For the shaded block, the deforming emergent feature would be the change in polygon shape, from symmetrical (normal) to asymmetrical (abnormal). For the shape outline, the emergent features would be the lines connecting the axes changing in angle and in length. Thus for the polygon objects in this experiment, an examination of the deforming emergent feature that best showed changing status of variables was performed among the following emergent features: deforming shapes, and changing angles and length.

The purpose of this experiment was to investigate the following hypotheses:

Hypothesis 1: The response time for first noticing a change in the status of a display with a particular graphical object will be dependent on the emergent feature of that graphical object and its subsequent deformation. Thus there will be a significant difference in response times among the designs because of different features being used.

Hypothesis 2: Lines connecting bars of axes will have the fastest response time since these displays exploit two features changing at the same time: line length and line angle.

Hypothesis 3: Moving or deforming shapes are predicted to be not as evident as the connecting lines for they only have one changing feature – shape.

These hypotheses were investigated through the experimental testing outlined in the following sections.

3.1 Method

3.1.1 Participants

The participants were 25 undergraduate and graduate students at the University of Waterloo and were paid \$10 for their time. Participants were required to have a 20/20 binocular level of vision (regular or corrected). This was tested using a Sloan Chart.

3.1.2 Materials

The experiment's tasks were made using Macromedia Flash MX 2004 on a Pentium 4, 2.53 GHz, Windows XP personal computer with 512 MB of RAM. Tasks were displayed on a 19-inch CRT monitor with a 1024 x 768 resolution.

This experiment consisted of 16 tasks consisting of a random mix of the polygon, vertical bar, and horizontal bar objects. The following objects were tested:

Object	Feature
Vertical Bar	Without indicator moving upward Without indicator moving downward With triangle indicator moving upward With triangle indicator moving downward With connecting bar moving upward With connecting bar moving downward
Horizontal Bar	Without indicator moving outward Without indicator moving inward With triangle indicator moving outward With connecting bar moving outward With connecting bar moving inward
Polygon (6 axis)	Shaded moving outward Shaded moving inward Outline moving inward Outline moving outward

Table 1: Graphical objects tested in Experiment 1

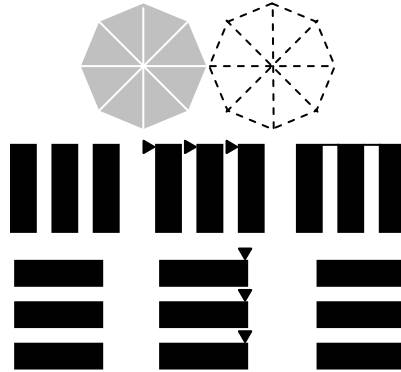


Figure 2: Sample graphical objects used in Experiment 1

Participants were to stop the task when they first notice a change in the display. This was to investigate the “just noticeable difference” (JND) of these types of graphical objects and features. A JND for these graphical objects and features is the smallest discernable change in movement or form detected by a supervisory monitor. In this experiment, the JND for these graphical objects was being sought.

Wertheim (1981) investigated the JND of moving objects in general. Through assessment of retinal (target) and extraretinal (background) signals, Wertheim concludes that the difference in velocity between the two signals determines the JND in movement. Wertheim’s work was the first of its kind to suggest that movement velocity dictates the JND, and thus does not prescribe the velocity at which a JND exists. McKee (1981) advises that the visual system’s response to motion is a complex process that depends on the object’s velocity of change. Through experimentation of moving targets relative to pursuit latency and saccadic latency, McKee concludes that “human observers can detect difference in velocity of less than 5%” (p. 497). This work by Wertheim (1981) and McKee (1981) concludes that velocity of movement dictates the JND, but does not prescribe the velocity or the features that should be used in graphical object movement for any types of graphical displays. From this work we can take the notion of velocity being important to JND and

investigate the JND for graphical objects to determine the features that allow the detection of the smallest change in graphical displays.

For each task, one of the graphical objects representing one variable or process started to change between 1 and 3 seconds. After a span of 20 seconds, the object had changed a total of 17 pixels.

The instructions for each of the tasks were the same. Participants were asked to start the task by using a mouse to click on the “START” button at the bottom right corner of the screen. When they first noticed a change in any of the graphics on the screen, they were to click the “STOP” button at the bottom left corner of the screen. The delay in start time was used to accommodate the participants moving the mouse pointer from the start button to the stop button. Participants were told that the graphics would “change size, move their position, etc. No matter what the change is, you should indicate when you FIRST notice the change”.

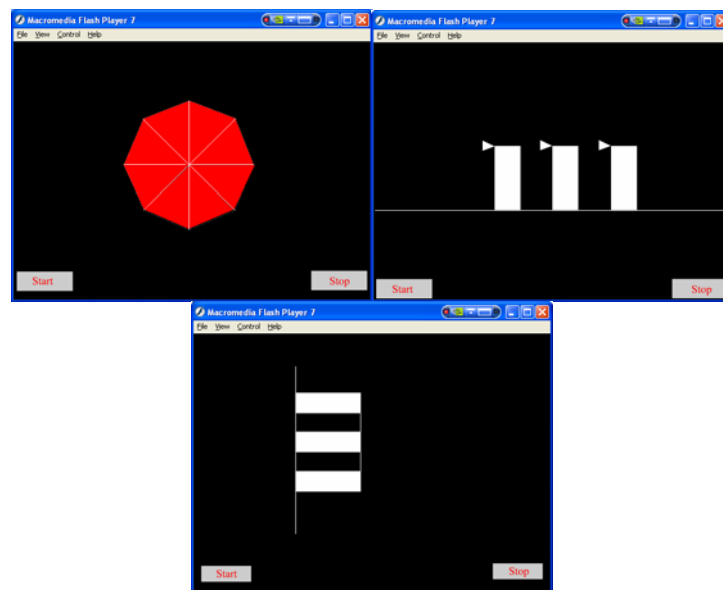


Figure 3: Sample computer tasks used in Experiment 1

Macromedia Flash MX 2004's Action Script feature was utilized to measure the number of pixels of change that occurred on the screen before the task was stopped.

3.1.3 Design and Procedure

A within-subjects design was used for each of the three graphical object types: vertical objects, horizontal objects, and polygon objects. The order of the tasks was counterbalanced across participants. The purpose of the experiment was to compare performance on the various graphical object designs, and find the optimal design. A within-subjects experimental design facilitated this.

Each participant was positioned 20-inches from the computer monitor and was asked to place their chin in a chin rest. The visual angle remained constant through the experiment, at 25.4 degrees. A standard fixation point and absolute position of stimuli on the computer screen was not used in order to keep the task as realistic to actual supervisory monitoring tasks as possible. A constant visual angle was used to ensure consistency in the results across all participants. The instructions stated that participants would see a series of 16 tasks in which they had to start the task, and then stop the task when they first noticed a change in the objects on the screen. The instructions further specified that changes will not happen immediately, so participants should take care in responding.

The number of pixels the object moved before the participant noticed a change was measured. This was to determine the magnitude of change necessary before the participant required before realizing a change had occurred.

After receiving the instructions, participants completed the tasks. The experimenter recorded the number of pixels of change measured for each of the tasks. This experiment required approximately 25 minutes to complete.

3.2 Results

The number of pixels of change required by each participant for each task was recorded using the Action Script tool. A within-subjects Univariate General Linear Model was used for statistical analysis on the number of pixels for each object type.

3.2.1 Vertical Objects

An overall significant difference was found in terms of the number of pixels of change required for the various designs presented ($F(5,120)=17.749$, $MSE=30.138$, $p \leq 0.001$). Thus there was a significant difference among the emergent features of moving shape indicators and connecting bars used. A Tukey-HSD post-hoc revealed that the connecting bar between the vertical objects required a significantly smaller pixel change ($p \leq 0.001$) and that the triangle indicator emergent feature required a significantly larger pixel change ($p \leq 0.001$). Thus the connecting bar had significantly the fastest response time (in number of pixels) to changes in status.

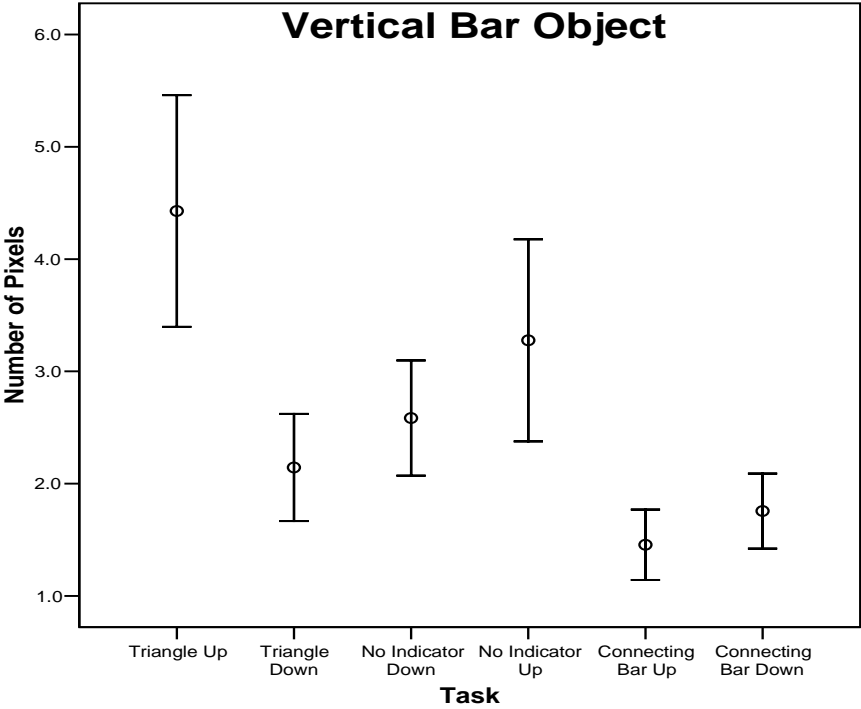


Figure 4: 95% Confidence interval plot for vertical bar objects

3.2.2 Horizontal Objects

An overall significant difference was found in the number of pixels of change required for the various design presented ($F(4,96)=3.608$. $MSE=0.876$. $p \approx 0.009$). Thus there was a significant difference among the emergent features of moving shape indicators and connecting bars used. A Tukey-HSD post-hoc revealed that the connector bar between the horizontal objects required a significantly smaller pixel change ($p < 0.02$). The connecting bar had significantly the fastest response time (in number of pixels) to changes in status.

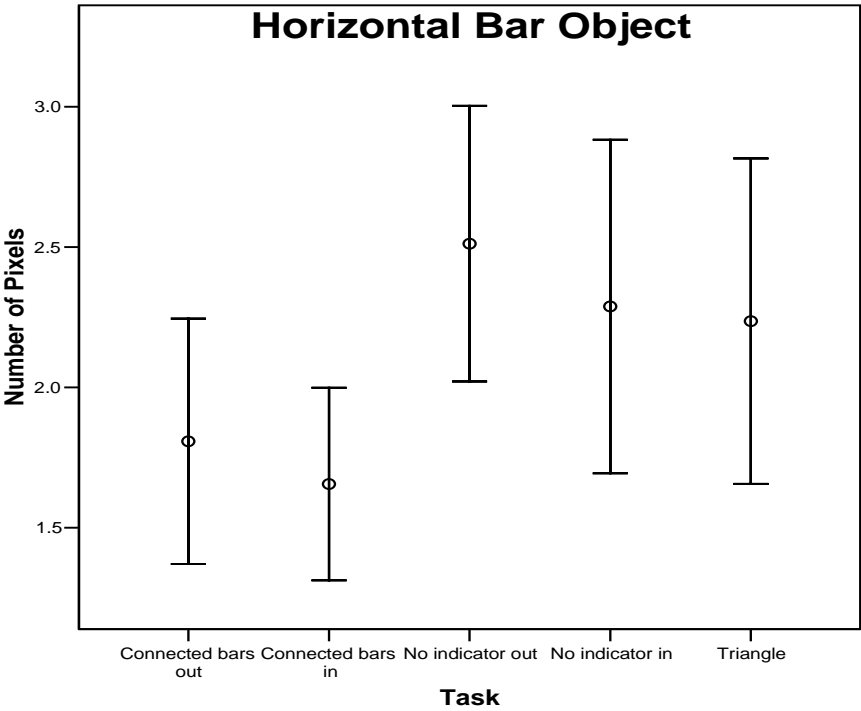


Figure 5: 95% Confidence interval plot for horizontal bar objects

3.2.3 Polygon Objects

A significant difference was found in the number of pixels of change required for filled polygons compared to unfilled polygons ($F(3, 72)=4.579$, $MSE=14.128$, $p < 0.01$). Thus changes in line angle and length outperformed deformation in shape for response time. Unfilled polygons required significantly fewer pixels of change.

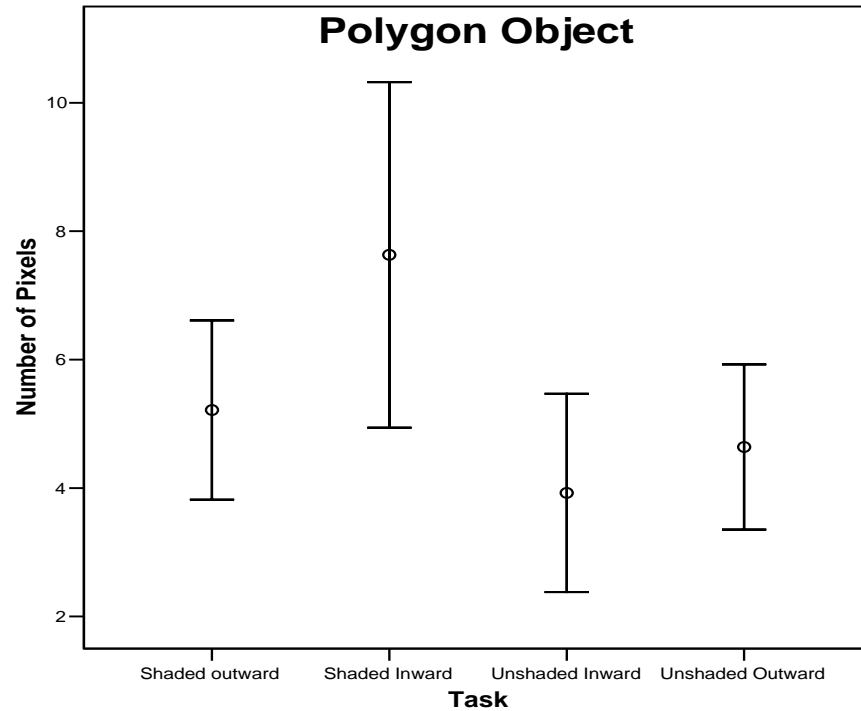


Figure 6: 95% confidence interval plot for polygon object

3.3 Discussion

The results of this experiment allow revisiting of the hypothesis to assess the initial predictions.

Hypothesis 1: The response time for first noticing a change in the status of a display with a particular graphical object will be dependent on the emergent feature of that graphical object and its subsequent deformation. Thus there

will be a significant difference in response times among the designs because of different features being used.

It was found that due to the difference in features used, there was an overall significant difference in the reaction time (based on number of pixels of change) for the different designs.

Hypothesis 2: Lines connecting bars of axes will have the fastest response time since these displays exploit two features changing at the same time: line length and line angle.

The results of this experiment indicate that changing angles of lines are the most noticeable feature in simple displays where values are changing. For the polygon object, the lines changing in angle proved to be more noticeable than a solid polygon changing in shape. Similarly, for the vertical and horizontal bars, solid indicators that did not change their shapes (such as the triangle indicator) were not as noticeable as the line indicator that connected the bars and changed in angle and length. These findings are in line with psychophysics literature that has indicated that there is greater precision of detecting deviations of lines from the horizontal and vertical axes than from any other orientation (Annis and Frost, 1973; Gibson and Radner, 1937).

Hypothesis 3: Moving or deforming shapes are predicted to be not as evident as the connecting lines for they only have one changing feature – shape

These results suggest that while emergent features make movement of graphical objects noticeable, the use of features that exploit changes in angle from the horizontal or vertical are the preferred emergent features. Designs that make use of multiple features are superior to those that use only one feature. Therefore a change in position and shape is superior to a change in only position or only shape.

