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SUMMARY

Recent developments in computer engineering have greatly enhanced the capabilities of display technology. As displays are no longer limited to simple alphanumeric output, they can present a wide variety of graphic information, using either static or dynamic presentation modes. At the same time that interface designers exploit the increased capabilities of these displays, they must be aware of the inherent limitation of these displays. Generally, these limitations can be divided into those that reflect limitations of the medium (e.g., reducing three-dimensional representations onto a two-dimensional projection) and those reflecting the perceptual and conceptual biases of the operator.

This paper considers the advantages and limitations of static and dynamic graphic displays. Rather than enter into the discussion of whether dynamic or static displays are superior, we explore general advantages and limitations which are contextually specific to each type of display.

INTRODUCTION

Displays are a mediated presentation of information about the state of a system. Unlike direct observation of a system, displays afford only a selected subset of information, formatted (one hopes) in a manner which optimizes processing of critical information. In the past two decades, computer displays have advanced from highly constrained, alphanumeric devices to trichromatic, graphic, and often dynamic media. As the capabilities of graphic displays improve, the advantages and disadvantages of such presenation modes must be discussed.

Often, such discussion becomes a debate about whether dynamic displays are superior to static ones. The outcome of such a debate is likely to differ from case to case, depending on the nature of the information to be represented, and the cost of providing a dynamic presentation. But beyond such considerations, there are the biases that result when information is presented in either representational context. This paper addresses those issues, summarizing well-established and current research on perceptual and conceptual biases of the human operator as well as limitations inherent in display media. Special emphasis will be placed on understanding

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how perceptual organization influences the processing of graphic information and how conceptual biases may alter the interpretation of the information presented.

THE NATURE OF DISPLAYS

A display is a mediated presentation of information about a system. The person who designs a display determines which parameters of the system should be presented to the operator, and how that information should be formatted to optimize information transfer. It is important to understand how displays differ from the direct observation of the system, and what advantages and disadvantages derive from these differences.

The human perceptual system has evolved to process ongoing events in the physical world. Gibson (1979) has described this natural perception process as "direct perception," and argues that our perceptual mechanisms are designed for this task. The processing of information presented by displays is indirect, or "mediated" perception; displays present a reduced subset of information, or an "impoverished" visual environment. On the other hand, displays can provide a window into systems that are not directly viewable, either because of safety or logistical constraints, or because the system parameters of interest are not visible to the human observer (e.g., level of gamma radiation). In computer systems, virtually none of the system parameters of interest are directly observable; all must be communicated via a display system. Thus, whereas displays are used in many applications to augment direct perceptual experience (e.g., avionics), displays serve as the only form of information specification in computer operations. All that is known about the internal state of the computer system is that which is conveyed to the operator via display devices.

Thus, computer systems present a particular challenge to display design. The designer has complete control over (and responsibility for) information specification. The challenge is to maximize information transfer while minimizing error in interpretation. Most of the research and theory on interface design has focused on the former--how should information be selected and formatted to optimize information transfer. Less emphasis has been placed on understanding the human interpreter. In particular, there has been scant attention to classic and recent finding in experimental psychology on operators' perceptual and cognitive biases and rules of organization.

In this paper, we focus on biases that occur in two modes of representation: static and dynamic. Global tendencies of both bias and organization are representation-specific. Thus, it is not merely the case that static displays offer less information than dynamic, or that dynamic displays are more complicated than static; rather, each mode of representation evokes unique sets of biases and organizational tendencies. Although there may be commonalities in these sets, there are operator tendencies which prove to be context-specific. We consider the two modes of representation in turn.

STATIC REPRESENTATIONS

Most computer displays employ static representations, which have the advantage of computational economy over dynamic displays. Further, since the introduction of graphic enhancements to the simple alphanumerics of early displays, most designers feel they can represent a great deal of information without the computational expense of motion. What are the limitations inherent in these displays? Which are specific to static representations and which generalize to dynamic displays as well?

CHARACTERISTICS OF THE MEDIUM

The experience of viewing a Cathode Ray Tube (CRT) display is very different from viewing an actual scene. The most critical difference is that the screen is a two-dimensional (2-D) reduction of three-dimensional (3-D) space. Any 2-D pattern that is taken as a projection of a 3-D object, is indefinitely ambiguous. There are an indefinite number of 3-D distal objects that could project the 2-D pattern. Consider the 2-D projection depicted in figure 1. Such a projection could result from a rectangle, a trapezoid, or any of a large family of forms, depending on the projection angle.

Observers attempt to resolve the inherent ambiguity of 2-D displays by employing pictorial depth cues. Traditionally, these cues are defined as interposition (occlusion), linear perspective, size perspective, familiar size, and shadow distribution (Hochberg, 1978). By employing these augmenting cues, an observer should be able, in theory, to reconstruct the spatial layout of the depicted 3-D scene.

