IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received September 9, 2016, accepted October 19, 2016, date of publication October 31, 2016,
date of current version November 28, 2016.

Digital Object Identifier 10.1109/ACCESS.2016.2623277

The Nature, Antecedents, and Impacts of Visuo-Spatial Mental Models of Web Interface Design

DANIEL S. SOPER AND SINJINI MITRA
Department of Information Systems and Decision Sciences, Mihaylo College of Business and Economics,
California State University, Fullerton, Fullerton, CA 92831, USA

Corresponding author: D. S. Soper (dsoper@fullerton.edu)

ABSTRACT This paper develops an integrated theoretical framework that links visuo-spatial mental models of Web interface design to user satisfaction, and reports on a controlled experiment aimed at investigating the nature of these mental models. Using data from more than 500 subjects in conjunction with both graphical and statistical analyses, we find that Web users possess a strongly cohesive shared mental model of the way in which a Web interface should be designed. In addition to describing and quantifying this shared visuo-spatial mental model, this paper also shows how both experience and the physiological properties of the human visual system give rise to such models, and discusses the implications of the results for organizational website design, scientific theory, and future research in this area.

INDEX TERMS User interfaces, human computer interaction, cognitive science, mental models.

I. INTRODUCTION

The World Wide Web is now comprised of more than one billion unique websites [1]. Given the sheer magnitude of this array, it is clear that only a tiny fraction of the world's websites have been designed or vetted by specialized professionals before being released to the public. In fact, and as noted by digital pioneer Alan Kay, "the web was done by amateurs" [2]. Individuals and small- and medium-sized enterprises often simply do not have or are unwilling to allocate sufficient resources to procure professional website design, development, and testing services. As a consequence, many organizations rely on HiPPOs (i.e., the Highest Paid Person's Opinion) when making web interface design decisions [3]. Although the acronym 'HiPPO' suggests a certain degree of sardonic whimsy, relying on HiPPOs in the context of interface design can have serious implications with respect to user satisfaction.

Almost everyone has had the occasional experience of interacting with a website that seems to be poorly designed or difficult to use. Text may be difficult to read due to poorly chosen colors or fonts, navigation may be challenging or unintuitive, advertisements may interfere with the user experience, or perhaps specific content or features may be difficult to locate. Regardless of the reasons for our discomfort – and regardless of whether we are consciously aware of these reasons – something simply feels "wrong" about the design of certain websites. The cognitive dissonance or discomfort that we feel at these times can, of course, have important negative consequences for organizations that publish and maintain such websites [4]. Users, for example, can become frustrated [5], can become disloyal or lose trust in the publisher [6], or can find their general opinions of the underlying organization declining [7]. A poorly designed or otherwise problematic website can therefore cause organizations not only to lose potential customers and their attendant revenues, but can also cause the organization to suffer losses in reputation and customer goodwill. Every sensible executive should therefore be highly interested in ensuring that the design of his or her organization's website engenders as much user satisfaction as possible. As most people can attest from personal experience, however, many organizational websites fall far short of this goal.

The question of why certain websites seem to be poorly designed is a daunting one, and answering that question in its entirety necessarily requires a multifaceted approach. To begin, one must define precisely what is meant by "website design". Depending upon the context, "website design" might alternately refer to a web designer's choice of colors, fonts, or multimedia elements (such as icons or images), the ease with which the website can be navigated,

2169-3536 © 2016 IEEE. Translations and content mining are permitted for academic research only.
Personal use is also permitted, but republication/redistribution requires IEEE permission.
See http://www.ieee.org/publications_standards/publications/rights/index.html for more information.

or the layout, arrangement, or consistency of the web interface [8]. Studies seeking to identify the factors that lead to positive user perceptions of website design must therefore carefully define their scope of inquiry. In that spirit – and acknowledging that we certainly do not dismiss the relevance of typography, color, or navigability – our efforts here are specifically constrained to the way in which the various elements that together comprise a web interface should be properly arranged in order to positively influence user expectations and user satisfaction. For this purpose we draw heavily on both cognitive science and research into the physiology of human vision, and place at the core of our investigation a key concept that resides at the intersection of these two areas of inquiry – that of a *visuo-spatial mental model*.