These results provide guidance for designers of dynamic graphical displays for they highlight the features that are most noticeable among the variety of emergent features that can be used. As discussed in Chapter 1, there is evidence that emergent features are beneficial in detecting system faults and failures in dynamic monitoring tasks. These results provide further evidence of the benefits of emergent features in providing evidence of the types of features that should be used to make changes in system status the most noticeable.

Chapter 4

Dynamic Monitoring Tasks: Flow Comparison

Complex dynamic monitoring environments have several key tasks. One task is to monitor variables and processes to determine when they are at their target values. When a variable or process is at its target value, the graphical object on the user interface should clearly show the operator that the target has been attained.

Detecting when a variable is at its target value is a common monitoring task. In the medical domain, anesthesiologists are concerned with the heart rate of a patient (along with monitoring other processes). In aviation pilots are interested in the optimal functioning of plane engines. Assembly line managers want to determine if their line is producing the desired number of widgets per hour. Anywhere there is a desired (or target) value, there is assessment of whether the variable or process in question is at its desired value.

In certain work domains, it is crucial that variables be at their target values. Nuclear power plants and medical operating rooms function within a very small variability envelope. If an important variable is not at its target value, there may be serious repercussions. In these types of domains, the graphical objects displaying target values need to make it extremely clear to the operator when the variable is at its target and when it is straying from the target.

Traditionally there have been several methods used for indicating when a variable is at its target value. Simple digital status displays have shown the numeric value of the variable in digital form. Binary iconic forms show whether the variable is at target with a simple yes/no manner of display. Analogue forms provide a frame of reference for the variable and indicate the

status of the variable with respect to the target zone and the other values the variable may take.

In considering work domains, for the second experiment, graphical objects that were actually used in industry were sought. Communication with graphical designers who specialize in creating graphical objects for petrochemical plants provided insight into the complex displays used in these environments. Hydrogen-Oil flow analogue comparison meters were investigated to determine the best design for displaying when the target ratio of hydrogen to oil had been attained. The original concepts showed the value of the oil flow on one meter, and the hydrogen flow on a second meter. A hollow circle along the hydrogen meter indicated the desired ratio. When the indicator for the hydrogen flow was in the hollow circle, the desired target ratio had been achieved.

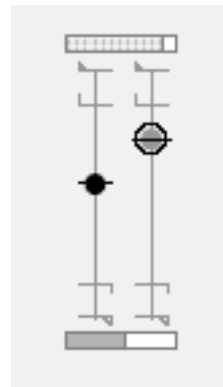


Figure 7: Original design concept for flow-comparison meter

The key issue in these displays was determining when the target ratio had been reached, based on discriminating if the indicator was in the hollow circle. Thus, investigation into the best design for showing when an indicator is on target is necessary to determine the best shapes that show this indicator-target relationship. The interest was in determining if operators would be able to notice that the indicator was at its target value based on the type of indicator and the type of target zone displayed.

A variety of shapes was used in determining the best target-indicator pairing for determining when an indicator is at its target value.

- The triangle indicator – square target pairing made use of an isosceles triangle with a non-congruent edge that was the length as the target square's height.
- The square indicator-square target pairing made use of a shaded square for the indicator, and the same size unshaded square for the target.
- The line indicator – line target pairing made use of two lines that were the same length. The target line was a slightly lighter shade than the indicator line.
- The diamond indicator – line target pairing used a filled diamond shape as the indicator and a line that was slightly longer than the widest part of the diamond as the target.
- The circle indicator – larger circle target pairing used a filled circle as the indicator and a slightly larger circle as the target. This design was taken from the original design concept.
- The circle indicator – circle target pairing used a shaded circle as the indicator and same diameter unshaded circle as the target.

The purpose of this experiment was to investigate the following hypotheses:

Hypothesis 1: The response time for detecting when the indicator is on target will be dependent on the indicator-target pairing used in the design. Thus there will be a significant difference in the response time among the designs because of the different indicator-target pairings used.

Hypothesis 2: Indicators that completely covered their targets are predicted to have the fastest response time for they visually fit together very well, and even slight deviations from the target are very evident.

Hypothesis 3: Indicators that are the same shape as their targets are predicted to have the fastest response time for they match their targets and fit seamlessly together.

As a prediction to the indicator-target pairings that will perform the best, the line indicator – line target pairing is predicted to best show the operator when the indicator was at its target value.

These hypotheses were tested in the experiment outlined in the following sections.

4.1 Method

4.1.1 Participants

The participants were 15 undergraduate and graduate students at the University of Waterloo and were paid \$10 for their time. Participants were required to have a 20/20 binocular level of vision (regular or corrected). This was tested using a Sloan Chart.

4.1.2 Materials

The experiment's tasks were made using Macromedia Flash MX 2004 on a Pentium 4, 2.53 GHz, Windows XP personal computer with 512 MB of RAM. Tasks were displayed on a 19-inch CRT monitor with a 1024 x 768 resolution.

This experiment consisted of six different designs that were randomly shown three times each, with different starting points each of the three times. The following objects were tested:

Object
a. Triangle indicator – square target
b. Square indicator – square target
c. Line indicator – line target
d. Diamond indicator – line target
e. Circle indicator – larger circle target
f. Circle indicator – same size circle target

Table 2: Graphical objects tested in Experiment 2

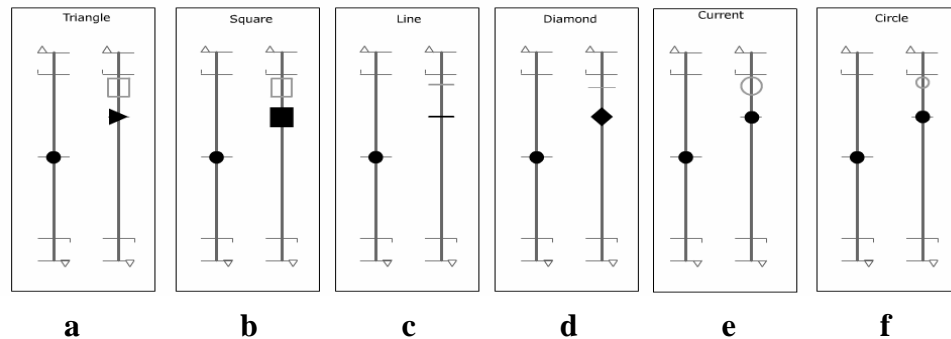


Figure 8: Graphical objects used in Experiment 2

For each task, the indicator moved along the dial and eventually toward the target. Over 40 seconds, the indicator had been in and out of the target a minimum of three times.

The instructions for each of the tasks were the same. Participants were asked to start the task by using a mouse to click on the “START” button at the bottom of the screen. When they thought the indicator was at its target, they were to click the “STOP” button at the bottom of the screen. A delay in start time was used to accommodate the participants moving the mouse pointer from the start button to the stop button. Participants were shown the indicator

and the target on the screen of a sample meter before beginning the experiment.

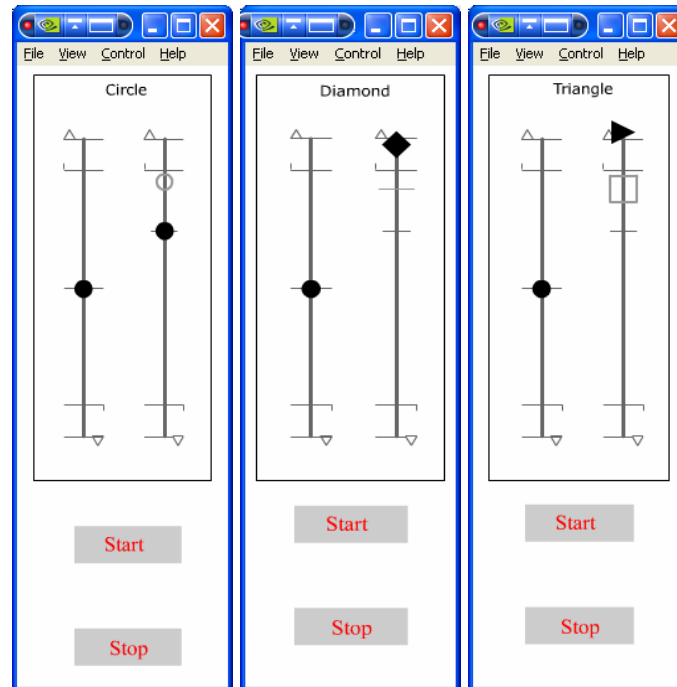


Figure 9: Sample computer tasks used in experiment 2

Macromedia Flash MX 2004's Action Script feature was utilized to determine the number of seconds the participant took to reach the target.

4.1.3 Design and Procedure

A within-subjects design was used for each of the six design alternatives. The order of the tasks was randomized across participants.

Each participant was positioned 20-inches from the computer monitor and was asked to place their chin in a chin rest. The visual angle remained constant through the experiment, at 25.4 degrees. A standard fixation point and absolute position of stimuli on the computer screen was not used in order to keep the task as realistic to actual supervisory monitoring tasks as possible. A constant visual angle was used to ensure consistency in the results across all

participants. The instructions stated that participants would see a series of tasks in which they had to start the task, and then stop the task when they believed the indicator was at its target location. The instructions further specified that the indicator will move into and out of the target area several times, so participants should take care in responding.

After receiving the instructions, participants completed the tasks. The experimenter recorded the time to reach the target for each of the tasks. This experiment required approximately 15 minutes to complete.

4.2 Results

The time required (number of seconds) to reach the target by each participant for each task was recorded using the Action Script tool. The time required for each task was subtracted from the prescribed time required to reach the target. The absolute value of this result was then taken. This result was deemed the deviation from the prescribed time. The three repetitions were then grouped by design type. A within-subjects Univariate General Linear Model was used for statistical analysis for the deviation time for each design alternative for each participant.

A significant difference for the deviation from the prescribed target time was found among the six design alternatives ($F(5,250)=8.793$. $MSE=1.918$. $p \leq 0.001$). Thus, certain designs outperformed others. A Tukey-HSD post-hoc revealed that the circle indicator-circle target meter had significantly slower reaction times ($p \leq 0.001$), followed by the line indicator-line target meter. In comparing those indicators that completely covered their targets to those meters where the targets can always be seen, it was found that reaction time was significantly better than for the indicators that did not completely cover their targets ($F(1,254)=17.474$. $MSE=2.077$. $p \leq 0.001$). Thus the Triangle indicator – square target, Circle indicator – larger circle target were superior

to the square indicator – square target, line indicator – line target diamond indicator – line target, circle indicator – same size circle target pairings.

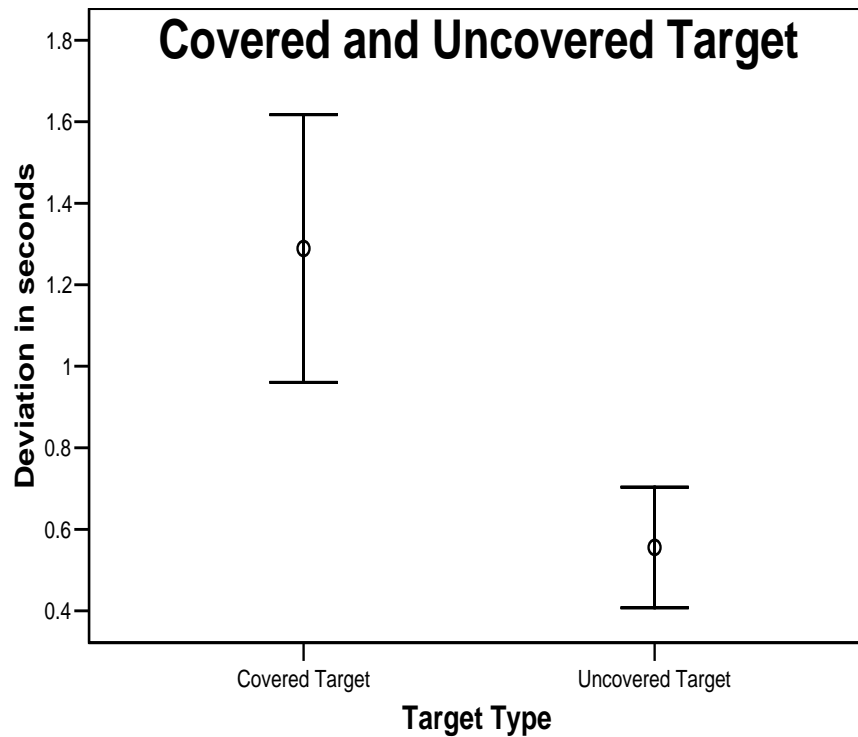


Figure 10: 95% confidence interval plot for covered and uncovered targets

Indicators that were the same shape as their targets had a significantly better reaction time than those indicators that were not the same shape as their targets ($F(1,254)=4.870$. $MSE=2.179$. $p \approx 0.03$). These were the square indicator – square target, line indicator – line target, circle indicator – larger circle target and circle indicator – same size circle target pairings.

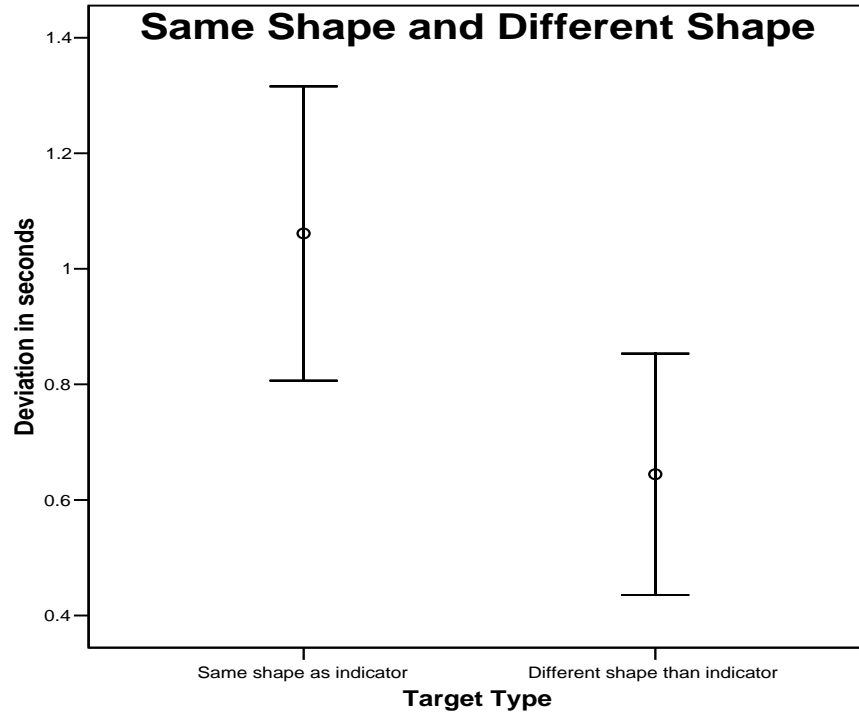


Figure 11: 95% confidence interval plot for shape indicator-target pairs

4.3 Discussion

The results of this experiment allow revisiting of the hypothesis to assess the initial predictions.

Hypothesis 1: The response time for detecting when the indicator is on target will be dependent on the indicator-target pairing used in the design. Thus there will be a significant difference in the response time among the designs because of the different indicator-target pairings used.

It was found that there was an overall significant difference in the detection of targets for the various designs due to the indicator-target pairings used.

Hypothesis 2: Indicators that completely covered their targets are predicted to have the fastest response time for they visually fit together very well, and even slight deviations from the target are very evident.

The prediction of the line indicator – line target pairing outperforming the other designs was not supported. Instead, the results of this experiment indicate that in complex monitoring tasks where an indicator is moving into a target zone, it is difficult to determine when the indicator is at the target if the indicator completely covers the target. Indicators that completely cover the targets lead to confusion and tend to signify the target has disappeared.

Hypothesis 3: Indicators that are the same shape as their targets are predicted to have the fastest response time for they match their targets and fit seamlessly together.

Targets and indicators being of the same shape lead to a “bull’s eye” effect. MacGregor and Slovic (1986) suggest that “compatibility between display and task requires matching the visual properties of displays to the psychological properties of the judgments and decisions users are called upon to make” (p. 198). Thus when the “bull’s eye” is formed, it parallels the look of a target and indicates when the target value has been reached.

These results lead to the conclusion that targets that are slightly larger than the indicators, and that are the same shape as the indicators, are the superior design for graphical objects that need to show when a value has reached its target level.