However, it is not clear how successful an operator is at this reconstruction. The operator's awareness of properties of the 2-D representation may contaminate the 3-D representation (McGreevy and Ellis, 1986; Proffitt and Kaiser, 1986a). This is the problem of dual awareness. A 2-D projective display contains depth cues for both the 2-D projection and the 3-D scene. All of the primary depth cues (e.g. eye convergence and accomodation) support the 2-D interpretation. Further, unless the display is yoked to the head movements of the observer (Rogers and Graham, 1979), the absence of motion parallax will further define the 2-D aspects of the display. Thus, even in the presence of pictorial depth cues, the operator may experience ambiguities and misinterpretations of the display.

In addition to the reconstruction of spatial layout, the interpretation of 2-D graphic representations often requires the operator to employ certain conventions (e.g., an arrow to imply a temporally subsequent event). Often, these conventions are implicit; if the designer and operator do not share a common convention base, the operator may misinterpret the representations.

Static graphic displays are also limited in resolution and detail. Whereas one can learn more about an object in the environment through closer examination, most graphic representations present a particular degree of detail. The interface may provide "zoom" or "blow-up" functions, but here too a conventional understanding that is removed from the natural perceptual experience is required. In short, a static graphic is a perceptually impoverished form of presentation which is dependent upon the application of often implicit conventions for comprehension. Unfortunately, since the necessary conventions are not usually made explicit, designers may make erroneous assumptions about how the information is interpreted. This may result in either a lack of information transfer, when the operator fails to employ the appropriate conventions, or a misinterpretation, when the designer fails to appreciate the biases inherent to the operator. These biases will be considered next.

Characteristics of the Operator

The human operator brings biases and organizational tendencies to the display interface. These can be broadly characterized as either perceptual or conceptual in nature. Perceptual tendencies influence how the operator encodes the information presented on the screen. Conceptual tendencies influence how the operator interprets that information and expands upon it by drawing upon internal models and representations.

Perceptual Organization.- Perceptual aspects can be further broken down into four categories: (1) organizational tendencies, (2) familiarity, (3) illusions, and (4) biases in processing. For each of these categories, well-established research findings in the psychological literature offer guidelines that should be considered in display design.

1. Organizational Tendencies.- Descriptive rules of how observers organize visual forms were put forth by the Gestalt psychologists in the early part of the 20th century (Koffka, 1935; Wertheimer, 1923). Figure 2 lists some of these organizational tendencies for static displays and gives examples. The Gestaltists demonstrated that observers are biased toward particular interpretations when presented with displays that could support several percepts. Recent research has focused on more formal models of these organizational biases (Julesz, 1965, 1975; Palmer, 1985), and many of the Gestaltists' ideas have been validated. In fact, Gestaltist principles are taught in many art and design courses, and may already be implicitly or explicitly followed by many display designers. Such crossover is less likely for familiarity biases, processing biases, and illusions.

2. Familiarity.- The observers' perceptions of displays are influenced by the observers' expectancies concerning shape, size, and spatial layout. This is particularly true when the display is impoverished such that the observer is forced to make assumptions in order to resolve ambiguities. Consider again the form depicted in Figure 1. As we have stated, a large family of shapes could have produced such a projection. Nonetheless, most people would immediately view the form as either a trapezoid or a rectangle. The trapezoid interpretation is justified since it is directly supported by the form on the page, but why is the rectangle such a compelling interpretation? It is because most of the four sided objects in our

environment are rectangular. Thus, an observer assumes an ambiguous, trapezoidal display depicts a rectangle.

The strength of these familiarity constraints on perceived structure is strikingly demonstrated in a series of objects constructed by Adelbert Ames (Ittelson, 1952). The Ames room is constructed such that it appears normal from one particular vantage point. In fact, the back wall of the room slants away from the observer, and the more distant side is actually much taller than the nearer sides. Since the distances and sizes exactly compensate one another, the back wall projects to the eye as rectangular instead of its true trapezoidal form. Similarly, the Ames window is trapezoidal yet appears to be a familiar, rectangular window. Both the room and window demonstrations are quite powerful. In order to preserve the rectilinearity of the objects, observers accept bizarre anomalies, e.g., water running uphill, children appearing larger than adults, and objects passing through the closed window.

3. Illusions.- From its inception, perceptual psychology has concerned itself with the study of visual illusions. Some psychologists find illusions the most interesting aspect of perception to study, since an analysis of a system's failure to process information veridically can tell much about how the system functions. Although the validity of this argument is hotly debated in perceptual psychology today, its acceptance during much of the history of the field has provided a rich catalogue of how people misperceive information presented in 2-D displays, particularly under time pressure. Figure 3 lists some well-established visual illusions that have implications for static graphic design. Discussion of these illusions and proposed underlying mechanisms can be found in most introductory texts on perception (e.g. Rock, 1975). Some of these same issues have been discussed in terms of graphic presentation of data (Cleveland, 1985). These issues are even more critical for computer graphic displays since the operator is often attempting to process information within time constraints, and the orientation of the display is fairly rigidly fixed.

