SUMMARY

In a 2012 paper, Patterson (submitted for publication in JSID) touched upon and highlighted key studies that support the usefulness of an *interactive stereo display*, which he classifies as *cognitive enhancement displays*. One of the first companies to develop and market such a display is Infinite Z and the product itself is called zSpace. You can visit www.zspace.com for a video demonstration that will provide context for the scientific and technical information Patterson presented throughout his paper.

What interactive stereo displays offer the user, or a group of users, is natural and comfortable interaction with stereoscopic images projected in open space above or in front of the display, depending on its physical orientation. These capabilities enable users to view and directly manipulate the spatial attributes of objects and data, which engage the users' spatial reasoning and enhance their understanding of spatial relationships. In turn, this activates the users' cognitive and intuitive reasoning systems for a faster, deeper and far greater sense of the information presented. This capability should be particularly useful in industry, medicine, government, and education.

The fundamental benefits of interactive stereoscopic displays include:

- Engagement of our cognitive and intuitive abilities in scenarios comprising complex objects, concepts, interactions, and data
- A sense of realism where stereoscopic images appear solid in open space similar to real physical objects
- Precise, fast and flexible interaction with three-dimensional objects and data
- An intuitive, comfortable and easy-to-use 3D interface
- Quick and insightful understanding of abstract visualizations and concepts

INTERACTIVE STEREOSCOPIC DISPLAYS

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ABSTRACT

Interactive stereo displays allow for the existence of a natural interaction between the user and the stereo images depicted on the display. In the type of display discussed here, this interaction takes the form of tracking the user's head and hand/arm position. Sensing the user's head position allows for the creation of motion parallax information, an immersive depth cue that can be added to the binocular parallax already present in the display. Sensing the user's hand or arm position allows the user to manipulate the spatial attributes of virtual objects and scenes presented on the display, which can enhance spatial reasoning. Moreover, allowing the user to manipulate virtual objects may permit the creation of a sense of spatial relations among elements in the display via proprioception, which may augment the two parallax cues. The congruence among binocular parallax, motion parallax, and proprioception should increase the sense of depth in the display and increase viewing comfort, as well as enhance the ability of our intuitive reasoning system to make reasoned sense out of the perceptual information. These advantages should make interactive stereo displays, which may be classified as a form of *cognitive enhancement display*, the display of choice of the future. Interactive stereo displays may be particularly important for applications in industry, medicine, government, and education.

INTRODUCTION

Interactive stereo displays, unlike most typical stereo displays, allow for the existence of an interaction between the user and the stereo images depicted on the display. Sensors attached to the physical display, which track the head and hand/arm position of the user, enable this interaction. Sensing the position of the user's head allows for new immersive depth information to be created and presented on the display, information beyond binocular parallax. This new depth information is called *motion parallax*, which can be added to the binocular parallax already present in the display. The advantage of motion parallax being added to binocular parallax is an increase in the comfort of viewing and the quality and sense of immersion of the experienced depth (Patterson & Silzars, 2009).

Sensing the position of the user's hand or arm allows the user to manipulate or interact with the virtual objects or scenes presented on the display. This type of human-device interaction is called a *direct manipulation interface* (Hutchens, Hollan & Norman, 1985). Using a direct manipulation interface may allow for the creation of a sense of spatial relations among elements in the display. This sense of spatial relations would come from sensing the position and movement of one's own body, which is called proprioception (Kandel, Schwartz & Jessel, 2000).

The congruence among binocular parallax, motion parallax, and proprioception, which is possible only in interactive stereo displays, may augment the sense of depth in the display (Keehner, Khooshabeh & Hegarty, 2008), and increase viewing comfort (Patterson & Silzars, 2009). The lack of congruence among these perceptual cues when a typical stereo display is viewed can lead to a situation that Patterson and Silzars (2009) called 'high-level cue conflict', which refers to multiple cues conveying different depths to a viewer, thus creating “eye” strain and discomfort. Patterson and Silzars argued that the basis for this discomfort is to be found in the mental processes of human reasoning. Specifically, immersive stereo displays that depict real-life objects or scenes primarily engage an *intuitive reasoning* system, which attempts (and fails) to make reasoned sense out of the conflicting perceptual information. However, when high-level cue conflict is minimized or eliminated by having congruent perceptual cues, the intuitive reasoning system should make reasoned sense out of the information that is presented.