Generally speaking, a mental model is an internal representation of some aspect of the real world [9], [10]. As we navigate through life, our minds distill all of our encounters and experiences into an ever-growing and ever-evolving series of mental models, and we rely upon these models to guide our reasoning, decision-making, behavior, and to help us form expectations about the world around us. Since the human brain constructs and refines mental models automatically and often without conscious effort, our minds are filled with an almost unimaginable number of these models. Research in this area has also concluded that the human brain generates several different varieties of mental models [11], [12]. First among these are visuo-spatial mental models, which represent relations that are easily envisaged both visually and spatially (e.g., ''the painting *is above* the fireplace''). Second are visual mental models, which reflect relations that are easy to visualize, but are difficult to envisage spatially (e.g., ''the plate *is dirtier than* the cup''). Third are abstract (or *control*) mental models, which reflect relations that are difficult to envisage either spatially or visually (e.g., ''Jennifer *is smarter than* Ali'').

In the current paper we focus on visuo-spatial relations, and we anticipate that most people are very familiar with this particular type of mental model. If a person knows, for example, how to type without looking at her keyboard, or can use her television's remote control without looking at the buttons, it is because her mind has constructed visuo-spatial mental models of the layout of those devices. If a person can find the light switch in her bedroom in the dark, or can make her way to her favorite restaurant without consulting a map, it is because her mind has built visuo-spatial mental models to assist her. Furthermore, it is important to note that many of our visuo-spatial mental models are not exclusively our own, but instead largely overlap with those of other people. Consider, for example, the chaos which would ensue if drivers did not possess a shared mental model of the rules of the road!

Although we may not be consciously aware of it, each of us who has used the web has also developed a visuo-spatial mental model of what to us constitutes ''good'' web interface design (i.e., an arrangement of interface elements that seems intuitive and natural, and is hence satisfying to the user). We simply cannot help it – the human brain constructs these models automatically. Unfortunately no theoretical framework currently exists that links mental models of web interfaces to user satisfaction, the result of which is to confound and impede research that addresses these phenomena. Further, the nature of people's mental models of web interface design is not currently well-understood, and this too has impeded efforts aimed at disentangling the ways in which mental models ultimately influence user satisfaction. In an effort to resolve these outstanding issues, the current paper seeks to (1) develop an integrated theoretical framework that speaks to both the antecedents and the consequences of visuo-spatial mental models of web interface design, (2) elucidate and describe the fundamental nature of visuo-spatial mental models of web interface design, and (3) establish whether and to what extent people possess a general, shared mental model of ''good'' web interface design. By addressing these three objectives the current paper provides managers, web designers, and researchers alike with powerful insights that not only speak to the nature and formation of mental models of web interface design, but that also reveal the ways in which such mental models influence user satisfaction, and, ultimately, an organization's long-term prospects for success.

II. AN INTEGRATED THEORETICAL FRAMEWORK

One of the core axioms of mental models theory is that the human brain relies on mental models as a basis for formulating expectations about the world [13]. Expectations, in turn, are posited by expectation confirmation theory to exert a strong influence on user satisfaction by means of mediational relationships with performance perceptions and disconfirmation of beliefs [14], [15]. In the context of web interface design assessments, expectations speak to the quality of the interface experience that a user believes a web interface should afford. These expectations, of course, are formed and present in the user's mind before she first encounters the web interface under consideration. Performance perceptions, by contrast, refer to a user's perceptions of the actual design and performance of a web interface, and are formed as the user sees, interacts with, and experiences the interface itself. Finally, disconfirmation of beliefs refers to the user's judgment about the extent to which the quality of the actual web interface accords with her expectations. If the quality of the actual web interface exceeds the user's initial expectations, then she will be more satisfied than she otherwise would have been if the quality of the actual interface had been judged to fall short of her expectations.

As an illustrative example of these theoretical relationships, consider a typical web user who is visiting a randomly chosen website for the first time. According to mental models theory, the user's expectations with respect to the design of the website's interface will be based on her general mental model of web interface design. Upon arriving at the new website, the user's mind will immediately – and often unconsciously – begin to compare the actual design of the new website's interface against her expectations. If the design of the actual interface conforms with or exceeds the user's original expectations, then, *ceteris paribus*, the user will be much more satisfied with the website than she otherwise would have been if the actual interface design had aligned poorly with her expectations. As is evident from this example, it is the user's expectations that serve as a theoretical bridge interconnecting the tenets of mental models theory with those of expectation confirmation theory.