4. Biases in stimuli processing.- The ability of observers to process stimuli quickly and accurately depends on basic physical characteristics such as orientation, luminance, chromaticity, and spatial frequency. These stimulus effects can be considered in terms of sensory sensitivities, or higher level cognitive processing. Most studies which focus on sensory aspects deal with the detection of stimuli at threshold level, and find that detectability is affected by spatial and temporal frequencies (Watson, 1983; Watson, Barlow and Robson, 1983), chromaticity (Judd, 1951), and orientation (Appelle, 1972). These effects become less critical when the stimuli are at a suprathreshold level. With suprathreshold stimuli, one is less concerned with the issue of simple detection than the tasks of identification and classification.

"Oblique effects" refer to the greater difficulty of processing stimuli which are obliquely aligned, as compared to horizontal or vertical stimuli. As mentioned, this effect is found on the level of sensory reception, but it is also found when higher level cognitive processing is involved. Further, these higher-order oblique effects depend on the phenomenal orientation rather than retinal orientation (Lasaga and Garner, 1983). Just as observers demonstrate an orientation bias, there is evidence that stimuli with abrupt onsets are processed more quickly and accurately. This may be due to the attraction that such stimuli present to attentional mechanisms (Yantis and Jonides, 1984).

Conceptual Influences.- The biases we have discussed thus far deal with perceptual tendencies of the operator. Even the higher order oblique effects deal with the observer's ability to encode and classify forms at a basic level of category assignment. We now consider how the operator's conceptual knowledge base can distort the information provided in static displays.

By employing static representations, designers often appeal to operators' conceptual models of systems. Hence, the operator is asked to use parameters specified by the display in conjunction with his or her conceptual framework so as to draw conclusion about the state of the system. For example, if an avionic display specifies an intercept target to have a slant range of 1000 m and a range rate of -10 m/sec, the operator might deduce that intercept will occur in 100 sec. However, the operator has made certain assumptions about the dynamics of the system which may not be valid. For instance, the operator has assumed that the two objects are on intercept trajectories and that the range rate remains constant. If either of these assumptions is violated, the conclusion the operator has drawn is erroneous.

The example just given demonstrates how the operator will impose simplifying assumptions about the workings of a system in the absence of contrary information. Of greater concern are recent findings which suggest that people's intuitive models of physical systems are not merely simplistic; they are often quite erroneous. These fallacious mental models lead not just to invalid extensions beyond the information specified, but to misinterpretations of the information.

Recent research has demonstrated that people hold striking misconceptions about simple physical concepts, even after formal instruction. Consider the problems presented in figure 4. When asked to predict the trajectory of a ball rolled through a curved tube, many people predict a curvilinear trajectory (fig. 4(a)). Likewise, many people incorrectly predict the trajectory of an object released from a moving body (fig. 4(b)), contending that the object will fall straight down from the point of release. These findings (McCloskey, 1983) suggest that many people misunderstand basic concepts of linear momentum.

Even more prevalent are misconceptions concerning angular momentum (Proffitt & Kaiser, 1986b). When asked to predict which of two wheels will roll down an incline plane more quickly, people erroneously report that radius and mass will effect the outcome (they do not). Moreover, people think the distribution of mass on the wheel (i.e., a solid disk vs. a rim) is irrelevant when, in fact, a disk rolls faster than a rim. In general, the basic properties of angular momentum are unintuitive; the motions of gyroscopes appear quite magical.

Another domain in which people demonstrate misconceptions is volume displacement (Whelan, 1987). Many have a fundamental misunderstanding of Archimedes' principle. A famous anedote relates that Robert Oppenheimer (the leader of the

Manhattan project) and two other eminent physicists were asked a seemingly simple displacement problem: Consider a boat with a weight on it floating in a tank of water. If the weight is taken off the boat and placed in the water, will the water level rise, stay the same, or be lowered? All three physicists answered incorrectly. The correct answer is that the water level will go down: when the weight is in the boat, it is displacing a volume of water equal to its mass but in the water, it displaces only its own volume.

People also reason erroneously and draw inappropriate analogies when presented with problems of fluid and electrical flow (Gentner and Gentner, 1983). In particular, people seem confused as to which dynamic properties are common and unique to the two domains. This is exacerbated by the tendency of many curricula to encourage analogical reasoning.

Since static displays are often employed to depict dynamic systems, designers depend upon the operator to augment the representation with his or her internal model. What this research suggests is that such augmentation leads to erroneous conclusions about the state of the system.