These three topics—motion parallax, direct manipulation interfaces, and intuitive reasoning--are discussed in more detail below. But before discussing these topics, however, a brief overview of binocular vision will be given, followed by a discussion of an assumed problem with stereo displays—accommodation-vergence mismatch. These topics were discussed in detail by Patterson (2009). The issue of a mismatch between accommodation and vergence will be related to interactive stereo displays later.

OVERVIEW OF BINOCULAR VISION

Stereopsis is the perception of depth based on horizontal binocular parallax, which is a difference in the perspective of viewing due to the existence of horizontally separated eyes. This binocular parallax creates binocular disparity, which is a difference in the lateral position of corresponding monocular images in the two eyes (Patterson, 2009).

When fixation is directed toward an object in the visual field, corresponding retinal areas in the two eyes are stimulated by the fixated images. Those images possess zero binocular disparity. In the literature on binocular vision, there is an imaginary construct consisting of a geometric arc that passes through the fixation point called the “horopter.” The locations along the length of the horopter define the positions in the visual field that also give rise to pairs of images that stimulate corresponding retinal areas; objects located at these positions will possess zero disparity (see Fig. 1). The horopter is considered a reference plane, passing through fixation, that defines zero disparity from which the depth of other objects are judged. That is, objects are either on the horopter, in front of the horopter, or behind the horopter.

An object located in a depth plane in front of the horopter will create images with “crossed disparity” (Fig. 1), whereas an object located in a depth plane behind the horopter will create images with “uncrossed disparity.” These terms, crossed disparity and uncrossed disparity, are used as labels for the relative direction of the disparity of objects from the horopter, either in front of (crossed) or behind (uncrossed) the horopter. Objects with small or moderate magnitudes of crossed or uncrossed disparity will fall within a region called Panum's fusional area (Figure 1), and the left-eye and right-eye images from those objects will be perceptually fused and the objects will be seen as single objects. Objects with large crossed or uncrossed disparity will fall outside Panum's fusional area, which will lead to diplopia (double images). With diplopia, reliable depth perception may fail, and one of the two monocular images may be perceptually suppressed and inhibited *via* a processed called binocular rivalry, which may not be noticed when viewing in the real world.

When vergence eye movements are made, an object that initially stimulates the binocular visual system with crossed disparity may end up stimulating the visual system with uncrossed disparity, or vice versa, as the observer shifts fixation to different locations in the visual field. In this case, the relative disparity between the objects remains constant, but their absolute disparity as registered by the visual system will change whenever vergence eye movements are made. It is thought that a mental representation of the visual field is constructed over time by integrating the depth information across vergence eye movements, which would increase the range of reliable depth perception (Patterson, 2009).

Thus, with a stereo display, the situation arises whereby a user can converge their eyes to fixate a virtual object in front of the display, or diverge their eyes to fixate a virtual object behind the display, while the stimulus for accommodation—the displayed images--remain on the face of the display. This creates the potential for a mismatch between accommodation and vergence, a topic that is discussed next.

ACCOMMODATION-VERGENCE MISMATCH

When viewing a stereo display, the stimulus for accommodation would be the surface of the display. However, when a user changes vergence angle to converge on a virtual object appearing in depth in front of or behind the display, the vergence angle can be mismatched relative to the accommodative response. Due to the synergy between accommodation and vergence, it is believed that converging or diverging to a depth plane that is different from the display surface will pull the accommodative response to that depth plane, thereby making the images on the display surface go out of focus. This, in turn, will tend to drive the accommodative response back to the display surface, and a conflict between accommodation and vergence will ensue. It is believed that such an accommodation-vergence mismatch can create problems such as eyestrain and visual discomfort (Patterson, 2009).

However, Patterson (2009) discusses how these problems should occur only for short viewing distances. The reason why these problems occur only for short viewing distances is due to the depth of field of the human eye. The depth of field refers to the interval in depth over which an image remains in focus and the accommodative response would not be differentially stimulated in a direct way. The depth of field will vary depending upon fixation distance: the eye can tolerate much larger intervals of depth when those intervals are viewed from a far distance than when they are viewed from a near distance before images go out of focus. Thus, converging or diverging to a depth plane that is different from the display surface may pull the accommodative response to that depth plane, but if that depth plane is within the depth of field, the images on the display surface will still be in focus and the accommodative response should not be driven back to the display surface. A conflict between accommodation and vergence should not occur if the virtual objects appear in depth planes within the user's depth of field.