Given the central role played by mental models in the formation of expectations, it is important to consider the factors that precipitate the construction and refinement of these mental models. According to mental models theory, one of the most critical factors that influences mental model formation is experience [11]. In the context of visuo-spatial mental models, a person's past experiences interacting with web interfaces (or closely related activities) can therefore be expected to strongly influence the nature of her mental model of web design. Other forms of indirect experience – such as reading about web interface design – can also be expected to influence the nature of the user's mental model. In the aggregate each user's experiences on the web are unique (in terms of websites visited, time spent interacting with each website, etc.), and as such a certain degree of variation should be expected among users' visuo-spatial mental models of web design. Nevertheless, billions of people also spend a great deal of time interacting with a relatively small number of prominent websites (such as Google, YouTube, Facebook, etc.), and these shared experiences can be expected to generate a certain degree of overlap among users' visuo-spatial mental models of web design. The nature of these mental models and the extent to which people possess a shared mental model of web interface design are, however, currently unknown.

Although experience undoubtedly exerts a powerful influence on the formation and refinement of visuo-spatial mental models, it is important to note that experience is not the only substantive factor that affects mental models in the context of web design. On the contrary, a growing body of literature suggests that the formation of mental models can also be strongly influenced by the physiological properties of the human body. Consider, for example, a mental model of how to use a keyboard or a computer mouse. Experience with these interface devices naturally engenders the formation of appropriate mental models. It is, however, critical to realize that the design of a keyboard or a mouse is strongly linked to the physiological properties of the human hand. If the human hand were twice as large or contained a different number of fingers, the design of a keyboard or computer mouse would be radically different, yielding corresponding differences in their associated mental models. In this way, the physiology of the human body can be clearly seen to influence the formation and nature of certain mental models.

Just as the designs of devices such as keyboards and computer mice are influenced by the physiological characteristics of the human hand, so too is the design of web interfaces influenced by the physiological characteristics of human vision. When light enters the eye it is focused by the cornea and the anterior lens [16], after which it is projected onto the retina. These retinal cells subsequently convert the incoming image into a series of electrical signals, which are then transmitted to the visual cortex in the brain by means of the optic nerves, thus allowing a person to see [17]. Near the center of the retina is an area known as the fovea, and it is this area that is responsible for providing us with the capacity for fine vision. The position and size of the fovea, however, mean that human beings can only see things with a high level of detail if they are located in the center of one's visual field. As items move from the center to the periphery of our visual field, we experience a sharp decline in both visual acuity and spatial resolution [18]. This is why, for example, if you turn your head to the left or to the right, you will find it very difficult to read this page out of your peripheral vision. Beginning in infancy, this simple physiological truth engenders a natural tendency to bring whatever it is at which we are looking into the center of our field of vision. Indeed, it has been well-established that the human brain contains specialized structures that allow a person to rapidly orient the movements of her head and eyes in order to bring objects of attention into the center of the visual field [19]–[21].

If we step back for a moment from website design and consider other forms of visual media such as paintings, photographs, television, or movies, we will soon perceive a common pattern – namely, that the subject or object of interest is typically located in the center of the composition, thus allowing the subject or object of interest to be observed with a maximal degree of visual acuity. The main content of a webpage is, of course, also typically intended to be the primary focus of the user's attention. If the innate physiological capabilities and constraints of the human visual system do indeed influence visuo-spatial mental model formation, then we should expect to find that the primary content of a webpage is centrally located in people's mental models of web interface design. Other ostensibly less important interface elements can be expected to be relegated to the periphery of the web interface, where, with a glance of the eye or a turn of the head, they can be brought into the user's central vision on a temporary, as-needed basis. By integrating mental models theory, expectation confirmation theory, and knowledge about the physiological capabilities and constraints of human vision, we can thus derive a comprehensive theoretical model that depicts both the antecedents of visuo-spatial mental models of web interface design, as well as the mechanisms through which those mental models subsequently influence user satisfaction. This theoretical model is shown in Figure 1 below.

III. IDENTIFYING AND STUDYING VISUO-SPATIAL MENTAL MODELS

While every web user has a visuo-spatial model of how websites should be designed, we still face two sizeable challenges if we want to describe and analyze those models. First, mental models are often tacit and hence difficult for people to articulate or describe [22]. In light of this situation, how can we