DYNAMIC DISPLAYS

With advances in computer architecture, hardware, and software, it has become possible to utilize real-time, dynamic graphic displays. The possibility of animation in displays leads to the question of what advantages and disadvantages result from adding motion. As we have stated, the costs and benefits of utilizing dynamic displays need to be assessed for each specific application. However, there are intrinsic properties of dynamic and static displays which should be considered.

The characterization of motion by perceptual psychologists has changed in the past two decades. Traditionally, motion was considered a complication, requiring that the observer somehow temporally integrate static sequences to derive motion information (Hochberg, 1978). More recently, motion has been proposed to be a basic perceptual attribute of the environment, just as primary as form and color (Gibson, 1979; Johansson, 1975). Such a theoretical shift has important implications for the kind of information that motion is thought to convey and the ease with which observers would be expected to process such information.

A major emphasis is now placed on the role motion plays in resolving the spatial ambiguities which exist in 2-D projections. Computational research has shown that it is theoretically possible to fully recover the 3-D structure from the motion information (Ullman, 1979). Current psychophysical research is examining the adequacy of these computational models as models of human performance (Proffitt and Bertenthal, 1985). While the competencies and limitations of human observers and computational models do not exactly coincide, it is clear that the presence of motion plays a major role in ambiguity resolution for both systems. Further, motion can be used in overcome the operator's organizational tendencies and illusions that were experienced in static displays. Virtually all of the static Gestaltist laws of organization are overruled by the dynamic law of common fate; that is, forms with common movement are grouped together. Then too, figure-ground ambiguities are firmly resolved by the occlusion specified by the motion information. Finally, most of the illusions demonstrated in Figure 3 can be overcome by orientation transitions, particularly alignment.

Thus, it can be seen that motion can contribute a good deal of information to a display, particularly information needed to reduce spatial ambiguities. We now consider issues that may limit the information value of motion displays, particularly when they are presented on a 2-D display.

Characteristics of the Medium

Although observers benefit from the specification of dynamics in motion displays, there are limitations inherent in presenting motion on CRT displays. As mentioned in the section of static displays, the CRT is a 2-D display medium on which 3-D spatial relations must be represented. This leads to a dual awareness of image presented on the picture plane and the three dimensional spatial relations that are projected on the plane (Proffitt and Kaiser, 1986a). In addition, motion-related depth cues, such as occlusion and appropriate size transformations, are often absent in displays. This leads to motion-display ambiguities. Consider the motion display depicted in Figure 5. Since the display lacks occlusion, binocular cues, appropriate size transformation, and other spatial information available in natural events, the motion of the objects is ambiguous. Thus the display is multistable; at least three interpretations of the motion are supported.

There are other problems with 2-D animated displays. Absolute depth and size are indeterminate, which creates a set of difficult problems in programming a natural-appearing simulation. Further, the size of the visual field is constrained by existing screen technology. Finally, the problem of drawing objects realistically (using, for example, texture and shadowing), which was considered for static displays, is exacerbated for dynamic displays because of the need for frequent redrawing (30-60 Hz). Such problems present important limitations for the quality of information which can be presented in a dynamic display (Proffitt and Kaiser, 1986a).

Of course, dynamic displays do not use true motion, but rather exploit the fact that rapidly updated static images are perceived as moving. As the update rate decreases (as it must as display complexity is increased), the dynamic display becomes distinguishable from true motion. Even so, the observer may experience the sensation of apparent motion, in which the perceptual system interpolates the motion between successive positions. The biases introduced by the perceptual system will be considered in the next section.

Thus, it must be recognized that dynamic displays are reduced and impoverished relative to actual dynamic events in the environment. Binocular information is not included, occlusion and other important depth cues are often absent, and object orientation information (e.g., texture and shading) is usually highly degraded. In some cases, the quality of the motion information is compromised. These factors can result in the introduction of motion ambiguities since the pure kinematics support multiple interpretations. Although the organizational biases of the observers limit the possible interpretations entertained, the displays are still usually multistable. Further, display designers, who are often unaware of the biases and constraints that observers impose on the displays and fail to consider which interpretations other than the intended one that observers may perceive. It is to these inherent biases of the observer that we now turn.

Characteristics of the Operator

As with static displays, the designers of dynamic displays must consider the perceptual tendencies and conceptual biases of the operator. Whereas the inclusion of motion resolves many of the ambiguities of static displays, it introduces a new set of organizational tendencies which influences how an observer interprets kinematic information. These tendencies must be understood and considered. In addition, dynamic displays may allow the operator to gain a more perceputally-based understanding of physical systems and engage in problem solving based upon these perceptual appreciations. These issues are considered in detail in the following sections.