According to calculations made by Patterson (2009), for a fixation distance of 0.5 m, the total depth of field would range from a distance of about 0.1 m in front of fixation to about 0.17 m behind fixation. For a fixation distance of 1 m, the total depth of field would range from a distance of about 0.33 m in front of fixation to about 1.0 m behind fixation. For a fixation distance of 2 m, the total depth of field would range from a distance of about 1 m in front of fixation to an infinite distance behind fixation. Thus, the total depth of field could be very large – from 1m in front of fixation to infinity behind fixation – when fixating an object 2m away. These values by Patterson were estimates because the depth of focus is affected by several factors, such as the size of the pupil, which in turn is affected by the luminance of the displayed imagery.

These estimates show that, in general, there is little change in the demand for accommodation with fixation distance set at 2m or farther, which should minimize any discomfort that could occur with accommodation-vergence mismatch. Patterson suggests that, in general terms, the remedy for an accommodation-vergence mismatch is to present the stereo depth information (*i.e.*, the perceived depth plane) so that it is within the depth of field of the human eye. One can estimate the depth of field, as well as the location of the perceived depth plane, by using the calculations given by Patterson (2009).

So where does the viewing discomfort that is experienced by many users of stereo displays come from? Patterson and Silzars (2009) have argued that, rather than accommodation-vergence mismatch being a ubiquitous problem with stereo displays, it is high-level cue conflict that creates the viewing discomfort and eye strain reported by many users when a typical stereo display is viewed. According to Patterson and Silzars, high-level cue conflict comes from the absence of another immersive depth cue in a typical stereo display, namely motion parallax. A high-level cue conflict can be created between the presence of one immersive depth cue, binocular parallax, and the absence of another immersive depth cue, motion parallax. The conflict is created when the visual system registers a non-zero value of binocular parallax and a zero value of motion parallax—the two immersive depth cues are incongruent.

Interactive stereo displays have significant advantages over non-interactive stereo displays because interactive displays allow for the creation of motion parallax, as well as the creation of a direct manipulation interface that generates proprioceptive cues. The congruence among binocular parallax, motion parallax, and proprioception, which is possible only in interactive stereo displays, may augment the sense of depth in the display (Keehner, Khooshabeh & Hegarty, 2008) and increase viewing comfort (Patterson & Silzars, 2009). This congruence should permit our intuitive reasoning system to make reasoned sense out of the information that is presented. We now turn to the topics of motion parallax, proprioception through direct manipulation interfaces, and intuitive reasoning.

MOTION PARALLAX

Sensing the position of the user's head allows for new immersive depth information to be created and presented on the display, namely motion parallax information. The term 'parallax' refers to the difference in direction or perspective of an object or scene as seen from two different points of viewing, which provides relative depth information to a viewer. With binocular parallax (the cue present in all stereo displays), the difference in perspective occurs when the user views an object or scene in the real world with horizontally separated eyes (Patterson, 2009). With motion parallax, the difference in perspective occurs when the observer views an object or scene in the real world at two (or more) successive positions due to head movements (Sekuler & Blake, 2005). Interestingly, strong cues to depth from motion parallax can be obtained from only very slight body sway.

For example, consider Figure 2. Here, a user moves her head laterally to the left while fixating an object. Arbitrarily, three objects are shown positioned at different depths in front of fixation, and three objects are positioned at different depths behind fixation (filled ovals). The dashed arrows attached to the various objects indicate the velocity of the movement of the objects *relative to the user* as the user undergoes lateral self-motion. Objects positioned at increasingly closer depths in front of fixation undergo opposing relative motion, and objects positioned at increasingly farther depths behind fixation undergo congruent relative motion (objects positioned behind fixation appear to move in the direction of user self-motion due to the rotational eye movement as the user maintains fixation while translating laterally).