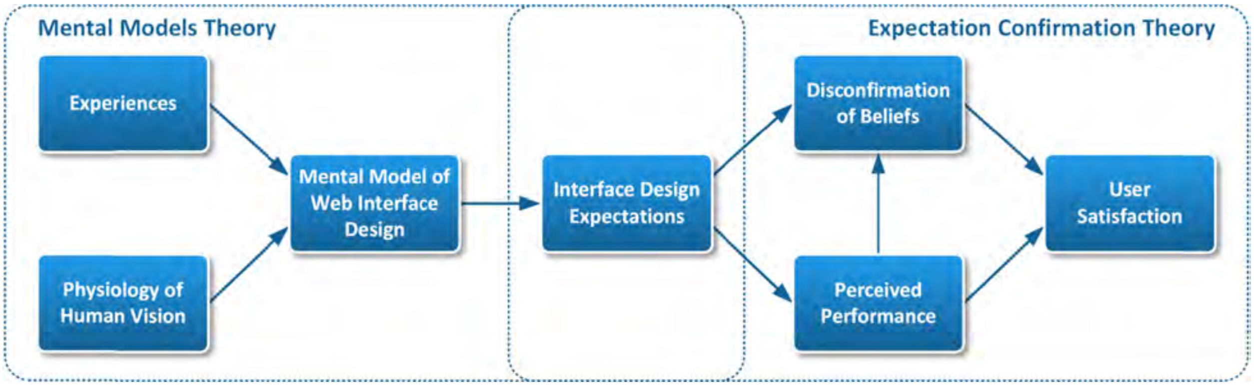

FIGURE 1. Theoretical model of the antecedents and impacts of mental models of web interface design.

peek inside web users' minds and extract the information that we need? Second, how can we combine the mental models from many different individuals to produce a general scientific conceptualization of visuo-spatial website design that can be subjected to systematic evaluation and exploration? To begin to address these challenges, we first need to consider the visual and spatial nature of web interfaces.

A. A GEOMETRIC ORIENTATION

From a cognitive perspective, interacting with or experiencing a web interface is largely a visual and spatial process. This is evident from the fact that web interfaces are composed of visual elements – such as text and images – that have measurable spatial relationships with one another (e.g., "the title is located above the content", "the advertisement is located to the right of the content", etc.). Since websites meant for human consumption are currently rendered on a flat, two-dimensional surface (i.e., a display screen), Euclidean geometry provides a natural framework for studying web interface layouts. Adopting a Euclidian approach also provides access to myriad geometric concepts – including coordinate axes, spatial locations, distance, and direction – that can be usefully leveraged to describe the arrangement of the elements that comprise a web interface. Further, the visuo-spatial structure of web interface mental models imparts an intuitive understanding of the geometric nature of website design, and leads users to unconsciously construct mental models of web interfaces that have strong roots in geometric relationships. Consider, for example, your answer to the following question: *Where should the navigation menu appear on a web page?* If you happen to be like most people in the western world, you probably believe that navigation menus should appear toward the top of the page on the left side, or perhaps a bit to the left of center. If we think more deeply about this reply it becomes evident that terms such as "top", "left side", and "left of center" are all points of reference in a two-dimensional geometric space (i.e., a Euclidean plane). When considering the question above, your mind immediately consulted a two-dimensional visualization of a web page – your mental model of a web interface – and identified where in the geometric space the navigation menu was most likely to appear. In recognition of the strong geometric nature of visuo-spatial mental models of website design, we developed what we call the "blank screen method" as an experimental mechanism for gathering data about such models.

B. THE BLANK SCREEN METHOD

The blank screen method is an approach that researchers and web designers can use to overcome the challenges associated with eliciting and describing users' visuo-spatial models of interface design. The method involves presenting research subjects with an image of an empty display screen, and then asking them to click on the screen at the point where they would expect a given interface element to appear. This simple interactive process is repeated for a series of interface elements, with the geometric coordinates of the selected location being recorded each time. At the conclusion of this process, the researchers will possess a set of (x, y) coordinate points, each of which represents the subject's best judgment of where a specific interface element should appear on a web interface. Together, the collection of point coordinates gathered from a research subject represents the subject's overall mental model of how an interface should be designed. Repeating the process for many subjects yields a collection of (x, y) coordinates for each interface element, and these points can be combined to produce a dataset that is amenable to exploration and study using established graphical and statistical techniques.

For the current study, we designed a web-based software system to perform the tasks described above. After collecting demographic data (age, gender, and level of web experience), the system asked subjects to identify the most likely screen locations for nine distinct web interface elements, namely: an advertisement, a copyright notice, a corporate logo, a login/logout feature, a navigation menu, a search box, the text content of the page, the page title, and the page's video content. The order in which these interface elements were presented was randomized for each subject to mitigate the possibility of any ordering or self-generated validity effects [23]. The system also asked subjects to verify their selected screen location before proceeding to the next interface element in order to ensure that the data gathered were of high quality. With a view toward eliciting responses that were as general as possible, we intentionally avoided asking subjects to consider any specific type of website during the experiment. This was an important methodological decision because the human brain's proclivity to construct mental models suggests that experienced web users likely possess sub-models for many different types or categories of websites. Since a major goal of the investigation was to elicit the general properties of visuo-spatial models of web design, it was necessary to avoid priming or prompting subjects by asking them to consider any particular type of website. A screenshot of our software system is shown in Figure 2.