Chapter 5

Dynamic Monitoring Tasks: Rate Indicator

Supervising the changes in variable and process values is the underlying principle of monitoring tasks. Most variables and processes are constantly experiencing small or large changes in their values. Part of supervisory monitoring is to keep track of these changes, and distinguish normal variations from abnormal variations. These types of monitoring tasks occur in many domains. For anesthesiologists, blood pressure is constantly fluctuating, and in aviation, airplane speed is constantly changing. This increase and decrease in variable and process values is normal for most domains. However, if this change is not desired, it should be caught quickly by monitors so that the problem can be diagnosed immediately. Determining when a variable reverses its direction of change is a task which requires monitors to determine the original direction of movement and to catch the change when it happens. Visually, it requires undisputable evidence that a variable or process has changed its direction of movement.

As discussed in the previous chapter, there are several key tasks in complex dynamic monitoring environments. Another important task is determining when a variable has changed its direction of activity. For example, a value could be increasing, and then could decrease. A flow could be in one direction and then could change to flow in the opposite. This detection of a changing direction is important in dynamic monitoring, for graphical objects displaying these changes contain crucial information on the status of certain variables and processes in the system.

Communication with graphical designers who specialize in creating graphical objects for petrochemical plants provided insight into these types of graphical objects. Rate indicator meters are used in petrochemical plants to indicate the

direction of flow of chemicals in the plants. The meters indicate the rate of flow as well as its direction.

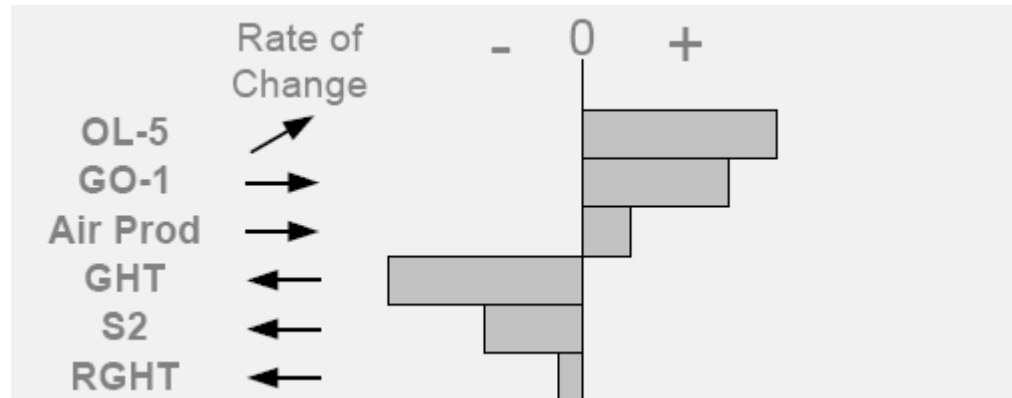


Figure 12: Original design concepts for rate indicator meter

Of interest in these types of displays was determining the direction of flow, when the flow direction changed, and previous states of flow. However the key issue in these displays was determining when the flow had changed. Thus, investigation into the best design for showing when a variable changes its flow direction is necessary to determine the graphic object types that indicate a change.

A variety of design alternatives were considered for these changing variable direction tasks. These designs showed the current and previous state so that when a change occurs, the operator would be able to verify this change based on if there are previous states displayed.

- Indicators that are made up of circles (all of the same size) showed the previous states. A filled circle shows the current state.
- Filled bars that show the current state, and arrows that show the direction of movement.
- Large triangles that show the previous state and a filled rectangle showing the current state.

- Circles showing the current state using connecting lines to show previous states.
- Triangles showing the current state using connecting lines to show previous states.
- Large circles showing the current state, with incrementally smaller circles showing the prior states.
- A dark shaded circle showing the current state with incrementally lighter shaded circles showing previous states.
- A dark outlined circle showing the current state with incrementally lighter shade outlined circles showing previous states.

The purpose of this experiment was to examine the following hypotheses:

Hypothesis 1: The response time for detecting when a variable or process has changed in flow direction will be dependent on the design used. Thus there will be a significant difference in the response time among the designs because of the different designs used.

Hypothesis 2: It is predicted that the circles showing the current state with connector lines showing the previous states would best show the operator when a change in variable direction had occurred because the lines connecting the current state circles would change in length and in angle.

Hypothesis 3: Designs that show changes in direction in an abrupt manner will have shorter reaction times than designs that make use of differences in shading to show flow direction.

These hypotheses were investigated through an experimental testing outlined in the following sections.

5.1 Method

5.1.1 Participants

The participants were 15 undergraduate and graduate students at the University of Waterloo and were paid \$10 for their time. Participants were required to have a 20/20 binocular level of vision (regular or corrected). This was tested using a Sloan Chart.

5.1.2 Materials

The experiment's tasks were made using Macromedia Flash MX 2004 on a Pentium 4, 2.53 GHz, Windows XP personal computer with 512 MB of RAM. Tasks were displayed on a 19-inch CRT monitor with a 1024 x 768 resolution.

This experiment consisted of eight different designs that were randomly shown two times each, with different starting points each of the two times. The following objects were tested:

Label	Object	Current State	Previous State
Dots	Same size circles	Filled circle	Unfilled circle
Current	Bars and arrows	End of Bar	Bar fill
Triangles	Triangle	Rectangle Indicator	Triangle shading
Connect Triangles	Connected triangle	Triangle Indicator	Connecting line to zero point
Connect Dots	Connected circle	Circle indicator	Connecting line to zero point
Circle/Dots	Incremental size circles	Largest circle	Incrementally smaller circles
Dots Shading	Shaded same size circles filled	Darkest shaded circle	Incrementally lighter shaded circles
Circles Shading	Shaded incremental size circles unfilled	Darkest circle outline	Incrementally lighter shaded circles outlines

Table 3: Graphical objects tested in experiment 3

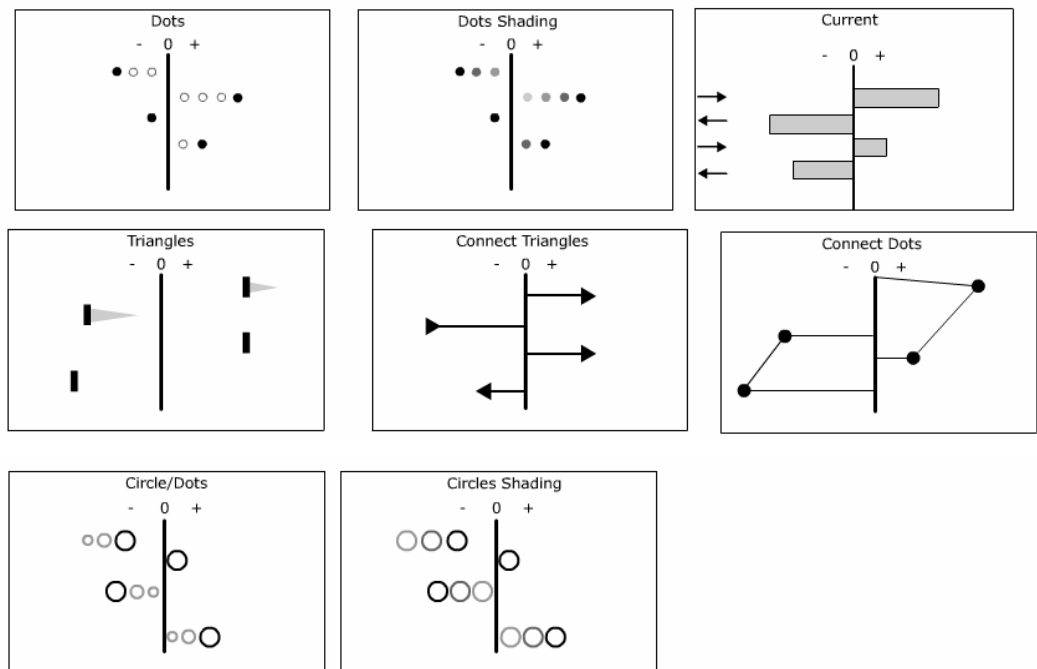


Figure 13: Graphical objects used in experiment 3

For each task, four variables were displayed. Each of the variables changed directions individually in each task. Over 40 seconds, each of the variables had changed directions a minimum of twice in an attempt to accommodate the notice of change by participants.

The instructions for each of the tasks were the same. Participants were asked to start the task by clicking on the “START” button at the bottom of the screen. When they thought the indicator had changed direction, they were to click the “STOP” button at the bottom of the screen. A delay in start time was used to accommodate the participants moving the mouse pointer from the start button to the stop button. Participants were shown each of the variables on the screen of a sample meter before beginning the experiment.

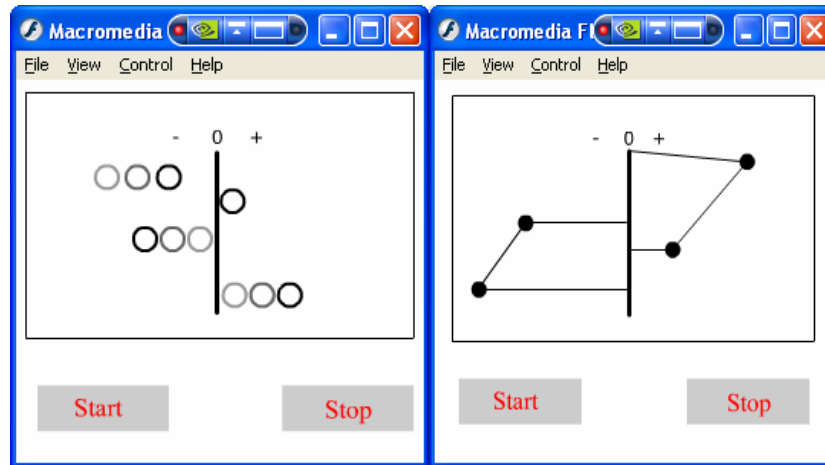


Figure 14: Sample computer tasks used in experiment 3

Macromedia Flash MX 2004's Action Script feature was utilized to determine the number of seconds the participant took to determine a variable had change direction.

5.1.3 Design and Procedure

A within-subjects design was used for each of the design alternatives. The order of the tasks was randomized across participants.

Each participant was positioned 20-inches from the computer monitor and was asked to place their chin in a chin rest. The visual angle remained constant through the experiment, at 25.4 degrees. A standard fixation point and absolute position of stimuli on the computer screen was not used in order to keep the task as realistic to actual supervisory monitoring tasks as possible. A constant visual angle was used to ensure consistency in the results across all participants. The instructions stated that participants would see a series of tasks in which they had to start the task, and then stop the task when they believed a variable had changed direction. The instructions further specified that the variables will all change together at once, so participants should be aware and respond once the initial change had happened.

After receiving the instructions, participants completed the tasks. The experimenter recorded the time to reach the target for each of the tasks. This experiment required approximately 20 minutes to complete.

5.2 Results

The time (in seconds) required to determine when a variable had changed direction by each participant for each task was recorded using the Action Script tool. The time required for each task was subtracted from the prescribed time when a variable changed direction. The absolute value of this result was then taken. This result was deemed the deviation from the prescribed time. The two repetitions were then grouped by design type. A Univariate General Linear Model was used for statistical analysis for the deviation time for each design alternative for each participant.

The amount of deviation of participant reaction times from the prescribed time in which the flow meters changed their flow direction showed a significant difference among the design alternatives for the rate indicator meters ($F(7,218)=5.611$. $MSE=14.889$. $p \leq 0.001$). Thus, certain design alternatives were superior to others with respect to reaction time. While the connected circles had a better mean reaction time than the other designs, this was not found to be significant. The alternatives that made use of incremental shading changes were found to have significantly slower reaction times than designs that did not make use of incremental shading.

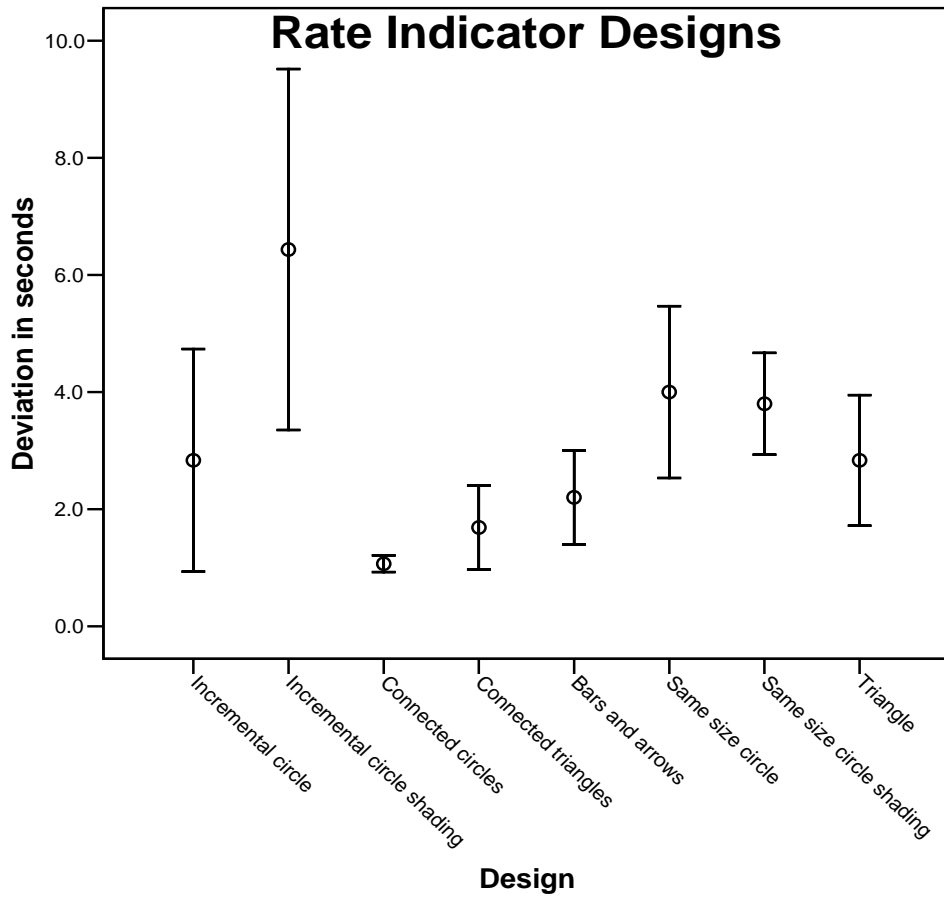


Figure 15: 95% confidence interval plot for rate indicator designs

For meters that made use of shading to show direction flow, participants had a significantly slower reaction time than for meters that showed direction flow through transforming shapes ($F(1,224)=20.641$. $MSE=15.658$. $p \leq 0.001$).

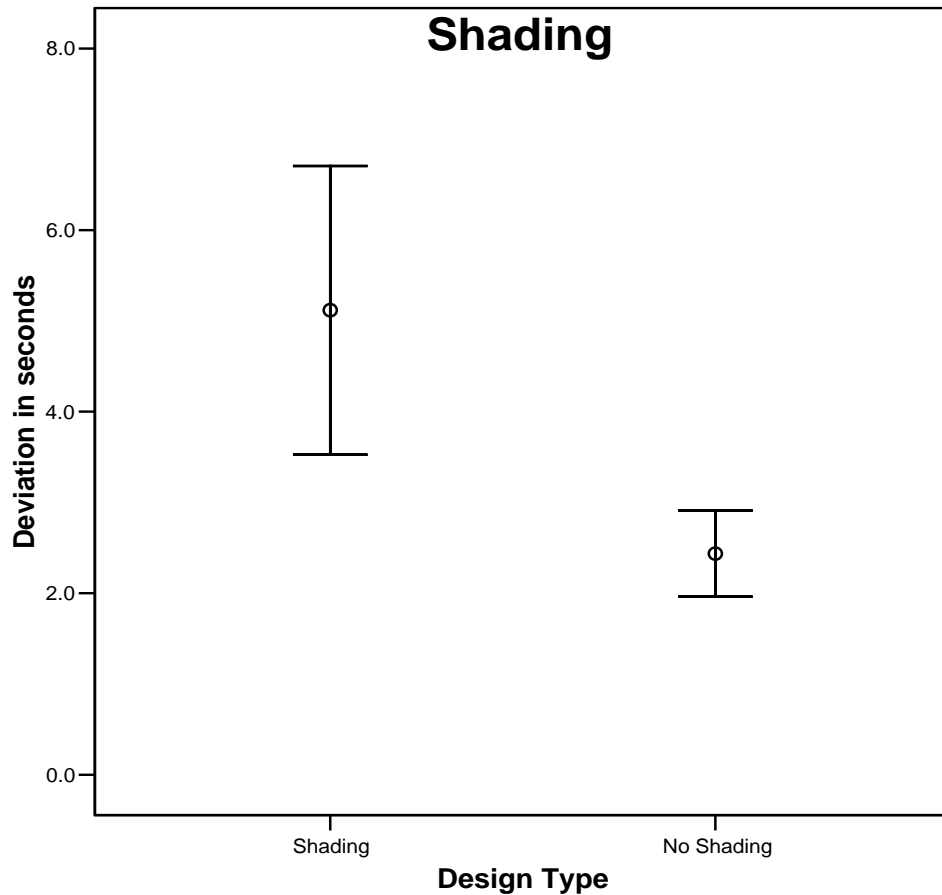


Figure 16: 95% confidence interval plot for shaded and non shaded designs

5.3 Discussion

The results of this experiment allow revisiting of the hypothesis to assess the initial predictions.

