The (Possible) Utility of Stereoscopic 3D Displays for Information Visualization: The Good, the Bad, and the Ugly

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ABSTRACT

The good, bad, and "ugly" aspects of stereoscopic three-dimensional display viewing are presented and discussed in relation to data and information visualization applications, primarily relating to spatial comprehension and spatial understanding tasks. We show that three-dimensional displays hold the promise of improving spatial perception, complex scene understanding, memory, and related aspects of performance, but primarily for (1) tasks that are multidimensional or spatial in nature; (2) for tasks that are difficult, complex, or unfamiliar; and/or (3) when other visual spatial cues are degraded or missing. No current 3D display system is capable of satisfying all visual depth cues simultaneously with high fidelity, though stereoscopic 3D displays offer the distinct advantage of binocular stereopsis without incurring substantial costs, or loss in the fidelity of other depth cues. Human factors problems that continue to plague 3D displays and that are especially pertinent to stereoscopic visualizations are considered. We conclude that stereo 3D displays may be an invaluable tool for some applications of data or information visualization, but warn that it is a tool that must be utilized thoughtfully and carefully.

Keywords

Stereoscopic displays, 3D displays, depth perception, spatial visualizations, multidimensional views, depth cue combination.

Human-centered computing; human computer interaction; visualization;

1. Introduction

By nature, humans perceive and conceptualize the world in three spatial dimensions. Decades of advances in sensors and computational technologies have eased the collection and analysis of 3D spatial and/or multidimensional data (3D+). Despite this embarrassment of riches in terms of available data, our *displays* of such data primarily remain stuck in only two-dimensions (2D). Traditional flat-panel 2D displays are inexpensive and ubiquitous in today's world, but the pulldown-transformation that occurs by portraying 3D+ data from a single flat 2D image surface means that relevant information in one or more dimensions can be distorted, lost, or otherwise invisible.

Some hints of 3D depth can be gleaned from viewing 2D representations through the use of perspective or *monocular* cues -- resulting in what is sometimes called "2.5D" displays (Dixon, Fitzhugh, & Aleva, 2009). This is why photographs or movies do not appear strictly flat; occlusions by nearer objects, relative size cues, shadows, relative motion of objects, aerial perspective, and a whole host of other cues help our brains automatically construct a three-dimensional representation of a scene, using the best available information from a 2D image (Cutting & Vishton, 1995). But current 2D imagery is unable to portray two particular highly informative spatial/depth cues:

- **self-motion parallax** (self-motion of the viewer in space over time, sometimes called 'motion perspective' or 'egomotion'), and
- **binocular disparity** (two different simultaneous vantage points for each eye, allowing for the perception of *stereopsis*).

Displays lacking the ability to show these extra sources of spatial information are thus providing a deficient, incomplete, unnatural, or possibly inaccurate representation of data to a viewer. This concern is likely to be most relevant to visualization applications in which complex 3D+ data must be studied, analyzed, understood, utilized, or interacted with in precise ways. Towards this end, we describe the (possible) utility of stereoscopic 3D display technology for 3D data visualization.

Stereoscopic 3D (S3D) displays are capable of providing all of the rich monocular depth cues available in modern 2D imagery, with the addition of one of the two most important spatial depth cues: *binocular disparity*. In contrast to state-of-the-art volumetric, light-field, or holographic 3D displays, which are only now in their infancy, stereoscopic display technology has matured such that these systems can provide high-fidelity color representations of 3D spatial information without extravagant costs in terms of additional hardware, software, imagery, or computational requirements. Reviews of the human performance benefits of S3D displays suggest mixed but mostly favorable findings across experimental literatures (McIntire, Havig, & Geiselman, 2012, 2014; Hofmeister, Frank, Cuschieri, & Wade, 2001; Getty & Green, 2007; van Beurden, van Hoey, Hatzakis, & IJsselsteijn, 2009; Held & Hui, 2011; Chen, Haas, & Barnes, 2007; Boff, 1982). These reviews demonstrate that S3D helps particularly for tasks such as the spatial manipulations of objects (e.g., real or virtual telemanipulation); for finding, identifying, or classifying objects and imagery (e.g., image analysis and interpretation tasks); and for understanding and comprehending complex spatial scenes, data, or information. It is this last task category, relating strongly to information or data visualization applications, which we will focus on in the present report.