As the user moves laterally, portions of the background scene that are initially hidden from view by the objects become revealed as the user reaches her new position; this was termed *'dynamic disclosure'* by Patterson and Silzars (2009). Portions of the background scene that are initially visible to the user become hidden by the objects as the user reaches their new position; this was termed *'dynamic occlusion'* (Patterson & Silzars, 2009). The visual system interprets the relative movement of the objects as being due to the user's self-motion. That is, the objects themselves appear fixed to a rigid scene as the user moves past them, and their relative motion provides relative depth information, which is called motion parallax.

As discussed by Patterson and Silzars, it is this relative movement—motion parallax--that is absent from many, if not most, non-interactive stereo displays, including 3DTVs and 3DTheaters showing stereo movies. In stereo displays that lack motion parallax information, when a user moves laterally, the apparent movement of a 3D object follows the direction of the observer's self-motion. There is no dynamic disclosure or dynamic occlusion of background elements. In this case, the visual system interprets the relative movement between observer and any 3D object as a movement of the 3D object itself, which does not appear to be fixed to a rigid scene. The 3D object appears to occupy a position along the observer's line of sight so that when the observer moves, so does the 3D object.

Recall that this absence of motion parallax cues in stereo displays can create high-level cue conflict between the presence of one immersive depth cue, binocular parallax, and the absence of another depth cue, motion parallax (Patterson & Silzars, 2009). The conflict is created by the visual system registering a non-zero value of binocular parallax and a zero value of motion parallax—the two immersive depth cues are incongruent. Patterson and Silzars argued that it was this high-level cue conflict, and not accommodative-vergence mismatch, that leads to much of the discomfort of viewing and eye strain reported in the literature when stereo displays lacking motion parallax information are viewed.

An interactive stereo display will solve this problem by tracking a user's head position, and then use that information to update the virtual objects or scene presented on the display. The virtual objects or scene will be presented to the user from a slightly different perspective, the exact amount of which will be determined by the user's head movement. The tracking of the user's head movement will be employed to create an appropriate amount of dynamic disclosure and dynamic occlusion, and thus an appropriate amount of motion parallax information.

The presence of motion parallax, together with binocular parallax, in an interactive stereo display will minimize or prevent the occurrence of high-level cue conflict that was deemed serious by Patterson and Silzars (2009). The reduction or elimination of high-level cue conflict, in turn, should increase the viewing comfort and the quality and sense of depth and immersion when an interactive stereo display is viewed.

DIRECT MANIPULATION INTERFACES

Sensing the position of the user's hand or arm or handheld stylus will enable the user to manipulate or interact with the virtual objects or scenes presented on the display, a so-called direct manipulation interface (Hutchens, Hollan & Norman, 1985). Using a direct manipulation interface may allow for the creation of a sense of spatial relations among elements in the display owing to proprioception.

Proprioception refers to the sense of the position and movement of one's own body without the use of other senses (e.g., vision, audition). Proprioception and the kinesthetic sense are two terms often seen as interrelated, yet there is considerable disagreement regarding their definitions. In this paper we will use the terms as defined by Kandel, Schwartz and Jessel (2000).

There are two submodalities of proprioception: the limb-position sense, which involves sensing the stationary position of limbs, and kinesthesia, which entails sensing the movements of limbs (Kandel, Schwartz & Jessel, 2000). As discussed by Kandel et al., proprioception is important for controlling the movements of the limbs, manipulating objects, and maintaining posture.

The proprioceptive sense may provide information about the spatial relations among elements in a direct manipulation display through the cumulative signals about body position and kinesthesia as one interacts with the virtual objects over time. Along a related vein, Keehner, Khooshabeh and Hegarty (2008) suggested that one advantage of a direct manipulation interface is that information about spatial relations can come from the motor commands made to control the display. In support of this idea, these authors cite Philbeck, Klatzky, Behrmann, Loomis and Goodridge (2001), who have shown that motor command signals during active exploration may provide cues about navigation through space. Thus, sensing body position and movement through proprioception, as well as the commands for executing motor movements themselves, may provide information about spatial relations when a direct manipulation interface is used. This information about spatial relations, in turn, may be combined with the binocular parallax and motion parallax information present in the interactive stereo display.