Hypothesis 1: The response time for detecting when a variable or process has changed in flow direction will be dependent on the design used. Thus there will be a significant difference in the response time among the designs because of the different designs used.

It was found that there was an overall significant difference in the reaction times for the various designs due to the graphical design used.

Hypothesis 2: It is predicted that the circles showing the current state with connector lines showing the previous states would best show the operator when a change in variable direction had occurred because the lines connecting the current state circles would change in length and in angle.

The prediction of connected circles outperforming the other designs on the premise that the changing length and angle of connector bars being very evident did hold to be true but did not produce a significant difference. In experiment 1, lines changing in length and location were found to be the best emergent features for monitoring when a change had occurred. It was felt that this result would be replicated in this flow comparison task. However, this task is somewhat different than the task in experiment 1 because the variables are not at a normal value and are constantly moving. The purpose of experiment was to determine when variables and processes stray from “normal”. The purpose of this experiment was to determine when process are changing in general, whether they start at a normal value or start at some other state.

Hypothesis 3: Designs that show changes in direction in an abrupt manner will have shorter reaction times than designs that make use of differences in shading to show flow direction.

As discussed in Chapter 1, for graphical objects, abrupt changes in status and the transformation of shapes catches operator attention in monitoring tasks (Yantis and Jonides, 1984). Thus the shapes changing in size for these types of meters makes changes in meter direction more noticeable than subtle changes in shading, and likely makes the task of determining previous states easier.

The results of this experiment revealed that for meters showing dynamic state information, the use of shapes and transformations in shapes to indicate meter flow direction is far superior to using changes in object shading.

Because the objective of this task was different from that of the previous tasks discussed in chapters 3 and 4, the results of the designs that show the best performance are different. This advises designers to create graphical objects based on the specific task and not to generalize designs based solely on the look of the graphical object. Designs for different tasks can have similar attributes, but the manner in which observers use these attributes is specific to the task at hand.

Chapter 6

Dynamic Monitoring Tasks: Levels Stacked

The comparison of values to maintain a ratio is a very common task in monitoring and also in other contexts. The notion of a “balance” is very prevalent in a variety of systems. Domains such as medical monitoring, energy generation and food services involve maintaining ratios to keep balances. In several monitoring tasks, if variables or processes go out of balance, serious interactions can occur, which can lead to unwanted results.

A key issue in determining ratios is measuring the values of the two variables or processes being compared. In order to determine the ratio between two variables or processes, the values of each need to be known. There are several methods of displaying these values. Digital forms or analog forms can be used for operators to determine the values of the variable. Another method that operators can use when comparing two values is examining the relationship that emerges between the variables or processes. Rather than taking the two variable values and computing the ratio, the inherent relationship between the two values is examined. This is the concept upon which this experiment is based.

This key task for complex dynamic monitoring environments addressed is determining when ratios exist between values. This is an important task in monitoring environments for determining relationships between variables or processes is often carried out by operators. The detection of when a desired ratio exists is an important task and can make use of several different types of graphical objects.

Petrochemical plant graphic designers provided insight into the graphical objects used to monitor ratios in plants by operators. A level stacked display

allows operators to compare the values of two variables on a common display. Water-oil mixture to oil levels was investigated to determine the best design for displaying when a desired ratio of water-oil mixture to oil ratio exists. The original concepts showed the level of the water-oil mixture overlaid by the level of oil. Operators can compare these two meter values to determine if a desired ratio exists.

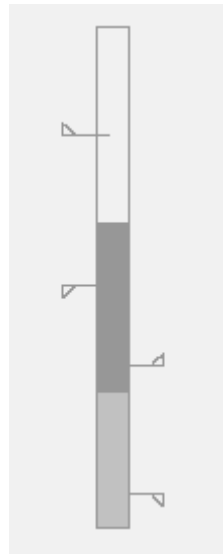


Figure 17: Original design concept for levels stacked meter

The key issue in these displays is determining when the desired ratio exists between the two level values. This is based on discriminating the height of each level from the baseline (the lowest point on the meter). Thus, investigation into the best design for comparing the two levels is necessary to determine the features that best show the ratio that exists.

Relationships between variables can visually be made very evident through graphical objects. In this experiment, various methods of showing the relationship between two variables are explored to determine the graphical objects that best make evident to operators the relationship between two

variable values. Here, we are interested in determining the graphical features that best convey this information to the operators.

A number of design alternatives were created for determining the graphical features that best show the relationship between variables to operators based on the original design concept that was provided.

- Current values shown by horizontal line indicators connected by an angled line.
- Current values shown by horizontal line indicators connected by an angled line with the space between the indicators and under the angled line shaded.
- One shaded rectangle indicator sitting in front of a second lighter shaded indicator.
- An angled line connecting the value of one variable to the other.
- An angled line connecting the value of one variable to the other with the space under the angled line shaded.
- An angled line connecting the value of one variable to the other with the space under the angled line to the point of the next variable value with a horizontal line drawn.
- Two differently shaded bars side by side, each showing the value of one variable.
- An angled line connecting the value of one variable to the other with the space under the angled line to the point of the next variable value shaded.
- An angled line connecting the value of one variable to the other with the space under the angled line to the point of the next variable value shaded and a horizontal line drawn.
- Horizontal lines indicating the value of each variable connected with a vertical line.

- Horizontal lines indicating the value of each variable connected with a vertical line, and the space under the vertical lines and the indicator shaded.

The purpose of this experiment was to examine the following hypotheses:

Hypothesis 1: The response time for determining when a particular ratio exists between the two values will depend on the design used. Thus there will be a significant difference in the response time among the designs because of the different designs used.

Hypothesis 2: Designs that made use of angled connector lines would outperform the vertical connector line alternatives, for the specific angle of the line would be attended to and the angle would be identified as the slope showing the desired ratio.

Hypothesis 3: Shading the space between the two indicators for each of the scales would aid operators in determining the ratio between the two values for shading makes the two values more evident. This would lead to a faster reaction time in determining the ratio.

These hypotheses were investigated through an experimental testing outlined in the following sections.

6.1 Method

6.1.1 Participants

The participants were 15 undergraduate and graduate students at the University of Waterloo and were paid \$10 for their time. Participants were required to have a 20/20 binocular level of vision (regular or corrected). This was tested using a Sloan Chart.

6.1.2 Materials

The experiment's tasks were made using Macromedia Flash MX 2004 on a Pentium 4, 2.53 GHz, Windows XP personal computer with 512 MB of RAM. Tasks were displayed on a 19-inch CRT monitor with a 1024 x 768 resolution.

This experiment consisted of 11 different designs that were randomly shown two times each, with different starting points each of the two times. The following objects were tested:

Object	Shading	Line Type	Indicator
Unstacked	Yes	N/A	Horizontal
Triangle	Yes	Angled	Spot
Triangle with line	Yes	Angled	Horizontal
Line with horizontal straight	No	Straight	Horizontal
Line with horizontal straight filled	Yes	Straight	Horizontal
Line with horizontal angled	No	Angled	Horizontal
Line with horizontal angled filled	Yes	Angled	Horizontal
Current (Stacked)	Yes	N/A	Horizontal
Angled line	No	Angled	Spot
Angled line with fill	Yes	Angled	Spot
Triangle with line no fill	No	Angled	Horizontal

Table 4: Graphical objects tested in experiment 4

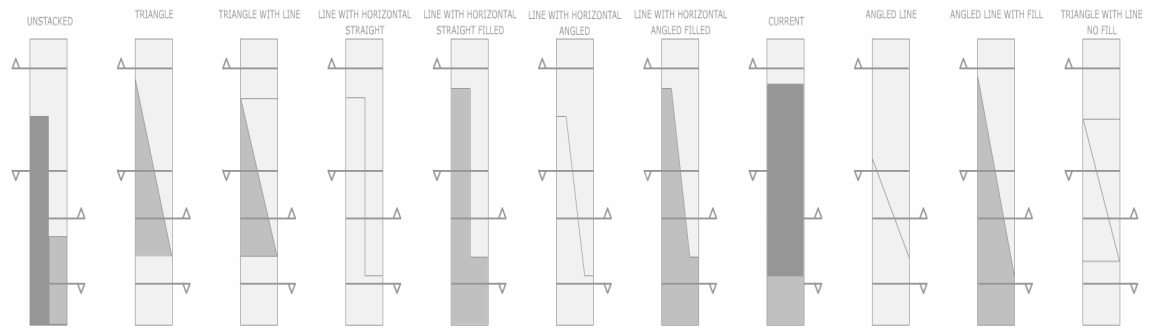


Figure 18: Graphical objects used in experiment 4

For each task, the indicators moved along the dials and eventually came to the targeted ratio of 3:1. Over 120 seconds, the ratio of 3:1 had been achieved at least three times.

The instructions for each of the tasks were the same. Participants were asked to start the task by clicking on the “START” button at the bottom of the screen. When they thought the indicators showed a 3:1 ratio, they were to click the “STOP” button at the bottom of the screen. A delay in start time was used to accommodate the participants moving the mouse pointer from the start button to the stop button. A 3:1 ratio was selected as the target since it is a ratio where there is an obvious visual distinction between the meters. Participants were shown each of the variables on the screen of a sample meter before beginning the experiment.

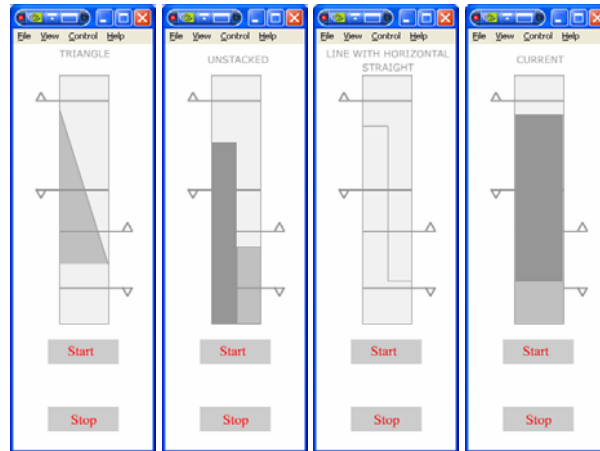


Figure 19: Sample computer tasks used in experiment 4

Macromedia Flash MX 2004's Action Script feature was utilized to determine the number of seconds the participant took to determine the variables were at a 3:1 ratio.

6.1.3 Design and Procedure

A within-subjects design was used for each of the design alternatives. The order of the tasks was randomized across participants.

Each participant was positioned 20-inches from the computer monitor and was asked to place their chin in a chin rest. The visual angle remained constant through the experiment, at 25.4 degrees. A standard fixation point and absolute position of stimuli on the computer screen was not used in order to keep the task as realistic to actual supervisory monitoring tasks as possible. A constant visual angle was used to ensure consistency in the results across all participants. The instructions stated that participants would see a series of tasks in which they had to start the task, and then stop the task when they believed a 3:1 ratio between the variables had been achieved. The instructions further specified that the variables will come to this ratio several times, so if the participant misses the ratio one time, it will return.

After receiving the instructions, participants completed the tasks. The experimenter recorded the time to reach the 3:1 ratio for each of the tasks. The experiment required approximately 30 minutes to complete.

6.2 Results

The time required to reach the ratio by each participant for each task was recorded using the Action Script tool. The time required for each task was subtracted from the prescribed time required to reach the ratio. The absolute value of this result was then taken. This result was deemed the deviation from the prescribed time. The three repetitions were then grouped by design type. A within-subjects Univariate General Linear Model was used for statistical analysis for the deviation time for each design alternative for each participant.

The amount of deviation of participant reaction times from the prescribed time in which the meters were at the 3:1 ratio showed a significant difference among the design alternatives for the levels meters ($F(10, 305)=16.688$. $MSE=3.756$. $p \leq 0.001$).

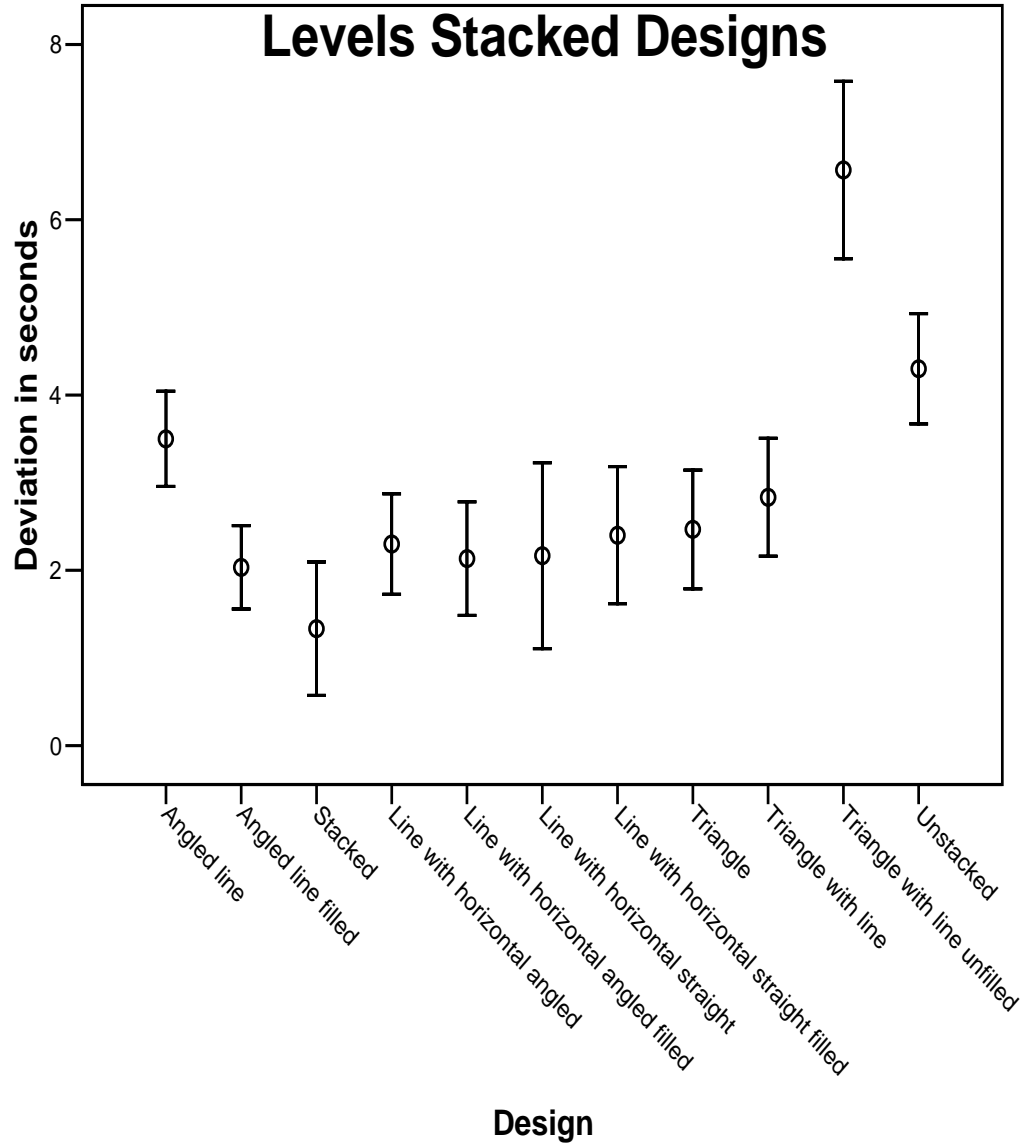


Figure 20: 95% confidence interval plot for levels stacked designs

For meters that had shading between the indicators, participants had a significantly smaller reaction time than for meters that did not have shading ($F(1, 314)=18.393$. $MSE=5.333$. $p \leq 0.001$).