Perceptual Organization.- When a reduced dynamic display is presented to an observer, there are often ambiguities which must be resolved. As with static displays, the observer has biases and organizational tendencies. These influence motion perception such that the class of viable interpretations is vastly constrained. This process is discussed in terms of the ways that motion constrains object configuration, and the complement: the ways configuration affects perceived motion.

Motion constrains perceived configuration.- One of the most striking examples of the role motion plays in defining form perception is the Kinetic Depth Effect (KDE). In the original demonstration, a shadow is cast by a wire shape onto a screen. When the shape is stationary, it is impossible to determine its actual 3-D form; an infinite number of forms could have cast the shadow. When the shape rotates, an observer can readily perceive its form from the dynamic shadow pattern (Wallach and O'Connell, 1953). Such a unique interpretation is possible only if the observer assumes the object is rigid. If the possibility of deformation concurrent with rotation is allowed, the form is still indeterminant. The perceptual system appears quite willing to make such an assumption.

Since CRT displays offer the same kinematic information as the shadow projections of Wallach and O'Connell, it should be noted that the rigidity assumption employed by the perceptual system constrains the processing of dynamic information. Thus, if a form undergoing a deforming transformation is displayed, observers may at least initially perceive the object to be undergoing a rigid transformation (e.g., rotation) that would yield an equivalent projection.

Another example of the recovery of structure from motion is the paradigm of point light displays. In this example, points of light are attached to an object. If the points are placed on the major joints of a biomechanical form (e.g., the shoulders, elbows, wrists, hips, knees, and ankles of a walking person), then it is easy to perceive the structure when the form is moving; when it stops, the points appear to be a meaningless jumble. Structure is defined by the motions of the points; from the motions, observers can derive the connectivity relations (Proffitt and Bertenthal, 1984).

As mentioned earlier, spatial information and depth order are specified by motion. Surface segregation is possible when motion occurs: texture on a surface move coherently and occluding edges (i.e., points at which surface is revealed or deleted) specify depth order (Gibson, Kaplan, Reynolds, and Wheeler, 1969; Yonis et al., private communication). Depth order is also specified by motion parallax; proximal objects are displaced more than distal objects for a given transition.

Configuration constrains perceived motion.- In theory, most motions displays can support a number of organizations and interpretations. What concerns us is how observers spontaneously organize motion displays, and what principles drive these organizations (Johansson, 1950). An observer of a given motion display can organize the motion in several ways. Consider a point light on the rim of a wheel. As the wheel rolls in a dark room, the light traces a cycloid path, which is the motion an observer perceives. If a second light is added to the wheel, 180° from the first, the two lights trace two cycloids, but this is not the motion that is perceived. Instead, the motion is now organized as two points rotating about a common center, which translates linearly. Thus, the observer no longer perceives the absolute motion of the two points. Instead, the motion is organized into the relative motion (rotation) and the common motion (translation) of the two points. A series of studies on the perception of wheel generated motion (Cutting and Proffitt, 1982; Proffitt and Cutting, 1979; Proffitt, Cutting, and Stier, 1979) has demonstrated that the configuration of the point lights on the wheel determines what motions are perceived, i.e., how the motion is organized.

Another manner in which the configuration influences perceived motion is demonstrated by the phenomenon of induced motion. Here, a stationary object may be perceived as moving because objects or texture surrounding it are in motion. Many people have experienced this when viewing the moon in a cloudy sky. The moon appears to move in the opposite direction of the cloud flow. Such misperceptions can easily occur when viewing displays as well. Although a stable frame is usually provided on displays, induced motion is caused primarily by objects and textures that are most proximal (Wallach, 1959).

The two examples just presented deal with how the configuration influences the perception and organization of real motions. But as mentioned, displays do not present real motion, but rely on the apparent motion that results from the rapid presentation of static sequences. Ongoing research in our laboratory demonstrates that the object configuration influences how observers interpolate the motion in such displays.

Consider the display depicted in figure 6. An L-shaped object is flashed intermittently at each position. When the timing parameters are correct, an observer perceives a single object moving back and forth between the two positions. The question arises as to what path the object is seen to take. In theory, there is an infinite number of pathways that could move the object between the two positions. In fact, the perceptual system will see the object move along a path that is, by some criteria, the minimal distance between the two positions. Now the question is: what minimalization criteria should be applied?

Shepard (1985) has suggested that there are two likely candidates for the minimization criteria. The first would attempt to find a minimal kinetic solution. In this case, that would mean the center of mass of the object would translate linearly, and the form would rotate about the center (fig. 6(b)). The second candidate would be a kinematic minimization. This would involve a single rotation of the form about an external axis (fig. 6(c)). Shepard cites finding by Foster (1975) to support the claim that observers prefer the kinematic minimalization solution and perceive the form to be moving in a curvilinear path.