We first investigate a variety of data and information visualization-related studies showing a clear benefit of S3D and discuss on what types of tasks S3D helped (i.e., **The Good – Section 2**). Next, we investigate some visualization circumstances under which S3D clearly offered no benefit over traditional 2D (i.e., **The Bad – Section 3**) and explore some possible reasons why. Finally, we discuss the negative human factors issues and concerns related uniquely to S3D displays of information (i.e., **The Ugly** – **Section 4**). Most of the papers to be discussed were derived from the task and outcome classification scheme described in the reviews by McIntire, Havig, & Geiselman (2012, 2014). We hope to emphasize to visualization and analytics professionals that S3D is a tool, and *only* a tool; one that may be particularly beneficial for many aspects of data or information visualization, yet may not be the right type of tool for many others. And like any complex tool, S3D can be easily misused or misapplied, and thus should be implemented delicately and applied carefully to situations likely to provide measureable performance benefits over traditional 2D visualizations.

2. The Good: When S3D Helps

In this section, we briefly review and discuss research in which a benefit of S3D has been shown (i.e., S3D is clearly better than 2D on most or all performance measures of interest). The reviewed studies relate specifically to spatial cognition and spatial information understanding tasks with possible direct relevance to scientific, information, and data visualization. Overall, the results demonstrate improved size and shape perceptions, and improved spatial scene understanding, across various tasks utilizing S3D visualizations. Improvements were evidenced with increases in speed or accuracy of task performance, or in some cases, both. Tasks under investigation primarily involved traditional mental rotation tasks, air traffic control airspace judgments, virtual object size judgments, and network data interpretation tasks.

2.1. Mental Rotation Tasks

Hubona, Shirah, & Fout (1997) studied the effects of both motion and S3D upon the accuracy and speed of a mental rotation judgment task, in which a participant must find which object out of a series of spatially-rotated objects matches a standard object. The task requires visually imagining an object being rotated through various positions until a match is found. Various 3D shapes were tested (combinations of wireframe versus solid, and cubes versus spheres). They found that S3D viewing resulted in both improved accuracy and faster judgments, thus clearly improving spatial understanding for all combinations of shapes and forms tested. S3D was helpful for either controlled or uncontrolled object motion (rotation), but was generally most accurate when the motion was under the direct control of the viewer, suggesting the alignment of visual spatial cues with manual interaction provides a significant further benefit to spatial comprehension.

Aitsiselmi & Holliman (2009) used a mental rotation task to show that S3D improves the cognitive aspects of 3D shape understanding (using block structures) which manifested as improved shape judgments, with comparable response times to 2D. This beneficial effect on spatial cognition was demonstrated on both an S3D desktop system and a simulated small-screen system (to emulate a cell phone-sized S3D display). Neubauer, Bergner, & Schatz (2010) also studied a mental rotation task in 2D versus S3D. These researchers found a general facilitating effect of S3D on response times and scores (accuracy), for both males and females, but with an even more pronounced accuracy benefit for females (who sometimes show difficulty in performing 2D and 3D rotations shown on 2D displays).

2.2. Air Traffic Control Tasks

Bourgois, Cooper, Duong, Hjalmarsson, Lange, & Ynnerman (2005) describe an evaluation of a virtual air traffic control (ATC) task involving the identification of critical flight levels in a scene; i.e., understanding the spatial relationships of moving objects in a scene. They found that participants (former air traffic controllers) had improved response times to critical conflict situations, and self-reported better clarity and understanding in their spatial judgments. Dang-Nguyen, Le-Hong, & Tavanti (2003) tested expert subjects on a similar ATC experiment in which virtual low-density aircraft traffic displays (no motion shown) required judgments regarding spatial de-confliction. They also found that response time judgments were improved with no loss in accuracy, suggesting an improvement in spatial understanding of the displayed data. Finally, Russi (2013) investigated the use of S3D for its ability to represent air traffic both laterally (as with traditional 2D displays) as well as vertically so participants could quickly and easily identify possible vertical conflictions and altitude deviations. Results showed improved ability to detect conflicts with the S3D display over the 2D representation of the same information. Also, participants reported lower workload and lower task difficulty with the S3D representation.