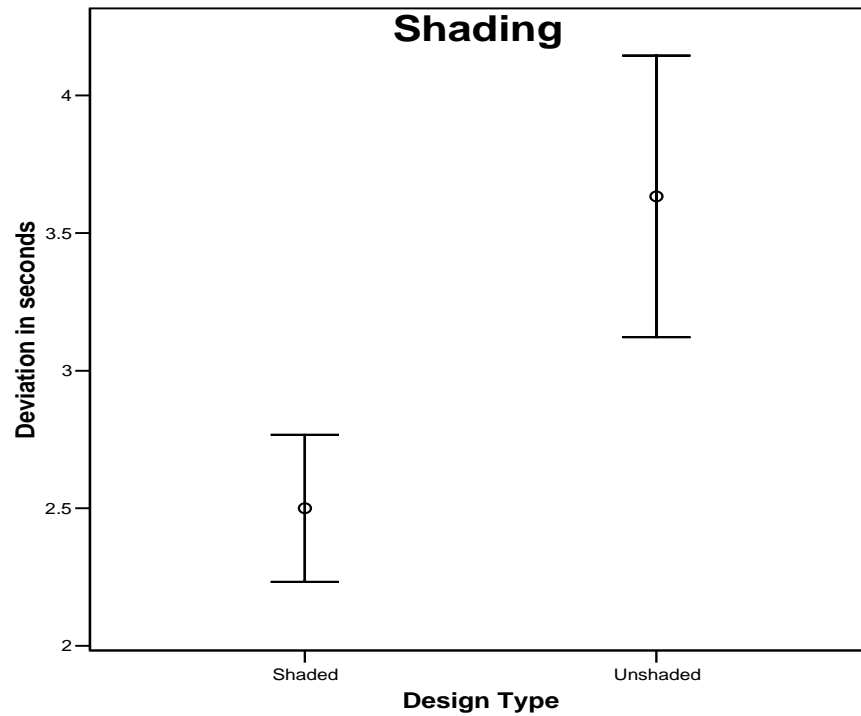


Figure 21: 95% confidence interval plot for shaded and unshaded designs

Additionally, meters that had vertical bars connecting the horizontal indicators had a significantly faster reaction time than meters that had angled bars connecting the indicators ($F(1, 254)=9.986$. $MSE=5.492$ $p \approx 0.016$).

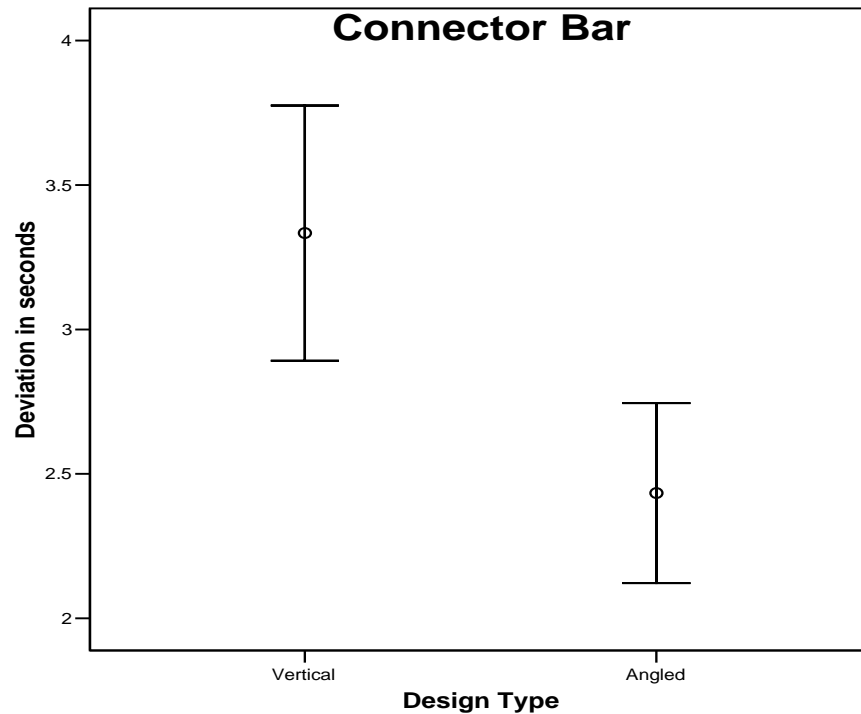


Figure 22: 95% confidence interval plot for angled and vertical connector designs

6.3 Discussion

The results of this experiment allow revisiting of the hypothesis to assess the initial predictions.

Hypothesis 1: The response time for determining when a particular ratio exists between the two values will depend on the design used. Thus there will be a significant difference in the response time among the designs because of the different designs used.

It was found that there was an overall significant difference in the reaction times for the various designs due to the graphical design used.

Hypothesis 2: Designs that made use of angled connector lines would outperform the vertical connector line alternatives, for the specific angle of the line would be attended to and the angle would be identified as the slope showing the desired ratio.

Results of the experiment indicate that angled lines were associated with a slower reaction time than vertical lines connecting indicators.

Hypothesis 3: Shading the space between the two indicators for each of the scales would aid operators in determining the ratio between the two values for shading makes the two values more evident. This would lead to a faster reaction time in determining the ratio.

Shading the space between the two indicators leads to a faster reaction time in determining the desired ratio, than not having shading between the two indicators.

In experiments on discriminating proportions in different types of graphs, Hollands (1992) found that bar graphs had faster reaction times for judged proportions than graphical objects that were not separated (such as pie charts). Hollands theorizes that observers were constructing virtual lines to aid their judgment with these types of bar graphs. This theory may be evident in the results of this experiment. With the use of shaded graphical objects, observers may be mentally converting these objects to bar graphs and then creating virtual lines to compare the two bar graphs. With angled lines, or graphical objects that are not shaded, this may be more difficult for observers since the features do not form a “solid” object, and thus make comparison more difficult.

Shading makes the meter appear “solid”, as does a vertical bar connecting two horizontal indicators. These “solid objects” perform better in judging moving meter values, for it would seem that one bar acts as a reference for the other. Thus, when meters are used to compare values, meters that show values in blocked elements lead to more accurate comparison readings than indicators that show values as connected data points. In investigating the judgment of proportions in graphical objects, the results of this experiment indicate that proportions are better judged when comparing “solid objects” versus slopes of lines.

Chapter 7

Discussion and Future Work

The series of experiments reported has provided insight into the design requirements of graphical objects used in certain dynamic monitoring tasks. Due to the nature of supervisory monitoring, not all tasks have been addressed in this study. Rather, samplings of tasks that are common in supervisory control have been investigated. The results of this study can be applied to the monitoring tasks discussed, but might also be applicable to different monitoring tasks that are similar to those investigated.

7.1 Discussion of experiments

Experiment 1 investigated emergent features used in supervisory graphical objects. While past research has shown that emergent features serve as targets in visual search tasks (Greaney and MacRae, 1997), and that emergent features aid observers in showing critical data states (Buttigieg and Sanderson, 1991; Bennett et al., 1993), the current research advises on the emergent features that most quickly allow observers to discriminate changes in states. Because the maximum velocity of change was the same for all of the designs, the features of the graphical object distinguish the designs. For detecting when variables and processes are no longer at their prescribed normal states, lines connecting graphical atoms (such as bar graphs or axes lines) allow the observer to quickly determine a departure from the normal state. When lines move on an angle they change both in length and in location. This change is most noticeable to observers, and allows for the quickest inference of a change in variable or process state for dynamic monitoring tasks.

Experiment 2 assessed different shapes and shape relationships for indicator-target meters. Results from the experiment lead to the conclusions that for

indicator-target pairs, indicators that are the same shape as their targets, but smaller in size best allow for observers to discriminate when a value or processes is at its target location. It can be considered that in this configuration, the indicator-target form a “bull’s eye” which mimics the purpose of the task. A bull’s eye is regarded as a target (such as in the billiards game of darts). Observers are quicker to detect when an indicator is at the target when this bull’s eye is formed. MacGregor and Slovic (1986) suggest that this compatibility between visual and psychological task objective is required for displays.

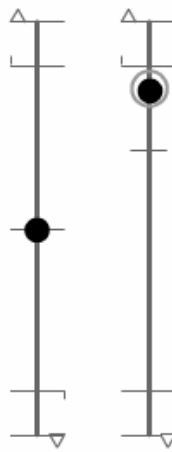


Figure 23: Recommended design from experiment 2

Experiment 3 compared different methods of displaying when variables or processes change in direction of movement. Based on the premise that abrupt changes draw operator attention (Yantis and Jonides, 1984), the graphical objects that made use of transforming shapes or abrupt movements were superior to those that showed change through subtle shading differences. Graphical displays that show changes in an abrupt manner parallel the way variables or processes change in reality. If the volume of a liquid is increasing, then decreases, this change is rather abrupt. Graphical objects behavior that matches the actual behavior of variables and processes are the most quickly attended to by observers.

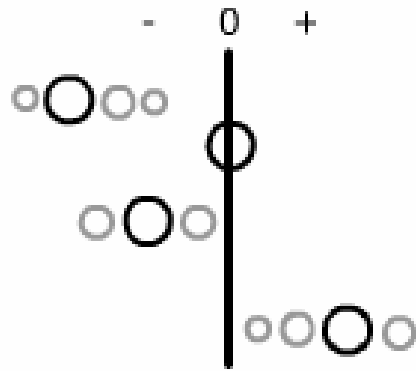


Figure 24: Recommended design from experiment 3

Experiment 4 tested various methods of showing the relationship between two values, and determining when a particular ratio existed between the values. Vertical lines connecting the horizontal value indicators with shading in the space between the values was the graphical object that best allowed observers to discriminate when the desired ratio existed. It has been shown that alignment, scale, and size play a part in judging proportions between static graphical objects (Hollands, 1992). This experiment took this work on static graphical objects and went a step further to determine judging proportions of dynamic graphical objects. The conclusions of this experiment add to Hollands (1992) work, and suggest that features that make the graphical object appear to be a “solid” bar are best for comparing two values.

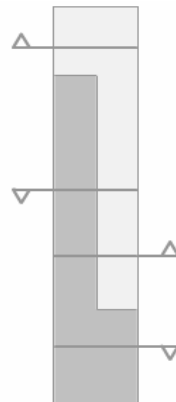


Figure 25: Recommended design from experiment 4

Designing graphical objects for monitoring tasks is task specific. The requirements of the task must be considered in designing the features of the graphical object used. Overall from the experiments it can be concluded that graphical objects that best portray the actual processes being monitored will provide the observer the best visual information for monitoring the process.

7.2 Limitations

This study took place in an “ideal” setting, as it was the first investigation of its kind into dynamic graphical objects. As the setting may not be entirely representative of actual supervisory monitoring, several limitations exist.

7.2.1 Attention

Participants in this study only focused on one part of the computer screen while completing the tasks. They were seated close to the computer screen and were placed in a chin rest. This ensured that their gaze was only on the computer screen in front of them. While this method of examination helped in determining the visual aspects of the displays, it is not representative of actual monitoring tasks. Future work would allow observers to be in a natural position and allow them to direct their attention when it was necessary. Additionally, only one graphic object was being monitored at a time. As discussed previously, supervisory control involves the monitoring of several processes simultaneously. Thus in addition to allowing observers to be in a natural position for monitoring, several processes could be monitored at the same time to investigate whether the results of these experiments on single processes hold true for multiple processes. The issue of divided attention may have an influence on the visual aspects of the graphical objects investigated.

7.2.2 Tasks

The tasks observed by the participants in the experiments were very short and very simple. In actual supervisory monitoring, observers must monitor the displays for an entire shift, and not only a few minutes. The purpose of

keeping these tasks short was to focus in on the visual aspects of the displays without having to consider observer vigilance and fatigue. Future work could place observers in a more natural setting and have more realistic task lengths.

7.2.3 Participants

The participants used in this experiment were students at the University of Waterloo, and were not actual operators. Using actual plant operators may make a difference in the reaction times to the displays. Likely the reaction times will be shorter since the operators are more experienced with the processes being displayed.

7.2.4 Environment

The environment in which the experiments were conducted was not very representative of a supervisory control room. Observers in supervisory control settings have several screens surrounding them in an entire room (Vicente et al., 2001). Additionally, observers were not faced with interruptions, multiple tasks, or alarms in these experiments. The experiments were focused entirely on the graphic object monitoring and did not distract the observers from their tasks. Alarms were not integrated for they were felt to take away from the investigation of the graphical objects and their features, and their assessment was beyond the scope of this work. Applying these design recommendations to an actual control room setting will provide valuable insight into the impact of the graphical designs recommended.

7.2.5 Color and sound

The graphical objects only made use of grayscale, and did not use any auditory feedback. The intention of this study was to investigate the visual aspects on a simple scale: physical form. Further studies into the effect of color and auditory feedback in monitoring may add to the findings of this study.

7.2.6 Data represented

The data represented in the tasks completed by the participants was not data from actual variables and processes. It was randomly generated data, used to investigate the graphical objects being tested. Actual process and variable data may differ in its variability, and thus graphic objects representing actual processes likely would not move in the manner represented in these experiments.

7.3 Recommendations for future work

The results and conclusions from this study can be taken further to learn more about visual sensitivities of dynamic graphical displays. In particular, the limitations discussed could be considered in future experiments to judge whether the results change when any of the factors discussed in chapter 7.2 change. In particular, the evaluation of when attention is given to single graphical object versus attention over an entire control panel would be useful in determining if visual sensitivities change with task demands. Having more demanding individual tasks (rather than the simple ones used in this study) along with a more realistic monitoring environment would also advise whether visual sensitivities change with task demands.

Considering alarms would add another interesting dimension to the present study. In reality, when a variable or process reaches critical level, an alarm would be triggered to notify observers of this occurrence. Incorporating visual or auditory alarms into tasks similar to those studied would advise graphical designers on the merits of alarms and on the types of alarms that best work with the graphical objects studied.

In EID, designers go through a design methodology that concludes with an interface that best suits the observers for a particular work environment. After assessing the work domain, designers perform an information requirement analysis to determine the variables and processes that should be displayed on

the user interface. Following this, designers determine the graphical atoms they wish to use to portray the information (e.g. iconic, analogical, etc.) and being to sketch out a preliminary design. The present work is applicable at this level of design, and encourages designers to consider the visual aspects of the graphical objects being used. In particular, designers now have verified objects that best suit their display requirements for:

- Showing when variables and processes have departed from their normal values (experiment 1)
- Displaying when variables and processes are on target (experiment 2)
- Presenting a series of variables and processes, and monitoring when they change in direction (experiment 3)
- Determining when a particular ratio exists between displayed values (experiment 4)

Chapter 8

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Appendix A

Experimental Materials

A1. Recruitment Flyer

PARTICIPANTS NEEDED FOR COMPUTER DISPLAY STUDY

We are looking for volunteers to take part in a study of graphical computer displays

Participants will be asked to perform computer-based tasks involving observing changing computer displays.

Your participation will take approximately 1 hour, and you will receive \$10 in compensation.

For information about this study, or to volunteer, please contact:

Munira Jessa

Systems Design Engineering

888-4567 ext. 4904

or mnjessa@engmail.uwaterloo.ca



This study has been reviewed by, and received ethics clearance through, the Office of Research Ethics, University of Waterloo.

A2. Information Letter

UNIVERSITY OF WATERLOO SYSTEMS DESIGN ENGINEERING

This is a study for just noticeable differences in computer displays. It is being conducted by Munira Jessa under the supervision of Professor Catherine Burns from the department of Systems Design Engineering at the University of Waterloo.

This study is being conducted to investigate just noticeable differences in normalized computer displays, as well as the visual differences of graphical elements used in petrochemical plants. Examples of displays are dials, vertical bars, or thin lines. We are interested in investigating various computer displays to determine which display provides the most information regarding change of state. We are interested in determining which display provides information in the best way.

As a participant in this study, you will be asked to complete computer based tasks. You will be given instructions and a brief tutorial of each task before beginning.