Another advantage of a direct manipulation display comes from Hutchens, Hollan and Norman (1985), who suggested that a reduction in cognitive effort occurs when using such a display because the capability of a direct manipulation interface to accomplish a given task should be well matched to the user's goals. Finally, Keehner, Khooshabeh and Hegarty (2008) suggest that consistent advantages should be obtained when using a direct manipulation interface provided that relatively simple stimuli are used (e.g., familiar objects) and the tasks involve simple recognition or visual inspection.

INTUITIVE REASONING

The congruence among binocular parallax, motion parallax, and proprioception should augment the sense of the spatial relationships in the display (Keehner, Khooshabeh & Hegarty, 2008), and increase viewing comfort (Patterson & Silzars, 2009). The lack of congruence among these perceptual cues when a stereo display is viewed can lead to 'high-level cue conflict' (Patterson & Silzars, 2009)--multiple cues conveying different depths to a viewer—which creates “eye” strain and discomfort. Patterson and Silzars argued that this discomfort can be related to our intuitive reasoning system, as explained later.

In the cognitive science literature, a number of authors (e.g., Evans, 2008; Hammond, 2007; Hogarth, 2001; Kahneman & Frederick, 2002; Sloman, 1996; Stanovich & West, 2000) have proposed that human reasoning is composed of a blend of two complementary systems, an analytical system and an intuitive system. See Figure 3. These two systems are thought to be engaged in parallel fashion when an individual interacts with the world, with the relative weight given to processing in one or the other system depending upon the task at hand. These two reasoning systems are explained in detail below.

Analytical Reasoning

Analytical reasoning involves the making of conscious decisions by contrasting of options (i.e., conscious deliberation). Evans (2003) has argued that the analytical system is evolutionarily recent, permits abstract reasoning, is correlated with measures of general intelligence, and is constrained by working memory capacity. This system is slow, deliberative, reflective, effortful, self-aware, abstract, and symbolic. Patterson and Silzars pointed out that *alphanumeric symbolic displays primarily engage the analytical reasoning system*.

Intuitive Reasoning

Intuitive reasoning entails the making of decisions based on situational pattern recognition whose steps are largely unconscious (we are aware of only the output of this system). Evans (2003) has argued that the intuitive system is evolutionarily old and it involves a set of autonomous subsystems that involve the recognition of domain-specific patterns. The intuitive system is fast, automatic, relatively effortless, and is *related to high-level perception*. Patterson and Silzars pointed out that *immersive stereo displays primarily engage the intuitive reasoning system*.

Their argument is based on the idea that the characteristics that engage intuitive reasoning correspond well with the cues provided by immersive stereo displays. Hammond, Hamm, Grassia and Pearson (1997) suggested that intuitive reasoning is activated by displays that involve perceptual material with multiple cues and no symbolic calculation. This is exactly the description of immersive stereo displays.

According to Patterson and Silzars, a typical stereo display engages our intuitive reasoning system, but it does so in a limited fashion relative to the viewing of scenes in the real world. In the real world, the congruence among binocular parallax, motion parallax, and proprioception should reinforce the sense of depth that is experienced by an observer. But with the typical stereo display, motion parallax cues and proprioceptive cues are absent. According to

Patterson and Silzars, the absence of depth cues like motion parallax, together with the presence of binocular parallax, leads to high-level cue conflict with a typical stereo display, which in turn produces viewing discomfort because *the intuitive reasoning system is attempting to make reasoned sense out of the incoming conflicted perceptual information*. High-level cue conflict creates a form of *mental* strain (not eye strain) that may become intolerable over time.

Thus, interactive stereo displays can create a form of congruence among binocular parallax, motion parallax, and proprioception, which should permit our intuitive reasoning system to make reasoned sense out of the incoming (congruent) perceptual information. Although interactive stereo displays can create a form of congruence among these various perceptual cues, these kinds of displays can do much more. In particular, interactive stereo displays can enhance spatial reasoning.

SPATIAL REASONING

Spatial reasoning is defined as the ability to make judgments and reason about objects and their spatial relations (Gardner, 1983/1991; Renz & Nebel, 2007). There are two aspects of spatial reasoning (Anderson, 2010): (1) *visual*, which entails judgments about the visual details of an object (or objects) like its color or size (Moyer, 1973; Thompson & Kosslyn, 2000); and (2) *spatial*, which involves judgments about the position or location of an object, or about the spatial relations among parts of an object, or about multiple objects (Brooks, 1968; Roland & Friberg, 1985).