2.3. Object and Scene Perception

Luo, Kenyon, Kamper, Sandin, & DeFanti (2007) studied the effects of scene complexity, S3D cues, and motion parallax on size perception within an immersive virtual environment (i.e., CAVE). The task required the judgment of virtual object sizes at various distances ranging from 1 to 9 feet away. They discovered that displaying more complex scenes (which provide additional perspective or monocular depth cues) and/or providing S3D cues improved size judgment accuracy, but the provision of motion parallax cues did not. They recommend the consideration of using S3D cues in combination with complex imagery (rich depth-cue environments) for applications requiring precise perceptions of size and distance in virtual environments, including *specifically* visual scientific data analysis.

Valsecchi and Gegenfurtner (2012) used natural scene imagery to determine if S3D would enhance long-term visual memory. They tested a variety of images (forests, cars, buildings) and found that presenting forest imagery in S3D resulted in better recognition than when presented in 2D. This advantage in performance was dependent on a long exposure time to the stimuli (7 seconds) for encoding of spatial information. It was thought that the imagery of cars or buildings did not show a performance enhancement from S3D because such scenes were encoded into memory as conceptual and familiar object representations, not as complex spatial representations. For scenes like forests that might lack high object structure, or other apparent features that might aid later retrieval from memory (conspicuous color, objects, people, etc.), then S3D can allow for unique features in depth to become visible as well as giving a general sense of spatial relationships within a scene.

2.4. Network Readability and Data Interpretability

van Beurden, IJsselsteijn, and de Kort (2011) used a virtual network path-tracing task to determine the effects of different levels of disparity on traditional measure of performance such as time and accuracy, but also on user perceived workload and user discomfort. Results of objective metrics showed that the higher the task complexity (number of changes in direction in the path), the more disparity was required to perform effectively. In terms of workload, there was in interaction between disparity and task complexity revealing that there was a stronger decrease in workload for difficult tasks as disparity increased. So as the task became more complex, the workload increased, but it was still lower than the difficult tasks with lower disparity.

Sollenberger and Milgram (1993) also used a path-tracing task to test 2D versus S3D. They conducted a series of experiments requiring visual tracing of a pathway defined by connected line segments in a complex network structure representing cerebral blood vessels. Comparisons were made among 2D, S3D, and rotational (motion parallax) displays. Both the stereo display and the rotational display individually improved performance over 2D, with the combination of both stereo and rotation producing the highest performance. In a similar experiment, Ware and Franck (1996) compared the additions of S3D and motion cues when presenting abstract data in a graph. The combination had been shown to enhance performance when viewing real objects as well as paths through tree structures, as in Sollenberger and Milgram (1993), but not when viewing highly abstract information such as arbitrary graphs, the structure of code, or hypertext links. Results showed that the combination of self-motion parallax (via head-tracking) and S3D cues *did* allow participants to understand abstract informational graphs three times larger than the 2D display condition. Stereo cues alone only increased size by a factor of 1.6 when compared to 2D. As in Sollenberger and Milgram (1993), Ware and Franck confirmed that the combination of motion and S3D most improved the understanding of network data, this time using abstract informational networks.

In Ware and Mitchell (2005), the addition of fine details to graph representations was studied. Instead of using lines to display the links in the graphs, 3D “tubes” or springs were presented. Again, results showed the lowest error rates with the combination of motion and stereo, and S3D views produced faster response times, regardless of the presence of motion cues.