Participants in this study must be between the ages of 19 and 65, and must have corrected vision to 20/20 level.

As a participant in this study, you will receive \$10 for your time. Additionally, the information obtained from this study may provide insight into standardized computer displays for various tasks. There are no known or anticipated risks in participating in this study.

Participation in this study is expected to take one hour of your time. You may refuse to participate or you may withdraw after the study has started without any loss of compensation. All information collected from participants in this study will be combined. Thus, your name will not appear in any report, publication or presentation resulting from this study. The data, with identifying information removed, will be kept for a period of 2 years and will be securely stored in a locked office in the research laboratory. You may withdraw from the study at any time by advising the researcher of this decision.

If you have any questions about participation in this study, please feel free to ask the researchers. If you have additional questions at a later date, please contact Dr. Catherine Burns at (519) 888-4567 ext. 3903 or by email at c4burns@uwaterloo.ca. This project has been reviewed by, and received ethics clearance through, the Office of Research Ethics. In the event you have any comments or concerns resulting from your participation in this study, please contact Dr. Susan Sykes at 519-888-4567, Ext. 6005.

A3. Consent Form

**UNIVERSITY OF WATERLOO
OFFICE OF RESEARCH ETHICS**

Consent of Participant

I have read the information presented in the information letter about the study being conducted by Professor Catherine Burns and Munira Jessa of the Department of Systems Design Engineering at the University of Waterloo. I have received satisfactory answers to my questions related to this study. I am aware that I may withdraw from the study at any time without penalty.

I understand that this project has been reviewed by, and received ethics clearance through, the Office of Research Ethics at the University of Waterloo. I further understand that if I have any comments or concerns resulting from my participation in this study, I may contact the Director, Office of Research Ethics, at (519) 888-4567 ext. 6005.

With full knowledge of all foregoing, I agree, of my own free will, to participate in this study.

Print Name: _____

Signature of Participant: _____

Dated at Waterloo, Ontario: _____

Witnessed: _____

A4. Feedback Letter

UNIVERSITY OF WATERLOO SYSTEMS DESIGN ENGINEERING

Thank you for participating in the Just Noticeable Difference Study. Your participation is very much appreciated.

The main purpose of this study is to investigate visual sensitivities in normalized computer displays. Many displays used in computer interfaces contained normalized data. This means that mathematically the data are adjusted so that the display takes on a consistent look. Typically in normalized displays, when all is "normal" the display takes on an even look. In this study, we are examining how much of a difference is noticeable when the display begins to change. We are interested in the time it takes to notice a change in the display, the minimum amount of change noticed, and how accurately people respond to various design alternatives. It is important that small amounts of change be noticeable for they can represent large amounts of change in a system. Through the use of various indicators, we wish to also see if indicators make a difference in the amount of time it takes to notice a change in the status of a display, if target values are detected, and if ratios can be maintained.

Further information regarding normalized displays can be found in the books:

- Wickens, C., & Hollands, J. (1999). Engineering Psychology and Human Performance. New Jersey: Prentice Hall. pp 89-90
- Wickens, C., Lee, J., Liu, Y., & Becker, S. (2004). An Introduction to Human Factors Engineering. New Jersey: Prentice Hall. pp 205-208

This project has been reviewed by, and received ethics clearance through, the Office of Research Ethics. In the event you have any comments or concerns resulting from your participation in this study, please contact Dr. Susan Sykes at 519-888-45467, Ext. 6005

Sincerely,
Munira Jessa

A5. Test Script

TEST SCRIPT

1. Information Form and Consent Form

Please read over the experiment information form.

Do you have any questions?

Please fill out the consent form.

2. Eye Test

Before beginning the experiment, I need to check your vision for acuity. The chart in front of you is to test your visual acuity. For this experiment we require 20/20 vision. For this we will use the Sloan chart.

- Please stand with your toes at the marking and read aloud the smallest line of letters you can on the chart. Please indicate which line of letters you are reading (eg. 3rd from bottom), and please read the letters left to right. - Take your time, and guess the letter if you are not sure. I may prompt you to read another line of letters, and will indicate to you which line of letters I'd like you to read.

- I will be taking some notes while you are reading out the chart.

- Do you have any questions?

3. First Change Tasks

You will now go through a series of sixteen tasks on the computer.

- First, you need to sit in the chair, up straight, and put your chin in the chin rest. Sit comfortably with your forehead against the rest. I will adjust it accordingly.

- You will see various displays on the computer screen. I would like you to indicate when you first notice a change in the displays on the screen. For example, they may change size, move their position etc. No matter what the change is, you should indicate when you FIRST notice the change. Not all tasks will have a change right at the beginning, so take your time in responding.

- To start the task, click on the "START" button at the bottom left of the screen. When you notice a change, click on the "STOP" button at the bottom right of the screen.

- Do you have any questions?

- In between each task, I will have to load the next task. I will take over control of the computer for a few seconds while I load the next task.

- I will be taking notes while you are completing each task.

- Do you have any questions?

4. Flow Comparison

We will now move onto our next set of tasks. In this, you will see a number of meters that compare the flow of two values in petrochemical plants. The point of these meters is to show when a target flow value is reached. An indicator moves along the meter, moving into and out of the target zone. I'd like you to stop the task when the indicator has reached its target value. It will be moving into and out of the target zone. Do your best to determine when it is at the target zone. Each task will have a different target value and indicator shape. For example, one of the meters looks like this [show the meter]. This is the moving indicator, and this is the target value.

- Do you have any questions?

5. Levels Stacked

In the next set of tasks, you will see a number of displays that show two meters. These two meters remain in ratio with each other. The point of these displays is to compare the two meter values. I'd like you to stop the task when the ratio of the two values is 3:1. So one meter is three times that of the second meter. This will be a bit tricky, but do your best to determine when this ratio exists. Each set of displays looks slightly different. One meter is measured by the vertical line on the right, where the second meter is measured by the vertical line on the left. For example [show the meter].

- Do you have any questions?

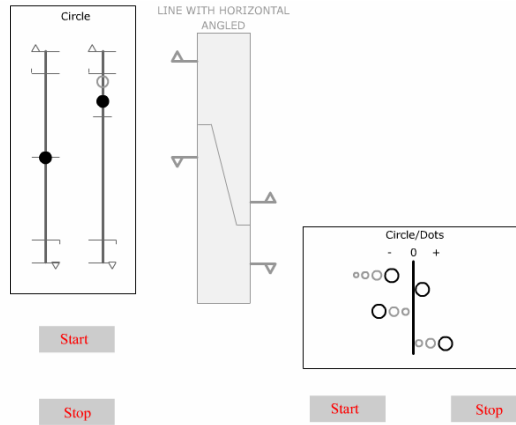
6. Rate Indicator

In the next set of tasks, you'll see a number of displays that show four meters. These displays are showing the rate of change of flow in a particular direction. The meters will start all at the same time (this will be very noticeable). Once the meters start, I'd like you to stop the task when you first notice a meter change its flow direction. That is, the flow will be in one direction, and once it changes, you will stop the task. Please indicate to me which meter you saw change its flow direction. An example meter is as follows [show the sample meter].

- Do you have any questions?

- Thank you for your participation. Here is sheet of information on this experiment for you.

- Here is an information letter for you on what we are investigating. Please sign the receipt for your payment.



A6. Experimental Setup

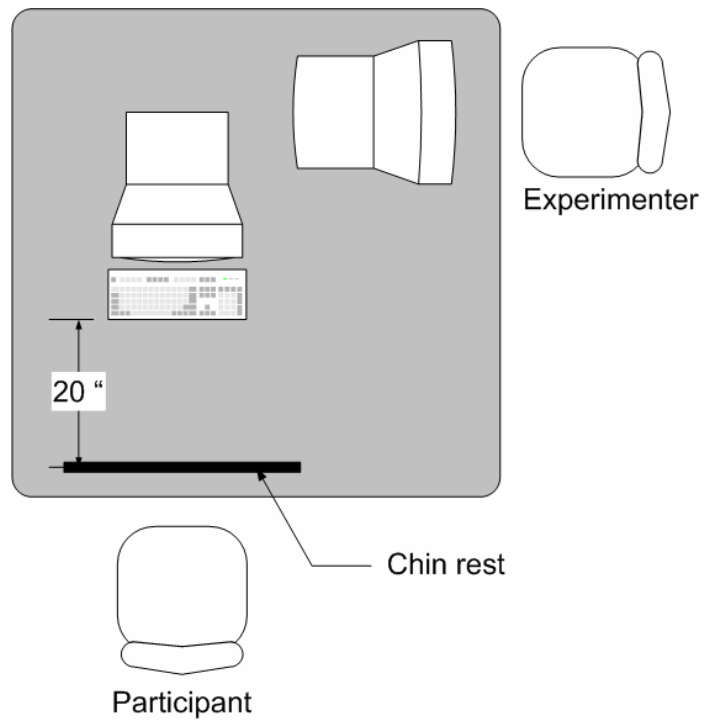


Figure 26: Experimental setup for participant and experimenter



Figure 27: Chin rest used in experiments

Appendix B

Detailed Results

B1. Experiment 1: Vertical Bars

Part.	Task	No. of px.			
1	Triangle Up	5.9	9	Triangle Up	5.2
	Triangle Down	4.6		Triangle Down	2.1
	No indicator Down	2.9		No indicator Down	2.8
	No indicator Up	3.9		No indicator Up	4.6
	Connecting line Up	1.4		Connecting line Up	3.6
	Connecting line Down	2.5		Connecting line Down	3.4
2	Triangle Up	4.3	10	Triangle Up	4.2
	Triangle Down	1.2		Triangle Down	2.8
	No indicator Down	2.2		No indicator Down	5.6
	No indicator Up	1		No indicator Up	5
	Connecting line Up	2.3		Connecting line Up	3.2
	Connecting line Down	1.7		Connecting line Down	4
3	Triangle Up	5.2	11	Triangle Up	3.6
	Triangle Down	1.3		Triangle Down	2.7
	No indicator Down	1.7		No indicator Down	3.4
	No indicator Up	2.5		No indicator Up	2.3
	Connecting line Up	1.6		Connecting line Up	1.4
	Connecting line Down	2		Connecting line Down	1.8
4	Triangle Up	4.5	12	Triangle Up	1.9
	Triangle Down	2.9		Triangle Down	2.2
	No indicator Down	1.6		No indicator Down	2.2
	No indicator Up	4.5		No indicator Up	5.4
	Connecting line Up	1.7		Connecting line Up	1.5
	Connecting line Down	2.5		Connecting line Down	1.4
5	Triangle Up	4.7	13	Triangle Up	1.4
	Triangle Down	2.5		Triangle Down	1.1
	No indicator Down	5.7		No indicator Down	2.3
	No indicator Up	3		No indicator Up	3.3
	Connecting line Up	2.3		Connecting line Up	1
	Connecting line Down	1.9		Connecting line Down	1.1
6	Triangle Up	1	14	Triangle Up	2.3
	Triangle Down	0.2		Triangle Down	0.5
	No indicator Down	1.3		No indicator Down	1.5
	No indicator Up	3		No indicator Up	1.3
	Connecting line Up	0.9		Connecting line Up	0.9
	Connecting line Down	0.9		Connecting line Down	1.2
7	Triangle Up	6.2	15	Triangle Up	4.3
	Triangle Down	3.2		Triangle Down	2.5
	No indicator Down	3.4		No indicator Down	4.1
	No indicator Up	0.8		No indicator Up	2.4
	Connecting line Up	0.9		Connecting line Up	1.5
	Connecting line Down	1		Connecting line Down	1.7
8	Triangle Up	5.7	16	Triangle Up	1.8
	Triangle Down	4.4		Triangle Down	0.8
	No indicator Down	2.6		No indicator Down	1.4
	No indicator Up	9.2		No indicator Up	1.7
	Connecting line Up	2.3		Connecting line Up	0.8
	Connecting line Down	2.9		Connecting line Down	0.9

17	Triangle Up Triangle Down No indicator Down No indicator Up Connecting line Up Connecting line Down	2.4 1 1.1 1.1 0.9 0.8	22	Triangle Up Triangle Down No indicator Down No indicator Up Connecting line Up Connecting line Down	10.7 4 2.9 7.5 1.6 1.9
18	Triangle Up Triangle Down No indicator Down No indicator Up Connecting line Up Connecting line Down	8.6 1.6 1.8 2.4 0.9 1	23	Triangle Up Triangle Down No indicator Down No indicator Up Connecting line Up Connecting line Down	4.1 2.5 1.8 2.5 1.3 1.9
19	Triangle Up Triangle Down No indicator Down No indicator Up Connecting line Up Connecting line Down	7.4 2.5 2.1 3.3 1.1 1.6	24	Triangle Up Triangle Down No indicator Down No indicator Up Connecting line Up Connecting line Down	1.4 1.2 1.3 0.7 0.7 0.9
20	Triangle Up Triangle Down No indicator Down No indicator Up Connecting line Up Connecting line Down	8.2 2.7 4.2 2.4 0.9 1.4	25	Triangle Up Triangle Down No indicator Down No indicator Up Connecting line Up Connecting line Down	4.3 1.7 2.4 6.8 0.8 2
21	Triangle Up Triangle Down No indicator Down No indicator Up Connecting line Up Connecting line Down	1.4 1.4 2.3 1.3 0.9 1.5			

B2. Experiment 2: Horizontal Bars

Part.	Task	No of px.			
1	Connecting bar outward Connecting bar inward No indicator outward No indicator inward Triangle indicator inward	1.7 2.5 2.2 4.4 3.1	6	Connecting bar outward Connecting bar inward No indicator outward No indicator inward Triangle indicator inward	1.6 0.9 2.2 0.8 1.5
2	Connecting bar outward Connecting bar inward No indicator outward No indicator inward Triangle indicator inward	4.9 1.9 1.6 1.3 1.5	7	Connecting bar outward Connecting bar inward No indicator outward No indicator inward Triangle indicator inward	2 1 6.7 1.9 2.3
3	Connecting bar outward Connecting bar inward No indicator outward No indicator inward Triangle indicator inward	1.2 1.3 2.2 2.1 3	8	Connecting bar outward Connecting bar inward No indicator outward No indicator inward Triangle indicator inward	2.7 2.3 3.8 5.3 6.7
4	Connecting bar outward Connecting bar inward No indicator outward No indicator inward Triangle indicator inward	3.4 2.1 0.7 1.5 1.8	9	Connecting bar outward Connecting bar inward No indicator outward No indicator inward Triangle indicator inward	1.9 1.9 3.1 3.7 2.7
5	Connecting bar outward Connecting bar inward No indicator outward No indicator inward Triangle indicator inward	3.6 3.5 2.8 3.5 1.9	10	Connecting bar outward Connecting bar inward No indicator outward No indicator inward Triangle indicator inward	2.9 2.8 3.6 4.4 3.6

11	Connecting bar outward Connecting bar inward No indicator outward No indicator inward Triangle indicator inward	1.5 2.1 2.7 1.8 2.9	19	Connecting bar outward Connecting bar inward No indicator outward No indicator inward Triangle indicator inward	1.2 1.4 2.6 3.8 4
12	Connecting bar outward Connecting bar inward No indicator outward No indicator inward Triangle indicator inward	1.2 1 2.9 1.8 1.7	20	Connecting bar outward Connecting bar inward No indicator outward No indicator inward Triangle indicator inward	0.7 1 2.3 2.1 1.9
13	Connecting bar outward Connecting bar inward No indicator outward No indicator inward Triangle indicator inward	1.1 1.8 1.9 1.3 1.2	21	Connecting bar outward Connecting bar inward No indicator outward No indicator inward Triangle indicator inward	0.8 1.9 2.5 1.2 2.1
14	Connecting bar outward Connecting bar inward No indicator outward No indicator inward Triangle indicator inward	1.2 0.7 2.7 0.9 0.7	22	Connecting bar outward Connecting bar inward No indicator outward No indicator inward Triangle indicator inward	2.9 3.6 3.3 5 2
15	Connecting bar outward Connecting bar inward No indicator outward No indicator inward Triangle indicator inward	2 1.9 2.7 3.4 4.5	23	Connecting bar outward Connecting bar inward No indicator outward No indicator inward Triangle indicator inward	1.2 0.9 2.3 0.7 1.4
16	Connecting bar outward Connecting bar inward No indicator outward No indicator inward Triangle indicator inward	0.8 0.8 1.7 0.7 0.6	24	Connecting bar outward Connecting bar inward No indicator outward No indicator inward Triangle indicator inward	0.8 0.9 1.3 1.9 0.8
17	Connecting bar outward Connecting bar inward No indicator outward No indicator inward Triangle indicator inward	0.8 0.8 1.1 1.2 0.6	25	Connecting bar outward Connecting bar inward No indicator outward No indicator inward Triangle indicator inward	2 0.8 0.8 1.6 2.5
18	Connecting bar outward Connecting bar inward No indicator outward No indicator inward Triangle indicator inward	1.1 1.6 3.1 0.9 0.9			