Visual Aspect

There are tasks for which interactive stereo displays could be beneficial that entail the visual aspect of spatial reasoning. For example, one could use an interactive stereo display to manipulate a virtual object in order to scan its features. Alternatively, one could rotate or manipulate a set of displayed objects in order to perform a visual comparison of their features.

Using an interactive stereo display to manipulate a virtual object (or objects) in order to scan its (their) features could improve the speed and accuracy of judgments made about the object(s). This is because memory for visual details decays very rapidly, even within the first tens of seconds (Mandler & Ritchey, 1977; Gernsbacher, 1985). Thus, one could manipulate a virtual object so as to re-position the part about which one is making the judgment so that the user would not have to remember its detail. Using an interactive stereo display to manipulate a virtual object(s) could eliminate the need to use memory.

Spatial Aspect

There are tasks for which interactive stereo displays could be beneficial that involve the spatial aspect of spatial reasoning. For example, one could use an interactive stereo display to manipulate a virtual object through three (x, y, z) dimensions in order to see the relationships among its parts. Alternatively, one could manipulate a set of virtual objects through three (x, y, z) dimensions in order to determine their spatial layout.

Using an interactive stereo display to manipulate a virtual object through three dimensions in order to see the relationships of its parts, or to determine the spatial layout of a set of objects, could enhance the speed and accuracy of judgments made about the object(s). This is because it takes much cognitive effort to manipulate objects mentally via visual imagery (Shepard & Metzler, 1971), which takes time and is error prone. Studies have shown that individuals would rather rotate shapes on a display rather than rotate them mentally (Kirsh & Maglio, 1994). Using an interactive stereo display to manipulate a virtual object(s) could eliminate the need to manipulate the objects mentally.

Another type of task for which interactive stereo displays could be beneficial is the alignment of the relationship among different kinds of maps (geospatial alignment). To discuss this idea further, several distinctions must first be made among (1) route map, (2) survey map, (3) an egocentric representation of space, and (4) an allocentric representation of space (Anderson, 2010; Burgess, 2006; Klatzky, 1997). A route map refers to a path linking up locations but it contains no spatial information (Anderson, 2010). An example of a route map would be a drawing showing a depiction of your driveway, an arrow pointing left followed by a stop sign, and then an arrow pointing rightward showing an entrance to a highway. It would be a drawing showing a path that linked up different locations (driveway, stop sign, highway) but it would be devoid of any real spatial information—the spatial relations among the locations would not be preserved (Anderson, 2010). A survey map, on the other hand, is a representation of locations that preserves their spatial relations (Anderson, 2010). An example of a survey map would be a map of the city in which you live.

An egocentric representation of space (Burgess, 2006; Klatzky, 1997) refers to space as viewed from an observer's perspective. An example of an egocentric representation would be the viewing of objects in your front yard from your front door. An allocentric representation of space is space independent of any observer's perspective or position (Anderson, 2010). An example of an allocentric representation would be the intrinsic spatial relations of the objects in your front yard independent of any one viewpoint.

Turning back to geospatial alignment, one could use an interactive stereo display to align an egocentric representation of a set of objects or scene with an allocentric representation, such as a survey map. Using an interactive stereo display to align egocentric and allocentric maps could improve the speed and accuracy of judgments. This is because people find it difficult to mentally integrate different representations of space. For instance, it is known that the degree to which an allocentric map is rotated from an egocentric viewpoint increases the difficulty of navigation (Gugerty, deBoom, Jenkins & Morley, 2000). Moreover, studies have shown that the time taken to recognize photographs from different viewpoints around an environment increases linearly with the difference in angle between an egocentric viewpoint and the other viewpoints (Diwadkar & McNamara, 1997). Individuals appear to mentally rotate a map when it is incongruent with their egocentric viewpoint, which takes time and is prone to errors (Anderson, 2010). A user could also use an interactive stereo display to align a route map with a survey map. An example of a situation for which geospatial alignment would be useful would be an individual using an interactive stereo display to manipulate a survey map that is being created or embellished with egocentric information from another source or with information from a route map. More generally, an interactive stereo display can be used to create and align multiple sets of objects for a variety of different purposes.