Wickens, Merwin, and Lin (1994) investigated the use of S3D as well as motion to evaluate multi-dimensional data. Results showed that S3D supported the best performance, whereas rotating views did not affect performance. The finding that motion did not enhance performance is contrary to previous research but may be explained by the fact that most previous studies (up to that time) did not provide sufficient perspective depth cues in the 2D control conditions. Comparing S3D views (with no perspective) to 2D views (again with no perspective cues) will not surprisingly show that S3D improves performance on multidimensional spatial tasks, in nearly all cases. But in this experiment, perspective cues were provided, thus the relative benefit provided by the *combination* of motion parallax with stereo disappeared.

Etemadpour, Monson, and Linsen (2013) also studied the presentation of multi-dimensional data in stereoscopic immersive environments. They compared both a 6-wall virtual reality (VR) environment and a 1-wall VR environment with a 2D representation of multi-dimensional data sets. They found that, for local analysis tasks (tasks that focus on a specific part of the visuals, such as distances between individual objects) the stereo immersive environments provided significantly better performance than the 2D presentation, but not for global analysis tasks (tasks that require the user to comprehend the distribution of the data). Interestingly, the study did not reveal a difference in performance between the two immersive environment representations of the data sets.

3. The Bad: When S3D Doesn’t Help

In the previous section, we explored studies and sets of particular tasks in which S3D provided significant performance benefits over 2D viewing conditions. In this section, we take the opposite approach by reviewing and discussing experimental research in which a benefit of S3D failed to appear; in which S3D was clearly no better than 2D. Failure to find a benefit of S3D is considered a “bad” situation in two primary ways: (1) Stereo imagery collection and display require additional software, double the imagery, difficult camera setups, special display hardware, eyeglasses, etc. All this additional effort is for naught if 2D displays can provide for the same level of task performance. (2) Stereo displays also can have an “ugly” aspect in their use, causing eyestrain and fatigue (to be further discussed in Section 4). Again, causing occasional discomfort or eyestrain is essentially pointless if no performance benefits can be evidenced, and so S3D might needlessly hamper usability and performance.

In this section, the reviewed studies relate specifically to spatial cognition and spatial information understanding tasks with possible direct relevance to scientific, information, and data visualization. Similar to the preceding section, the tasks under investigation primarily involved traditional mental rotation tasks, air traffic control airspace judgments, virtual environment interaction and navigation, and network data interpretation tasks. Differences in findings will be contrasted with the previous section where appropriate and possible reasons will be explored.

3.1. Mental Rotation Tasks

Gallimore & Brown (1993) performed a mental-rotation-like matching task, but users could manually control the rotation of virtual CAD objects. They compared S3D versus 2D viewing but found no accuracy or response time differences, suggesting that the addition of stereopsis was not needed as a depth cue for their visualization since the presence of other (monocular) cues was apparently sufficient.

3.2. Air Traffic Control Tasks

Van Orden and Broyles (2000) examined four visuospatial tasks in an air traffic control context, comparing performance on a variety of 2D and 3D formats including stereo and volumetric systems. Volumetric displays are 3D systems that present true light-field images with (nearly) all conceivable spatial cues, though current volumetric systems are generally of poor relative image quality lacking in spatial and temporal resolution, low brightness/contrast, and poor color fidelity. These researchers found that, in no situation, did S3D result is better performance than 2D or volumetric 3D displays. They speculated that the poor performance in the stereo condition may have been due to the lack of veridicality across depth cues (disparity, parallax, and convergence). The lack of a *need* for 3D understanding for most ATC tasks was also questioned by these researchers, who noted that 3D data displays only seemed to help for complex spatial deconfliction tasks within limited volumes. Most other ATC tasks were primarily two-dimensional in nature, they argued, so 3D data displays should only be expected to help on very specific spatial 3D tasks.

Miller and Beaton (1991) also looked at a task involving air space control. They asked participants to judge relative depth positions of objects and extrapolate object motion in 2D and S3D. Performance when using S3D showed very few advantages statistically, although the trend favored stereo across the tasks. S3D cues helped only when coupled with a plan view, and only for the course prediction task. One prominent aspect of their research was the impoverished nature of their stimuli, even in the case of perspective formats. The stimuli were created using computer-generated views assuming an infinite viewing distance and lacking all other depth cues except for the ones under manipulation, resulting in stimuli that appeared highly unrealistic. This may have resulted in a weaker depth percept than might be expected from previous related research. The magnitudes of stereoscopic disparity were also not reported in this work, so it is unclear if sufficiently sized cues were utilized. The authors did speculate that their study may have been underpowered, and that further replications or additional subjects could have supported the use of disparity cues, since the trends seemed to clearly favor S3D (p. 255).