B3. Experiment 2: Polygon Object

Part.	Task	No of px.			
1	Shaded Inward Shaded Outward Unshaded Inward Unshaded Outward	1 8.18 4.3 7.1	6	Shaded Inward Shaded Outward Unshaded Inward Unshaded Outward	15.2 2.68 1.4 2.4
2	Shaded Inward Shaded Outward Unshaded Inward Unshaded Outward	9.7 10.38 6.9 4	7	Shaded Inward Shaded Outward Unshaded Inward Unshaded Outward	13 4.58 2.3 2.4
3	Shaded Inward Shaded Outward Unshaded Inward Unshaded Outward	0.8 5.08 10.2 5.4	8	Shaded Inward Shaded Outward Unshaded Inward Unshaded Outward	4.7 16.37 13 14.9
4	Shaded Inward Shaded Outward Unshaded Inward Unshaded Outward	3.3 3.38 2.1 4.4	9	Shaded Inward Shaded Outward Unshaded Inward Unshaded Outward	13 8.58 3 5.8
5	Shaded Inward Shaded Outward Unshaded Inward Unshaded Outward	17 8.18 12.4 5.5	10	Shaded Inward Shaded Outward Unshaded Inward Unshaded Outward	13 9.18 8.1 7.9

11	Shaded Inward Shaded Outward Unshaded Inward Unshaded Outward	4.5 2.83 2 1.9	19	Shaded Inward Shaded Outward Unshaded Inward Unshaded Outward	1.4 2.93 4.6 9.8
12	Shaded Inward Shaded Outward Unshaded Inward Unshaded Outward	2.2 3.33 3 4.3	20	Shaded Inward Shaded Outward Unshaded Inward Unshaded Outward	6.6 2.83 5.6 3.2
13	Shaded Inward Shaded Outward Unshaded Inward Unshaded Outward	0.9 3.33 0.4 1.8	21	Shaded Inward Shaded Outward Unshaded Inward Unshaded Outward	15.2 7.23 0.2 7.5
14	Shaded Inward Shaded Outward Unshaded Inward Unshaded Outward	1 6.08 0.2 1.4	22	Shaded Inward Shaded Outward Unshaded Inward Unshaded Outward	12.8 3.43 6.3 2.6
15	Shaded Inward Shaded Outward Unshaded Inward Unshaded Outward	17 4.83 3.8 4.2	23	Shaded Inward Shaded Outward Unshaded Inward Unshaded Outward	0.2 2.13 1.7 3.1
16	Shaded Inward Shaded Outward Unshaded Inward Unshaded Outward	4.6 2.63 0.5 1.5	24	Shaded Inward Shaded Outward Unshaded Inward Unshaded Outward	0.3 3.33 0.4 2.4
17	Shaded Inward Shaded Outward Unshaded Inward Unshaded Outward	0.5 3.83 0 1.6	25	Shaded Inward Shaded Outward Unshaded Inward Unshaded Outward	17 2.93 1.7 6.5
18	Shaded Inward Shaded Outward Unshaded Inward Unshaded Outward	15.9 2.13 4 4.4			

B4. Experiment 2: Flow Comparison

Participant	Task	Deviation
1	Circle indicator – same size circle target 1	2
	Circle indicator – same size circle target 2	2
	Circle indicator – same size circle target 3	2
	Circle indicator – larger circle target 1	0
	Circle indicator – larger circle target 2	0
	Circle indicator – larger circle target 3	0
	Diamond indicator – line target 1	5
	Diamond indicator – line target 2	5
	Diamond indicator – line target 3	3
	Line indicator – line target 1	14
	Line indicator – line target 2	1
	Line indicator – line target 3	0
	Square indicator – square target 1	0
	Square indicator – square target 2	0
	Square indicator – square target 3	1
	Triangle indicator – square target 1	1
	Triangle indicator – square target 2	1
	Triangle indicator – square target 3	0
2	Circle indicator – same size circle target 1	3
	Circle indicator – same size circle target 2	1

	Circle indicator – same size circle target 3	1
	Circle indicator – larger circle target 1	0
	Circle indicator – larger circle target 2	0
	Circle indicator – larger circle target 3	0
	Diamond indicator – line target 1	1
	Diamond indicator – line target 2	0
	Diamond indicator – line target 3	0
	Line indicator – line target 1	1
	Line indicator – line target 2	0
	Line indicator – line target 3	0
	Square indicator – square target 1	1
	Square indicator – square target 2	0
	Square indicator – square target 3	0
	Triangle indicator – square target 1	0
	Triangle indicator – square target 2	0
	Triangle indicator – square target 3	0
3	Circle indicator – same size circle target 1	1
	Circle indicator – same size circle target 2	2
	Circle indicator – same size circle target 3	2
	Circle indicator – larger circle target 1	0
	Circle indicator – larger circle target 2	1
	Circle indicator – larger circle target 3	0
	Diamond indicator – line target 1	0
	Diamond indicator – line target 2	1
	Diamond indicator – line target 3	0
	Line indicator – line target 1	0
	Line indicator – line target 2	1
	Line indicator – line target 3	1
	Square indicator – square target 1	1
	Square indicator – square target 2	0
	Square indicator – square target 3	0
	Triangle indicator – square target 1	1
	Triangle indicator – square target 2	0
	Triangle indicator – square target 3	1
4	Circle indicator – same size circle target 1	2
	Circle indicator – same size circle target 2	2
	Circle indicator – same size circle target 3	2
	Circle indicator – larger circle target 1	1
	Circle indicator – larger circle target 2	1
	Circle indicator – larger circle target 3	0
	Diamond indicator – line target 1	1
	Diamond indicator – line target 2	0
	Diamond indicator – line target 3	0
	Line indicator – line target 1	0
	Line indicator – line target 2	1
	Line indicator – line target 3	0
	Square indicator – square target 1	1

	Square indicator – square target 2	0
	Square indicator – square target 3	0
	Triangle indicator – square target 1	1
	Triangle indicator – square target 2	1
	Triangle indicator – square target 3	0
5	Circle indicator – same size circle target 1	2
	Circle indicator – same size circle target 2	1
	Circle indicator – same size circle target 3	2
	Circle indicator – larger circle target 1	1
	Circle indicator – larger circle target 2	0
	Circle indicator – larger circle target 3	1
	Diamond indicator – line target 1	1
	Diamond indicator – line target 2	0
	Diamond indicator – line target 3	1
	Line indicator – line target 1	1
	Line indicator – line target 2	1
	Line indicator – line target 3	1
	Square indicator – square target 1	0
	Square indicator – square target 2	1
	Square indicator – square target 3	1
	Triangle indicator – square target 1	0
	Triangle indicator – square target 2	0
	Triangle indicator – square target 3	0
6	Circle indicator – same size circle target 1	3
	Circle indicator – same size circle target 2	2
	Circle indicator – same size circle target 3	2
	Circle indicator – larger circle target 1	0
	Circle indicator – larger circle target 2	0
	Circle indicator – larger circle target 3	0
	Diamond indicator – line target 1	2
	Diamond indicator – line target 2	4
	Diamond indicator – line target 3	1
	Line indicator – line target 1	12
	Line indicator – line target 2	12
	Line indicator – line target 3	2
	Square indicator – square target 1	1
	Square indicator – square target 2	0
	Square indicator – square target 3	0
	Triangle indicator – square target 1	1
	Triangle indicator – square target 2	0
	Triangle indicator – square target 3	0
7	Circle indicator – same size circle target 1	3
	Circle indicator – same size circle target 2	1
	Circle indicator – same size circle target 3	1
	Circle indicator – larger circle target 1	0
	Circle indicator – larger circle target 2	0
	Circle indicator – larger circle target 3	1

	Diamond indicator – line target 1	1
	Diamond indicator – line target 2	0
	Diamond indicator – line target 3	0
	Line indicator – line target 1	0
	Line indicator – line target 2	0
	Line indicator – line target 3	1
	Square indicator – square target 1	1
	Square indicator – square target 2	1
	Square indicator – square target 3	0
	Triangle indicator – square target 1	1
	Triangle indicator – square target 2	0
	Triangle indicator – square target 3	1
8	Circle indicator – same size circle target 1	3
	Circle indicator – same size circle target 2	1
	Circle indicator – same size circle target 3	2
	Circle indicator – larger circle target 1	0
	Circle indicator – larger circle target 2	0
	Circle indicator – larger circle target 3	1
	Diamond indicator – line target 1	1
	Diamond indicator – line target 2	0
	Diamond indicator – line target 3	0
	Line indicator – line target 1	0
	Line indicator – line target 2	0
	Line indicator – line target 3	1
	Square indicator – square target 1	0
	Square indicator – square target 2	1
	Square indicator – square target 3	1
	Triangle indicator – square target 1	0
	Triangle indicator – square target 2	1
	Triangle indicator – square target 3	0
9	Circle indicator – same size circle target 1	3
	Circle indicator – same size circle target 2	2
	Circle indicator – same size circle target 3	2
	Circle indicator – larger circle target 1	0
	Circle indicator – larger circle target 2	0
	Circle indicator – larger circle target 3	1
	Diamond indicator – line target 1	2
	Diamond indicator – line target 2	0
	Diamond indicator – line target 3	3
	Line indicator – line target 1	1
	Line indicator – line target 2	0
	Line indicator – line target 3	1
	Square indicator – square target 1	1
	Square indicator – square target 2	1
	Square indicator – square target 3	0
	Triangle indicator – square target 1	0
	Triangle indicator – square target 2	0

	Triangle indicator – square target 3	1
10	Circle indicator – same size circle target 1	2
	Circle indicator – same size circle target 2	2
	Circle indicator – same size circle target 3	2
	Circle indicator – larger circle target 1	0
	Circle indicator – larger circle target 2	0
	Circle indicator – larger circle target 3	1
	Diamond indicator – line target 1	1
	Diamond indicator – line target 2	1
	Diamond indicator – line target 3	1
	Line indicator – line target 1	0
	Line indicator – line target 2	1
	Line indicator – line target 3	0
	Square indicator – square target 1	1
	Square indicator – square target 2	1
	Square indicator – square target 3	0
	Triangle indicator – square target 1	0
	Triangle indicator – square target 2	1
	Triangle indicator – square target 3	1
11	Circle indicator – same size circle target 1	3
	Circle indicator – same size circle target 2	2
	Circle indicator – same size circle target 3	2
	Circle indicator – larger circle target 1	0
	Circle indicator – larger circle target 2	1
	Circle indicator – larger circle target 3	1
	Diamond indicator – line target 1	0
	Diamond indicator – line target 2	1
	Diamond indicator – line target 3	1
	Line indicator – line target 1	1
	Line indicator – line target 2	1
	Line indicator – line target 3	0
	Square indicator – square target 1	1
	Square indicator – square target 2	0
	Square indicator – square target 3	0
	Triangle indicator – square target 1	0
	Triangle indicator – square target 2	0
	Triangle indicator – square target 3	1
12	Circle indicator – same size circle target 1	1
	Circle indicator – same size circle target 2	1
	Circle indicator – same size circle target 3	1
	Circle indicator – larger circle target 1	0
	Circle indicator – larger circle target 2	1
	Circle indicator – larger circle target 3	0
	Diamond indicator – line target 1	0
	Diamond indicator – line target 2	1
	Diamond indicator – line target 3	0
	Line indicator – line target 1	1

	Line indicator – line target 2	0
	Line indicator – line target 3	1
	Square indicator – square target 1	1
	Square indicator – square target 2	2
	Square indicator – square target 3	1
	Triangle indicator – square target 1	0
	Triangle indicator – square target 2	1
	Triangle indicator – square target 3	0
13	Circle indicator – same size circle target 1	3
	Circle indicator – same size circle target 2	2
	Circle indicator – same size circle target 3	2
	Circle indicator – larger circle target 1	1
	Circle indicator – larger circle target 2	0
	Circle indicator – larger circle target 3	0
	Diamond indicator – line target 1	0
	Diamond indicator – line target 2	0
	Diamond indicator – line target 3	1
	Line indicator – line target 1	1
	Line indicator – line target 2	0
	Line indicator – line target 3	1
	Square indicator – square target 1	0
	Square indicator – square target 2	1
	Square indicator – square target 3	0
	Triangle indicator – square target 1	0
	Triangle indicator – square target 2	1
	Triangle indicator – square target 3	0
14	Circle indicator – same size circle target 1	3
	Circle indicator – same size circle target 2	2
	Circle indicator – same size circle target 3	1
	Circle indicator – larger circle target 1	0
	Circle indicator – larger circle target 2	1
	Circle indicator – larger circle target 3	0
	Diamond indicator – line target 1	1
	Diamond indicator – line target 2	0
	Diamond indicator – line target 3	0
	Line indicator – line target 1	0
	Line indicator – line target 2	1
	Line indicator – line target 3	1
	Square indicator – square target 1	0
	Square indicator – square target 2	1
	Square indicator – square target 3	1
	Triangle indicator – square target 1	0
	Triangle indicator – square target 2	1
	Triangle indicator – square target 3	0
15	Circle indicator – same size circle target 1	2
	Circle indicator – same size circle target 2	1
	Circle indicator – same size circle target 3	2

	Circle indicator – larger circle target 1	1
	Circle indicator – larger circle target 2	1
	Circle indicator – larger circle target 3	1
	Diamond indicator – line target 1	0
	Diamond indicator – line target 2	0
	Diamond indicator – line target 3	0
	Line indicator – line target 1	0
	Line indicator – line target 2	0
	Line indicator – line target 3	1
	Square indicator – square target 1	1
	Square indicator – square target 2	1
	Square indicator – square target 3	1
	Triangle indicator – square target 1	1
	Triangle indicator – square target 2	0
	Triangle indicator – square target 3	0

B5. Experiment 3: Rate Indicator

Part.	Task	Deviation
1	circle dots 1	1.2
1	circle dots 2	27.2
1	Circle shading 1	15.7
1	Circle shading 2	21.7
1	connect dots 1	0.9
1	connect dots 2	1.9
1	connect triangles 1	2.1
1	connect triangles 2	1.9
1	current 1	2
1	current 2	3
1	dots 1	4
1	dots 2	11
1	dots shading 1	6
1	dots shading 2	6
1	triangles 1	5.2
1	triangles 2	3.8
2	circle dots 1	1.2
2	circle dots 2	2.2
2	Circle shading 1	0.7
2	Circle shading 2	0.7
2	connect dots 1	0.9
2	connect dots 2	0.9
2	connect triangles 1	0.1
2	connect triangles 2	0.9
2	current 1	1
2	current 2	2
2	dots 1	2

2	dots 2	8
2	dots shading 1	5
2	dots shading 2	5
2	triangles 1	0.8
2	triangles 2	2.8
3	circle dots 1	1.2
3	circle dots 2	1.2
3	Circle shading 1	0.7
3	Circle shading 2	24.7
3	connect dots 1	0.9
3	connect dots 2	0.9
3	connect triangles 1	0.9
3	connect triangles 2	0.9
3	current 1	2
3	current 2	3
3	dots 1	1
3	dots 2	2
3	dots shading 1	4
3	dots shading 2	4
3	triangles 1	1.8
3	triangles 2	1.8
4	circle dots 1	1.2
4	circle dots 2	10.2
4	Circle shading 1	1.7
4	Circle shading 2	6.7
4	connect dots 1	0.9
4	connect dots 2	0.9
4	connect triangles 1	0.9
4	connect triangles 2	0.9

	current 1	2
4	current 2	3
4	dots 1	2
4	dots 2	3
4	dots shading 1	3
4	dots shading 2	3
4	triangles 1	0.8
4	triangles 2	0.8
5	circle dots 1	1.2
5	circle dots 2	5.2
5	Circle shading 1	0.7
5	Circle shading 2	15.7
5	connect dots 1	0.9
5	connect dots 2	0.9
5	connect triangles 1	0.9
5	connect triangles 2	0.9
5	current 1	0
5	current 2	1
5	dots 1	0
5	dots 2	15
5	dots shading 1	2
5	dots shading 2	2
5	triangles 1	1.8
5	triangles 2	1.8
6	circle dots 1	1.2
6	circle dots 2	3.2
6	Circle shading 1	5.7
6	Circle shading 2	17.7
6	connect dots 1	0.9
6	connect dots 2	0.9
6	connect triangles 1	0.1
6	connect triangles 2	0.1
6	current 1	1
6	current 2	1
6	dots 1	0
6	dots 2	8
6	dots shading 1	1
6	dots shading 2	1
6	triangles 1	0.8
6	triangles 2	1.8
7	circle dots 1	1.2
7	circle dots 2	1.2
7	Circle shading 1	0.7
7	Circle shading 2	5.7
7	connect dots 1	0.9
7	connect dots 2	0.9
7	connect triangles 1	0.9