A final type of task for which interactive stereo displays could be beneficial is the creation of a spatial layout of a set of displayed objects from the translation of words (Anderson, 2010; Franklin & Tversky, 1990; Taylor & Tversky, 1992). Using an interactive stereo display to help create the spatial layout of a set of displayed objects in this way may increase the speed and accuracy of the layout construction.

Thus, interactive stereo displays will allow the user to manipulate the spatial attributes (e.g., orientation, angle of view) of displayed objects and scenes presented on the display. This, in turn, should enhance the user's spatial reasoning abilities.

CONCLUDING REMARKS

In this paper, I have discussed a number of important advantages that interactive stereo displays have over the typical (non-interactive) stereo display. Interactive stereo displays allow for the existence of an interaction between the user and the stereo images depicted on the display in the form of tracking the user's head and hand/arm position. Sensing the user's head position allows for the creation of motion parallax information, an immersive depth cue that can be added to the binocular parallax already present in the display. Sensing the user's hand or arm position allows the user to manipulate the spatial attributes of the virtual objects, which can enhance spatial reasoning. Permitting the user to manipulate virtual objects may also allow for the creation of a sense of spatial relations among elements in the display via proprioception, which may augment the two parallax cues. The congruence among binocular parallax, motion parallax, and proprioception should increase the sense of depth in the display and increase viewing comfort, as well as enhance the ability of our intuitive reasoning system to make reasoned sense out of the incoming perceptual information.

For all these reasons, I would classify interactive stereo displays as a kind of *cognitive enhancement display* (Patterson, 2012). These advantages should make interactive stereo displays the display choice of the future. Interactive stereo displays may be particularly important for applications in industry, medicine, government and education.

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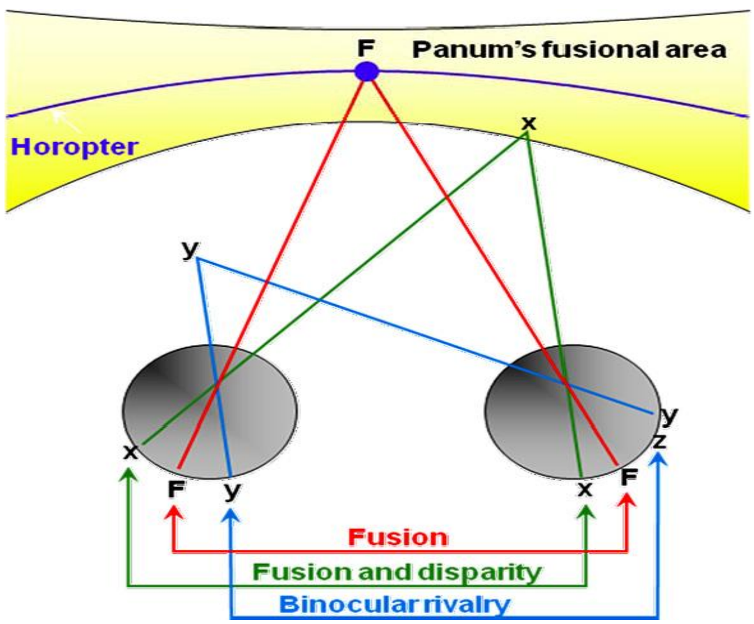

Figure 1. From Patterson (2009). Drawing depicting a top-down view of two eyes, fixation point F, the horopter passing through the fixation point, Panum's fusional area, and object X and object Y. When fixation point F is fixated, the images from F stimulate corresponding retinal points in the two eyes and are fused. Object X is positioned in front of the horopter and carries a crossed disparity; the images from X that stimulate disparate retinal points in the two eyes are fused because X falls within Panum's fusional area. Object Y is positioned farther in front of the horopter and also carries a crossed disparity, but the images from Y that stimulate disparate retinal points in the two eyes are seen as double because Y falls outside Panum's fusional area. Because Y has its two retinal images on very disparate retinal areas, the image of Y in the left eye may stimulate a retinal area that is corresponding to an area in the right eye that is stimulated by an image z from a different object in the visual field, thus inducing binocular rivalry.