3.3. Navigation, Spatial Comprehension, and Environmental Interaction

Price and colleagues studied the effects of S3D on science learning in children. In Price and Lee (2010), students were presented with three types of spatial tasks (letter rotation, block rotation, and paper folding) both in 2D and S3D, and time and accuracy of responses was recorded. Results showed that accuracy was consistent between the two presentation styles but students took more time performing the task with S3D. When asked about their strategies for performing the tasks in 2D and in S3D, participants claimed that they perceived the stereoscopic images as flat representations and apparently did not utilize the depth cues provided by S3D. Later, Price, Lee, and Malatesta (2014) conducted a study in which children answered spatial and application-based questions about static images of a scientific nature. This time S3D did not significantly change accuracy or speed, but children tended to remember more details about an image if it had been viewed in S3D. These disappointing results at least suggest that S3D may be of utility for more cognitively-demanding (complex) tasks such as recalling spatial details from visual memory. Perhaps this result merely reflects the novelty or stimulating aspects of S3D technology, which of course can be important and engaging in educational settings, especially in regards to children, thus helping in memory formation.

Trindade, Fiolhais, and Almeida (2002) were also interested in the effects of S3D on learning, specifically if S3D could enhance visual-spatial learning based on a person's learning style. Results from their research showed that S3D did not contribute to conceptual understanding in their application, regardless of people's spatial aptitude. Baştanlar, Cantürk, & Karacan (2007) tested object recognition and spatial understanding (memory) within a virtual environment model of a two-story museum. Object recognition was scored by asking participants, after visiting the virtual museum, to identify which objects had been seen in the museum. Spatial understanding was scored by asking participants, after visiting the virtual museum, to distinguish among resembling floor plans. There were no differences in performance between the 2D and S3D viewing groups. Depth cueing from motion parallax (viewpoint motion through the virtual environment) seems to have been sufficient for viewers to perform well in either viewing condition.

Lampton, Gildea, McDonald, & Kolasinski (1996) tested a standard desktop monitor versus two different types of stereo displays (head-mounted displays) for virtual environment usability tasks. Tasks included visual search for target objects, manual spatial-tracking of virtual objects, and locomotion through several virtual environments. No significant differences were found across display devices, presumably because high resolution, wide field of view, or enhanced depth perception was not required for successful task completion. The tasks seemed to always involve large stimuli that were readily visible and whose spatial positioning was obvious, with multiple available cues to support performance.

3.4. Network Readability and Data Interpretability

Alper, Höllerer, Kuchera-Morin, & Forbes (2011) studied the effectiveness of stereo 3D "highlighting" for network graph visualizations, versus a control condition of static highlighting (color). Tasks tested several aspects of graph reading performance, relating primarily to adjacency determinations of target nodes. When comparing non-stereo (2D) highlighting versus stereo (3D) highlighting, there was no main effect of display on accuracy across tasks, nor on response times. The failure of S3D in this case may be due to the fact that the task did not strictly require spatially-precise perception of the graphs.

Lee, MacLachlan, & Wallace (1986) tested graphical data interpretability using 3D scattergram data. They found the S3D presentation to result in faster and more accurate interpretations of the data. However, stereo display of the same data presented in block form (adapted from tabular form) provided no benefit; perhaps due to the non-intuitive nature of displaying such data in this format – as the tested participants were already familiar with such data presented in traditional tabular form.

Interestingly, van schooten, van Dijk, Zudilova-Seinstra, Suinesiaputra, and Reiber (2010) found no performance advantage (time or accuracy) for the addition of S3D in a path-following task when rotation was already available. This is not consistent with previous research that has shown an additive effect of motion and S3D (Sollenberger and Milgram, 1993; Ware and Franck, 1996) and may be attributed to the fact that the task was not as difficult as similar network interpretation tasks, and/or that monocular depth cues (e.g., shading and occlusion) were present in this task, reducing the need or utility of stereo depth cues.