Our research suggests that Foster's findings do not generalize beyond the specific stimuli he used. In particular, we find that observers prefer a kinetic minimalization when the angle of rotation is large, or when the axes of the form do not coincide with the external axis of rotation. Thus we find that the configuration of the display constrains the perceived motion between specified locations in periodically updated displays. The manner in which the visual system resolves the inherent ambiguities of these displays is influenced by configural parameters.

Conceptual Influences.- Recently, consideration has been given to whether motion information is sufficient to specify the dynamics of simple physical systems. Runeson (1977) formally demonstrated that the kinematics (pure motions) of linear collision events are sufficient to specify certain kinetic parameters (e.g., relative masses of the colliding objects and the coefficient of restitution). This analysis easily generalizes to oblique collisions. Empirical studies (Todd and Warren, 1983; Kaiser and Proffitt, 1986) have demonstrated the sensitivity of observers to this information. Other research demonstrates the ability of observers to extract kinematically specified dynamics for a variety of physical systems, including lifted weights (Kaiser and Proffitt, 1984; Runeson and Frykholm, 1981), pendulums (Pittenger, 1985), and bouncing balls (Warren, Kim, and Husney, private communication).

The demonstration of perceptual sensitivity to dynamic information raises the issue of whether an operator's perceptual competence might surpass his or her conceptual understanding. If so, it might be possible to bypass an operator's conceptual biases by presenting dynamic information directly rather than representationally. This idea is supported in the literature. People who erroneously believe that free-falling objects fall at a constant rate nonetheless correctly select a accelerating display as the best exemplar of free-fall (Shanon, 1976). Both children and adults are better at recognizing dynamic anomalies in collisions when viewing motion displays than when viewing static representations (Kaiser and Proffitt, 1984). Adults and fifth graders who predict that a ball exiting a c-shaped tube will take a curvilinear path nonetheless recognize the correct linear trajectory when presented with dynamic displays, but not with static diagrams (Kaiser, Proffitt, and Anderson, 1985).

Thus, many of the misconceptions that people manifest when asked to reason about physical systems do not occur when these same people are asked to make judgments about dynamic displays. In the latter situation, people are able to exploit their perceptual appreciation of dynamic invariants (e.g., the conservation of momentum) to solve the problems. This perceptual problem-solving ability presents both a challenge and great promise for dynamic display design. The promise is that dynamic displays can reduce the cognitive load of the operator in monitoring and problem-solving of dynamic systems. The challenge is to determine what aspects of the dynamic display are critical and how best to engage the problem-solving capability of operators while integrating their perceptual and conceptual understanding.

CONCLUSIONS

As advances in computer technology increase the availability of graphical and dynamic displays, it becomes increasingly important for display designers to appreciate the perceptual and conceptual biases operators bring to the interface. Static displays are often employed because of their computational economy. However, such displays can be understood only through the implementation of conventions. Few of these conventions are explicitly known or understood. Further, some draw on operators' intuitive mental models which are known to manifest conceptual errors. Even trained operators will resort to less formal modes of reasoning in problem-solving situations, which will lead to the introduction of erroneous models and logic.

The introduction of motion in displays can eliminate some of the operator's conceptual biases by directly providing dynamic information. However, these reduced dynamic displays lack much of the spatial and object information available in actual events which forces the operator to make assumptions in order to resolve ambiguities in the displays. Caution must be taken to ensure that the operator's perception matches the information the designer intended to convey. Further, the designer must appreciate the inherent tendencies of perceptual organization for motion perception and the particular organizational issues associated with periodically updated displays.

The display technologies currently available (and those being developed) vastly improve the capability of information tranfer between operator and machine. The challenge now is to appreciate operators' context-specific biases in order to enhance the likelihood that what is transferred is information, not misinformation.

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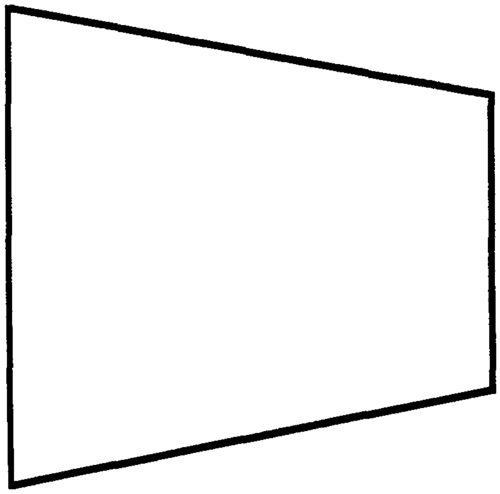


Figure 1.- Trapezoidal projection which could result from a large class of 3-D objects.