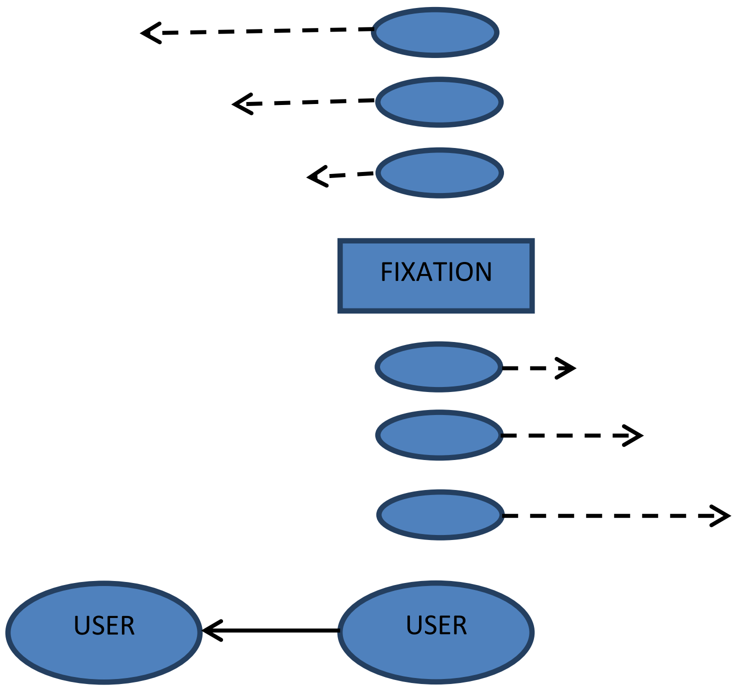

Figure 2. From Patterson & Silzars (2009). Top down view of the type of situation that yields motion parallax information to a moving user. A User who moves laterally to the left fixates an object called "FIXATION". Three arbitrary objects (ovals) are positioned at different depths in front of fixation, and three objects (ovals) are positioned at different depths behind fixation. The dashed arrows attached to the objects indicate the velocity of their apparent movement as the User undergoes self-motion. Objects positioned at increasingly greater depths in front of fixation and closer to the User appear to undergo opposing relative motion, whereas objects positioned at increasingly greater depths behind fixation and farther from the User appear to undergo congruent relative motion. The apparent relative movement of stationary objects provides relative depth information to a moving observer.

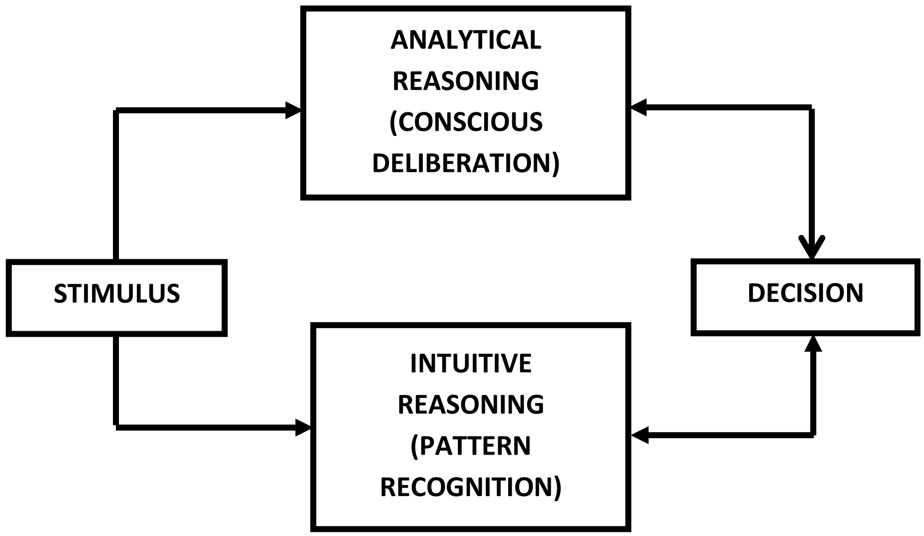

Figure 3. Diagram of dual-process reasoning model. Both the analytic reasoning system (which includes working memory and long-term declarative memory), and the intuitive reasoning system (which includes intuitive pattern recognition and long-term procedural memory) are shown.