4. The Ugly: When S3D Hurts

In this section, we review and discuss the "ugly" dark side of stereoscopic imaging and display: viewer discomfort, eyestrain, and fatigue effects caused by S3D viewing. The prevalence of S3D viewer discomfort appears to be alarmingly high. Previous independent research with large public surveys and/or observational studies had suggested as many as 25-50% of viewers find S3D uncomfortable or straining, or otherwise report eyestrain and fatigue-related symptoms (AOA.org, 2010; Wilkinson, 2011; Solimini, 2013). A more recent large-scale study with proper experimental control suggests that the true prevalence rate is probably lower than previously believed, but still relatively high (Read & Bohr, 2014). Specifically, 14% of viewers experience adverse effects (primarily headache and eyestrain) from S3D viewing itself; while a further 8% of people seem to report discomfort either due to the eyewear (3D glasses) and/or due to negative expectations akin to *self-fulfilling prophesies* and the *nocebo effect* (Read & Bohr, 2014). Whatever the exact prevalence rate (likely somewhere around 15-25% of the general population), we know that eyestrain, fatigue, and discomfort effects from S3D display viewing are serious human factors concerns that can adversely affect training, usability, and the ultimate utility of such systems, and so must be taken seriously by the visualization and analytics communities.

Some recent and thorough reviews of this topic are available from the following works, listed in alphabetical order: Bando, Iijima, & Yano (2012); Howarth (2011); Kim, Yoo, & Seo (2013); Lambooij, IJsselsteijn, & Heynderickx (2007); Lambooij, IJsselsteijn, Fortuin, & Heynderickx (2009); Lambooij, Fortuin, IJsellsteijn, Evans, & Heynderickx (2010); Mikšícek (2006); Tam, Speranza, Yano, Shimono, & Ono (2011); Urvoy, Barkowsky, & Le Callet (2013). The exact causes of eyestrain and fatigue effects from S3D viewing are not entirely clear, but primary contributors are:

- Vergence-Accommodation (focus-fixation) conflict and excessive vergence demands (e.g., Kim, Kane, & Banks, 2012)
- Motion, especially motion-in-depth (e.g., Ukai & Howarth, 2008)
- Crosstalk; image leakage from one eye's channel to the other (Woods, 2013)
- Misalignment or imperfections in stereopairs, contributing to binocular rivalry (Kooi & Toet, 2004)
- Spatial imaging and/or display distortions (e.g., Woods, Docherty, & Koch, 1993)
- Other perceptual or cognitive conflicts, including motion parallax conflict, frame/boundary violations, high-level violations of our intuitive understanding of reality, etc. (e.g., Patterson, 2009; Patterson & Silzars, 2009)

In terms of discomfort mitigation, one possibility mentioned by the stereo imaging and display communities is to use a fixed "disparity bracket" or "depth budget," which effectively controls vergence demands (and focus-fixation conflicts) so that human comfort or tolerance levels are not exceeded (e.g., Kytö, Hakala, Oittinen, & Häkkinen, 2012). This concept is sometimes referred to as the *One-Degree Rule*, and is based upon previous human factors research showing that limiting binocular disparity to no more than +/-1 degree of arc relative to the screen distance permits comfortable viewing for most people, most of the time (e.g., Wöpking, 1995; Shibata, Kim, Hoffman, & Banks, 2011).

A similar idea is to use real or virtual stereo camera separations that are unrealistically small (smaller than human interpupillary distances) so that only small amounts of binocular disparity are presented to a viewer. This is the concept of *microstereopsis*, or what Siegel and colleagues referred to as "good enough 3D" and "kinder, gentler stereo" (Siegel, 1999; Siegel, Tobinaga, & Akiya, 1999; Siegel & Nagata, 2000). Their preliminary work on microstereo suggests that it does indeed result in a more comfortable depth percept, but recent experimental work by McIntire (2014) suggests that while microstereo is advantageous over no stereo (2D), orthostereoscopic or near-orthostereoscopic levels of camera separation are even better, and so are recommended for critical and high precision depth-related spatial tasks (see also McIntire, Havig, Harrington, Wright, Watamaniuk, & Heft, *under review*).