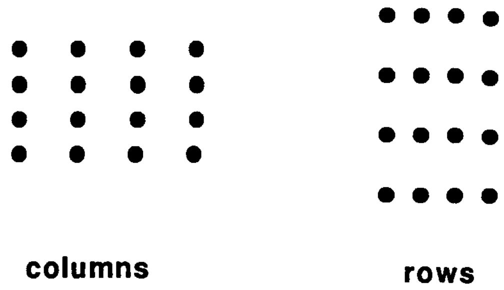
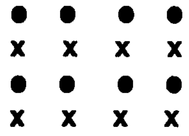
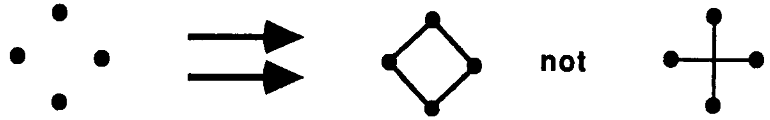
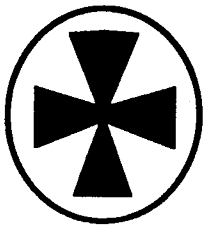
Principle	Example
Proximity Spatially proximal stimuli are grouped together.	
Similarity Objects possessing similiar color, brightness, or form are grouped together.	
Good Continuation Interpretations in which lines continue their previous curvature are preferred.	
Closure Stimuli will be grouped so as to construct closed forms.	
Figure-Ground Organization In perception of figure-ground relations, those areas which are smaller, surrounded, oriented on the principle axes, or symmetric are favored as figures.	

Figure 2.- Gestaltist laws of form organization.

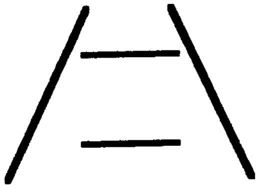
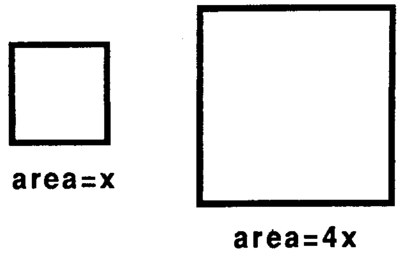
	Type of Illusion	Example
Length	1. Horizontal/vertical illusion. Vertical lines appear 5-10% longer than an objectively-equal horizontal line.	
	2. Bisected lines appear shorter than nonbisected lines.	
	3. Muller-Lyer illusion. End elements can influence the perceived legths of lines.	
	4. Ponzo illusion. Framing lines can influence the perceived length of interior lines	
Angle	1. The magnitude of acute angles tends to be underestimated; obtuse angles overestimated.	
	2. Angles with horizontal bisectors are perceived as larger than those with vertical bisectors.	

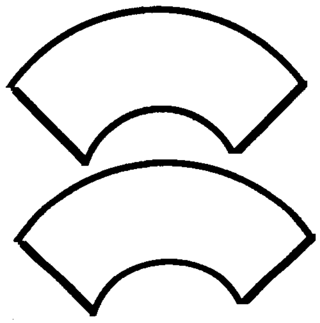
Figure 3.- Visual illusions in static, 2-D displays.

Area

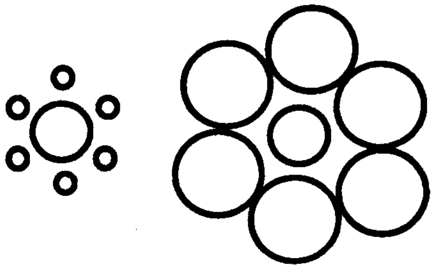
Magnitude errors. Observers tend to underestimate larger areas relative to smaller areas.



2. Jastrow illusion. Relative area judgment depend on orientation.



3. Ebbinghaus illusion. Perceived areas are influenced by surrounding figures.



Orientation/Curvature

1. Poggendorff illusion. Disrupting a form makes the line appear discontinuous.

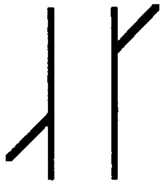
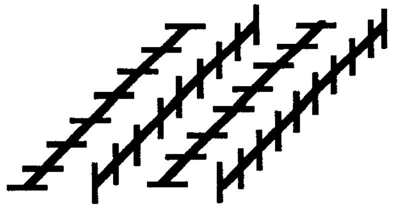


Figure 3.- Continued.