7	connect triangles 2	1.9
7	current 1	0
7	current 2	1
7	dots 1	1
7	dots 2	3
7	dots shading 1	0
7	dots shading 2	0
7	triangles 1	0.8
7	triangles 2	1.8
8	circle dots 1	0.2
8	circle dots 2	0.2
8	Circle shading 1	0.7
8	Circle shading 2	1.7
8	connect dots 1	0.9
8	connect dots 2	1.9
8	connect triangles 1	0.9
8	connect triangles 2	0.9
8	current 1	3
8	current 2	2
8	dots 1	2
8	dots 2	4
8	dots shading 1	1
8	dots shading 2	1
8	triangles 1	1.8
8	triangles 2	1.8
9	circle dots 1	1.2
9	circle dots 2	1.2
9	Circle shading 1	0.7
9	Circle shading 2	1.7
9	connect dots 1	0.9
9	connect dots 2	0.9
9	connect triangles 1	6.1
9	connect triangles 2	6.1
9	current 1	6
9	current 2	2
9	dots 1	1
9	dots 2	1
9	dots shading 1	2
9	dots shading 2	2
9	triangles 1	0.8
9	triangles 2	2.8
10	circle dots 1	1.2
10	circle dots 2	2.2
10	Circle shading 1	0.7
10	Circle shading 2	0.7
10	connect dots 1	1.9
10	connect dots 2	1.9

10	connect triangles 1	7.1
10	connect triangles 2	6.1
10	current 1	1
10	current 2	2
10	dots 1	1
10	dots 2	8
10	dots shading 1	3
10	dots shading 2	3
10	triangles 1	1.8
10	triangles 2	1.8
11	circle dots 1	1.2
11	circle dots 2	1.2
11	Circle shading 1	1.7
11	Circle shading 2	11.7
11	connect dots 1	0.9
11	connect dots 2	0.9
11	connect triangles 1	0.9
11	connect triangles 2	0.9
11	current 1	6
11	current 2	1
11	dots 1	1
11	dots 2	3
11	dots shading 1	4
11	dots shading 2	4
11	triangles 1	0.8
11	triangles 2	1.8
12	circle dots 1	1.2
12	circle dots 2	2.2
12	Circle shading 1	0.7
12	Circle shading 2	1.7
12	connect dots 1	0.9
12	connect dots 2	1.9
12	connect triangles 1	0.9
12	connect triangles 2	0.9
12	current 1	1
12	current 2	2
12	dots 1	4
12	dots 2	4
12	dots shading 1	5
12	dots shading 2	5
12	triangles 1	8.2
12	triangles 2	1.8
13	circle dots 1	1.2
13	circle dots 2	1.2
13	Circle shading 1	1.7
13	Circle shading 2	2.7

13	connect dots 1	0.9
13	connect dots 2	0.9
13	connect triangles 1	0.9
13	connect triangles 2	0.9
13	current 1	1
13	current 2	1
13	dots 1	1
13	dots 2	9
13	dots shading 1	6
13	dots shading 2	6
13	triangles 1	1.8
13	triangles 2	2.8
14	circle dots 1	1.2
14	circle dots 2	1.2
14	Circle shading 1	0.7
14	Circle shading 2	1.7
14	connect dots 1	0.9
14	connect dots 2	0.9
14	connect triangles 1	0.9
14	connect triangles 2	0.9
14	current 1	2
14	current 2	11
14	dots 1	1
14	dots 2	1
14	dots shading 1	7
14	dots shading 2	7
14	triangles 1	13.2
14	triangles 2	11.2
15	circle dots 1	1.2
15	circle dots 2	8.2
15	Circle shading 1	19.7
15	Circle shading 2	25.7
15	connect dots 1	0.9
15	connect dots 2	0.9
15	connect triangles 1	0.9
15	connect triangles 2	1.9
15	current 1	1
15	current 2	2
15	dots 1	7
15	dots 2	12
15	dots shading 1	8
15	dots shading 2	8
15	triangles 1	4.2
15	triangles 2	1.8

B6. Experiment 4: Levels Stacked

Part	Task	Dev
1	Angled line 1	5
1	Angled line 2	2
1	Angled line filled 1	2
1	Angled line filled 2	2
1	Current 1	0
1	Current 2	0
1	Line with Horizontal angled 1	0
1	Line with Horizontal angled 2	1
1	Line with Horizontal angled filled 1	0
1	Line with Horizontal angled filled 2	0
1	Line with horizontal straight 1	5
1	Line with horizontal straight 2	9
1	Line with horizontal straight filled 1	1
1	Line with horizontal straight filled 2	2
1	Triangle 1	0
1	Triangle 2	0
1	Triangle with line 1	1
1	Triangle with line 2	1
1	Triangle with line no fill 1	7
1	Triangle with line no fill 2	5
1	Unstacked 1	3
1	Unstacked 2	2
2	Angled line 1	2
2	Angled line 2	1
2	Angled line filled 1	2
2	Angled line filled 2	0
2	Current 1	0
2	Current 2	1
2	Line with Horizontal angled 1	1
2	Line with Horizontal angled 2	2
2	Line with Horizontal angled filled 1	1
2	Line with Horizontal angled filled 2	4
2	Line with horizontal straight 1	1
2	Line with horizontal straight 2	0
2	Line with horizontal straight filled 1	1
2	Line with horizontal straight filled 2	4
2	Triangle 1	0
2	Triangle 2	2
2	Triangle with line 1	0
2	Triangle with line 2	0
2	Triangle with line no fill 1	5
2	Triangle with line no fill 2	1
2	Unstacked 1	2

2	Unstacked 2	5
3	Angled line 1	4
3	Angled line 2	4
3	Angled line filled 1	2
3	Angled line filled 2	2
3	Current 1	2
3	Current 2	2
3	Line with Horizontal angled 1	3
3	Line with Horizontal angled 2	2
3	Line with Horizontal angled filled 1	1
3	Line with Horizontal angled filled 2	2
3	Line with horizontal straight 1	0
3	Line with horizontal straight 2	0
3	Line with horizontal straight filled 1	1
3	Line with horizontal straight filled 2	1
3	Triangle 1	3
3	Triangle 2	2
3	Triangle with line 1	5
3	Triangle with line 2	2
3	Triangle with line no fill 1	6
3	Triangle with line no fill 2	4
3	Unstacked 1	3
3	Unstacked 2	7
4	Angled line 1	3
4	Angled line 2	1
4	Angled line filled 1	3
4	Angled line filled 2	2
4	Current 1	1
4	Current 2	0
4	Line with Horizontal angled 1	3
4	Line with Horizontal angled 2	2
4	Line with Horizontal angled filled 1	2
4	Line with Horizontal angled filled 2	3
4	Line with horizontal straight 1	0
4	Line with horizontal straight 2	5
4	Line with horizontal straight filled 1	6
4	Line with horizontal straight filled 2	5
4	Triangle 1	6
4	Triangle 2	3
4	Triangle with line 1	5
4	Triangle with line 2	4
4	Triangle with line no fill 1	9
4	Triangle with line no fill 2	8
4	Unstacked 1	4

4	Unstacked 2	4
5	Angled line 1	4
5	Angled line 2	2
5	Angled line filled 1	4
5	Angled line filled 2	1
5	Current 1	1
5	Current 2	1
5	Line with Horizontal angled 1	4
5	Line with Horizontal angled 2	3
5	Line with Horizontal angled filled 1	1
5	Line with Horizontal angled filled 2	1
5	Line with horizontal straight 1	0
5	Line with horizontal straight 2	0
5	Line with horizontal straight filled 1	6
5	Line with horizontal straight filled 2	5
5	Triangle 1	3
5	Triangle 2	3
5	Triangle with line 1	6
5	Triangle with line 2	3
5	Triangle with line no fill 1	9
5	Triangle with line no fill 2	6
5	Unstacked 1	4
5	Unstacked 2	3
6	Angled line 1	3
6	Angled line 2	3
6	Angled line filled 1	5
6	Angled line filled 2	2
6	Current 1	1
6	Current 2	0
6	Line with Horizontal angled 1	5
6	Line with Horizontal angled 2	3
6	Line with Horizontal angled filled 1	0
6	Line with Horizontal angled filled 2	3
6	Line with horizontal straight 1	8
6	Line with horizontal straight 2	5
6	Line with horizontal straight filled 1	6
6	Line with horizontal straight filled 2	1
6	Triangle 1	6
6	Triangle 2	2
6	Triangle with line 1	4
6	Triangle with line 2	2
6	Triangle with line no fill 1	6
6	Triangle with line no fill 2	4
6	Unstacked 1	5
6	Unstacked 2	4
7	Angled line 1	3
7	Angled line 2	1

7	Angled line filled 1	3
7	Angled line filled 2	2
7	Current 1	2
7	Current 2	0
7	Line with Horizontal angled 1	3
7	Line with Horizontal angled 2	1
7	Line with Horizontal angled filled 1	4
7	Line with Horizontal angled filled 2	4
7	Line with horizontal straight 1	1
7	Line with horizontal straight 2	0
7	Line with horizontal straight filled 1	5
7	Line with horizontal straight filled 2	1
7	Triangle 1	4
7	Triangle 2	0
7	Triangle with line 1	6
7	Triangle with line 2	3
7	Triangle with line no fill 1	10
7	Triangle with line no fill 2	10
7	Unstacked 1	6
7	Unstacked 2	5
8	Angled line 1	1
8	Angled line 2	4
8	Angled line filled 1	2
8	Angled line filled 2	1
8	Current 1	8
8	Current 2	8
8	Line with Horizontal angled 1	5
8	Line with Horizontal angled 2	4
8	Line with Horizontal angled filled 1	1
8	Line with Horizontal angled filled 2	3
8	Line with horizontal straight 1	1
8	Line with horizontal straight 2	3
8	Line with horizontal straight filled 1	1
8	Line with horizontal straight filled 2	1
8	Triangle 1	5
8	Triangle 2	5
8	Triangle with line 1	2
8	Triangle with line 2	3
8	Triangle with line no fill 1	2
8	Triangle with line no fill 2	1
8	Unstacked 1	4
8	Unstacked 2	0
9	Angled line 1	6
9	Angled line 2	5
9	Angled line filled 1	3
9	Angled line filled 2	1
9	Current 1	1

9	Current 2	1
9	Line with Horizontal angled 1	0
9	Line with Horizontal angled 2	1
9	Line with Horizontal angled filled 1	1
9	Line with Horizontal angled filled 2	1
9	Line with horizontal straight 1	1
9	Line with horizontal straight 2	1
9	Line with horizontal straight filled 1	4
9	Line with horizontal straight filled 2	2
9	Triangle 1	5
9	Triangle 2	3
9	Triangle with line 1	5
9	Triangle with line 2	3
9	Triangle with line no fill 1	9
9	Triangle with line no fill 2	9
9	Unstacked 1	7
9	Unstacked 2	5
10	Angled line 1	5
10	Angled line 2	5
10	Angled line filled 1	3
10	Angled line filled 2	2
10	Current 1	1
10	Current 2	0
10	Line with Horizontal angled 1	4
10	Line with Horizontal angled 2	3
10	Line with Horizontal angled filled 1	4
10	Line with Horizontal angled filled 2	1
10	Line with horizontal straight 1	0
10	Line with horizontal straight 2	1
10	Line with horizontal straight filled 1	6
10	Line with horizontal straight filled 2	3
10	Triangle 1	1
10	Triangle 2	1
10	Triangle with line 1	2
10	Triangle with line 2	1
10	Triangle with line no fill 1	9
10	Triangle with line no fill 2	5
10	Unstacked 1	5
10	Unstacked 2	4
11	Angled line 1	3
11	Angled line 2	3
11	Angled line filled 1	0
11	Angled line filled 2	4
11	Current 1	4
11	Current 2	2
11	Line with Horizontal angled 1	3
11	Line with Horizontal angled 2	1

11	Line with Horizontal angled filled 1	4
11	Line with Horizontal angled filled 2	4
11	Line with horizontal straight 1	5
11	Line with horizontal straight 2	0
11	Line with horizontal straight filled 1	4
11	Line with horizontal straight filled 2	2
11	Triangle 1	3
11	Triangle 2	2
11	Triangle with line 1	5
11	Triangle with line 2	4
11	Triangle with line no fill 1	3
11	Triangle with line no fill 2	4
11	Unstacked 1	3
11	Unstacked 2	2
12	Angled line 1	4
12	Angled line 2	4
12	Angled line filled 1	2
12	Angled line filled 2	0
12	Current 1	2
12	Current 2	1
12	Line with Horizontal angled 1	4
12	Line with Horizontal angled 2	1
12	Line with Horizontal angled filled 1	4
12	Line with Horizontal angled filled 2	4
12	Line with horizontal straight 1	0
12	Line with horizontal straight 2	4
12	Line with horizontal straight filled 1	0
12	Line with horizontal straight filled 2	0
12	Triangle 1	3
12	Triangle 2	0
12	Triangle with line 1	5
12	Triangle with line 2	4
12	Triangle with line no fill 1	9
12	Triangle with line no fill 2	9
12	Unstacked 1	5
12	Unstacked 2	5
13	Angled line 1	5
13	Angled line 2	6
13	Angled line filled 1	3
13	Angled line filled 2	0
13	Current 1	0
13	Current 2	0
13	Line with Horizontal angled 1	0
13	Line with Horizontal angled 2	1
13	Line with Horizontal angled filled 1	4
13	Line with Horizontal angled filled 2	0
13	Line with horizontal straight 1	1

13	Line with horizontal straight 2	9
13	Line with horizontal straight filled 1	1
13	Line with horizontal straight filled 2	1
13	Triangle 1	0
13	Triangle 2	1
13	Triangle with line 1	0
13	Triangle with line 2	2
13	Triangle with line no fill 1	8
13	Triangle with line no fill 2	8
13	Unstacked 1	6
13	Unstacked 2	3
14	Angled line 1	4
14	Angled line 2	3
14	Angled line filled 1	3
14	Angled line filled 2	0
14	Current 1	0
14	Current 2	1
14	Line with Horizontal angled 1	5
14	Line with Horizontal angled 2	2
14	Line with Horizontal angled filled 1	1
14	Line with Horizontal angled filled 2	0
14	Line with horizontal straight 1	0
14	Line with horizontal straight 2	1
14	Line with horizontal straight filled 1	0
14	Line with horizontal straight filled 2	1
14	Triangle 1	4
14	Triangle 2	3
14	Triangle with line 1	2

14	Triangle with line 2	1
14	Triangle with line no fill 1	10
14	Triangle with line no fill 2	5
14	Unstacked 1	7
14	Unstacked 2	7
15	Angled line 1	5
15	Angled line 2	4
15	Angled line filled 1	3
15	Angled line filled 2	2
15	Current 1	0
15	Current 2	0
15	Line with Horizontal angled 1	1
15	Line with Horizontal angled 2	1
15	Line with Horizontal angled filled 1	0
15	Line with Horizontal angled filled 2	6
15	Line with horizontal straight 1	4
15	Line with horizontal straight 2	0
15	Line with horizontal straight filled 1	0
15	Line with horizontal straight filled 2	1
15	Triangle 1	2
15	Triangle 2	2
15	Triangle with line 1	1
15	Triangle with line 2	3
15	Triangle with line no fill 1	8
15	Triangle with line no fill 2	8
15	Unstacked 1	5
15	Unstacked 2	4