In any case, viewer discomfort on S3D display systems is a complex human factors problem that admits to no one single, all-encompassing, sweeping solution; thus, this issue may demand unavoidable trade-offs in terms of imaging, display and system design, and usability. Perhaps most importantly, for the data and information visualization community interested in the use of S3D, the primary question to ask is whether gains in performance and understanding can outweigh the costs of viewer discomfort that might possibly be incurred. This question may require a task-specific, application-specific, or even viewer-specific answer.

A final human factors concern to keep in mind is that even viewers who possess clinically-normal binocular and stereoscopic vision may not receive the expected performance benefit from S3D cues (McIntire, Havig, Harrington, Wright, Watamaniuk, & Heft, 2014); at least not in the way or with the consistency that color-cueing or color-coding can be expected to help viewers with normal color vision, or similar related visual-coding attributes for perception. Although the focus-fixation conflict, as already discussed, may be a contributing issue to high individual variability in S3D task performance, other less-well-known issues in the vision science literature that may contribute to this problem include *pseudo-stereoanomaly* (e.g., Fujisaki, Yamashita, Kihara, & Ohtsuka, 2012; Kihara, Fujisaki, Ohtsuka, Miyaho, Shimamura, Arai, & Taniguchi, 2013) and perhaps *stereoanomaly* (e.g., Richards, 1971). What these concerns suggest is that much more research may be required to fully characterize human visual depth perception in regards to 3D display technologies. Until a better understanding is obtained, visualization and visual analytics researchers, designers, and engineers may need to approach these technologies with some caution in implementing their 3D applications.

5. Discussion, Conclusions, & Recommendations

The experimental studies reviewed in this work might initially appear to provide a mixed picture, with some number of studies supporting the use of S3D for information and data visualization; but numerous other studies suggesting the exact opposite. However, a clearer understanding might be gained by considering the specific results found in our previous reviews, upon which this work was primarily based (McIntire, Havig, & Geiselman, 2012/2014). We had found that for the task category relating to spatial comprehension and understanding, as discussed herein, 52% of experiments showed a clear benefit of S3D, a further 24% of experiments showed a mixed or unclear benefit of S3D, and only the remaining 24% of experiments clearly showed no benefit of S3D over 2D control conditions. Similar (or even better) magnitudes of S3D benefits were found in other task categories that may also be relevant to data and information visualization applications, including precise spatial localization of objects (judging absolute and/or relative positions or distances), complex imagery analysis (finding, identifying, or classifying objects or imagery types), and manually interacting with data or virtual information (performing spatial manipulations).

This review was also able to demonstrate, importantly, that S3D can provide performance benefits *which seem to reflect cognitive benefits*, providing for an increased understanding of spatial and/or multidimensional data. For instance, S3D provides a clear benefit to users for mental rotation tasks that involve using the visual sense to study and conceptualize spatial objects, imagery, or environments. S3D also seemed to help for understanding spatial relationships among objects within a complex 3D scene (i.e., for many air traffic control type tasks, or memory for complex imagery like forest scenes).

Where we see a failure of S3D to provide clear and consistent performance benefits is in tasks in which additional depth cues may not be needed (there are already sufficient and high-quality monocular depth cues present); tasks that are simple, easy, or already well-learned; or tasks in which depth information is not vital or perhaps not even useful for successful task completion (not strictly a spatial or multi-dimensional task). These “failures” of S3D can be exacerbated by the presence of viewer discomfort, leading many researchers to rightfully question whether the utility of S3D can ever be considered advantageous enough to overcome both the “bad” and “ugly” sides of S3D. We hope the review presented herein makes clear the specific and strong advantages that S3D can provide for some data and information visualization types of tasks, while straightforwardly acknowledging the human factors and technological limitations that exist in modern 3D visualization systems.

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