2. Zoller illusion. Crossing lines distort apparent orientation such that parallel lines no longer appear parallel.



3. Hering and Wundt illusions. Oblique lines distort the perception of parallel lines.

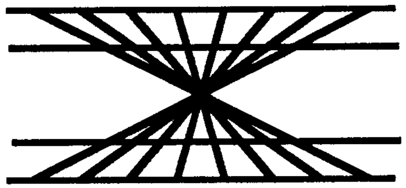
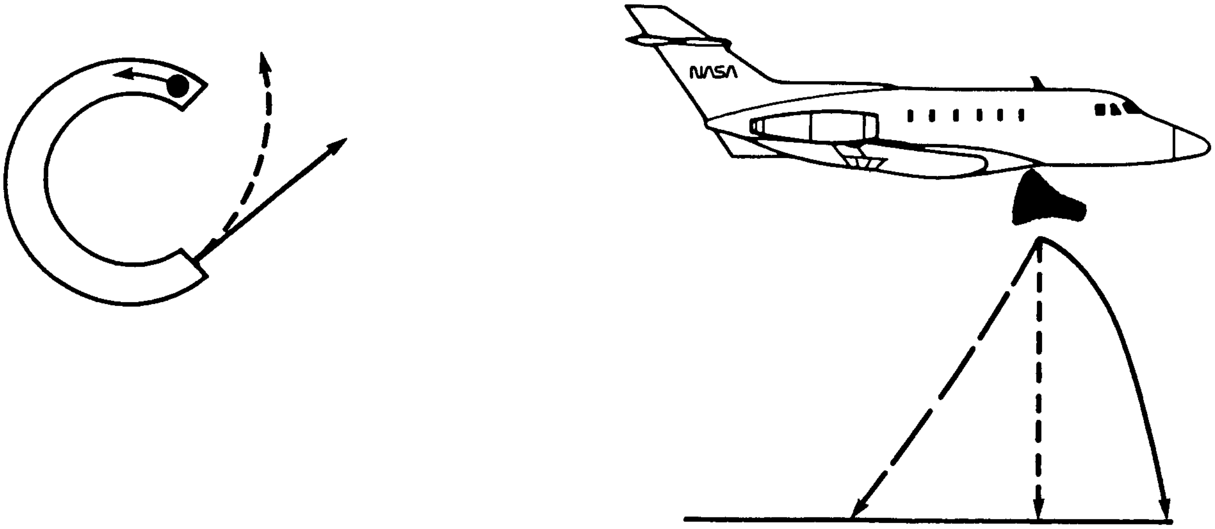


Figure 3.- Concluded.

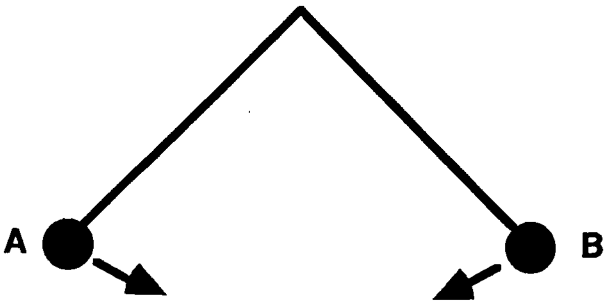


C-SHAPED TUBE PROBLEM

FALLING OBJECT PROBLEM

Figure 4.- Motion problems with correct solutions (solid lines) and common incorrect responses (dotted and dashed lines).

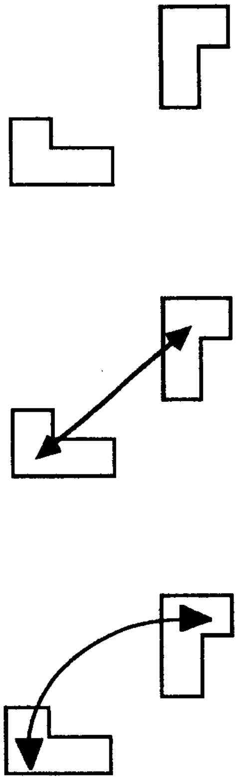
Display



Interpretations

1. Two pendulum bobs swinging in the picture plane 180 deg out of phase.
2. A and B collide at the center and recoil back to the apexes.
3. A and B rotate in depth about the pivot point.

Figure 5.- An example of multistability in a 2-D motion display.



a) Apparent motion display (the two forms are flashed in alternation)

b) Kinetic minimalization interpretation

c) Kinematic minimalization interpretation

Figure 6.- Possible perceived trajectories in an apparent motion display.

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15. Supplementary Notes

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16. Abstract

Recent developments in computer engineering have greatly enhanced the capabilities of display technology. As displays are no longer limited to simple alphanumeric output, they can present a wide variety of graphic information, using either static or dynamic presentation modes. At the same time that interface designers exploit the increased capabilities of these displays, they must be aware of the inherent limitation of these displays. Generally, these limitations can be divided into those that reflect limitations of the medium (e.g., reducing three-dimensional representations onto a two-dimensional projection) and those reflecting the perceptual and conceptual biases of the operator.

This paper considers the advantages and limitations of static and dynamic graphic displays. Rather than enter into the discussion of whether dynamic or static displays are superior, we explore general advantages and limitations which are contextually specific to each type of display.

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