C. RESEARCH SUBJECTS, DATA, AND ANALYSIS

The target population for our investigation was English-speaking adult web users, and to that end we engaged the leading online marketing firm to craft a targeted advertising campaign for the purpose of soliciting volunteers for the research study. It is important to note that the firm's advanced technology afforded the capability to constrain recruitment exclusively to subjects within the target population. It is also important to note that the firm's advertising network extends across millions of different websites, with the size, location, and colors of the advertisements being chosen by each website's publisher. With such a wide variety of websites, advertisement sizes, colors, etc., we believe it is unlikely that the structural properties of the advertisements themselves introduced any bias into the study with respect to the composition of the subject pool. IP address restrictions were also enforced to prevent the same person from participating in the study more than once. In total, our campaign attracted 533 subjects, of whom 47.8% were male and 52.2% were female. Subjects reported an average level of web experience of 3.84 on a five-point Likert-type scale (anchored at *1 = very little experience* and *5 = extensive experience*). Subjects ranged in age from 18 to 78 years. The average age was 32.9 years with an interquartile range of 25 to 37 years, indicating an age distribution skewed in the direction of youth. These values were consistent with overall Internet usage demographics among adults in the United States [24].

As noted previously, the primary data for the study were a series of (x, y) coordinates, each of which represented the screen location at which a subject indicated that he or she would expect a given web interface element to appear. With 9 distinct interface elements and 533 subjects, we collected a total of 4,797 coordinate points. Analysis of these coordinate points and the underlying visuo-spatial mental models that they represent was carried out using both graphical and statistical techniques. Since human beings are highly visual creatures, we began by transforming the coordinate points into a thermal image or "heat map" of each website element included in the study [25]. These heat maps embrace the same principle as infrared thermal imaging, but instead of using different colors to show variations in temperature, they instead show the relative density of user clicks on different areas of the display screen, with "hotter" areas indicating greater density. The images which resulted from this process serve as graphical representations of people's general mental models of web interface design, and are both fascinating and deeply insightful. Before discussing these heat maps, however, it remains for us to describe the statistical methods that were used in conjunction with the visual analysis.

The statistical methods used for analyzing the mental models data can be broadly divided into two categories: (1) clustering methods, and (2) exploratory methods. Regarding the first of these categories, hierarchical clustering was used to identify clusters within the data for each of the webpage elements in the study, as well as to evaluate the degree of cohesion therein [26]. More specifically, average linkage-based hierarchical clustering was used due to its ability to automatically quantify the optimal number of clusters for each interface element. This approach not only provided insight into the most common locations selected by subjects for the various interface elements, but also served as a statistical basis for examining subject expectations about centrally vs. peripherally located elements. With this information, we were able to perform both inter-element comparisons and an assessment of the extent to which a general, overall visuo-spatial model of web interface design exists among web users.

Regarding the second of these categories, the objective of the exploratory methods was to determine whether statistically significant differences were present in the locations of the various web elements according to a subject's age, gender, or level of web experience. For this purpose we employed multivariate analyses of variance (MANOVA) using the (x, y) coordinates of each interface element as dependent variables and the study's demographic variables (age, gender, and level of web experience) as independent variables. In order to accommodate the requirements of the MANOVA framework, subjects were assigned into one of four different age categories (18-29 years, 30-44 years, 45-59 years, and 60 or above). Together, these statistical analyses provided a deeper understanding of people's mental models of web design than could otherwise be gained through visualization alone.

IV. FINDINGS AND DISCUSSION

It has often been remarked that a picture is worth a thousand words, and in that spirit we begin the presentation of our findings with Figure 3 below, which contains heat maps depicting people's visuo-spatial mental models of the locations of the interface elements investigated in the study.

Each of the heat maps above depicts the relative density of clicks obtained from the research subjects for its corresponding interface element. In examining these heat maps, we were immediately struck by two phenomena. First, recalling that the heat maps were generated from the responses of more than 500 web users, there appears to be a remarkable degree of similarity among people's visuo-spatial models of website layout. Put another way, there appears to be comparatively little variability from one person to the next regarding

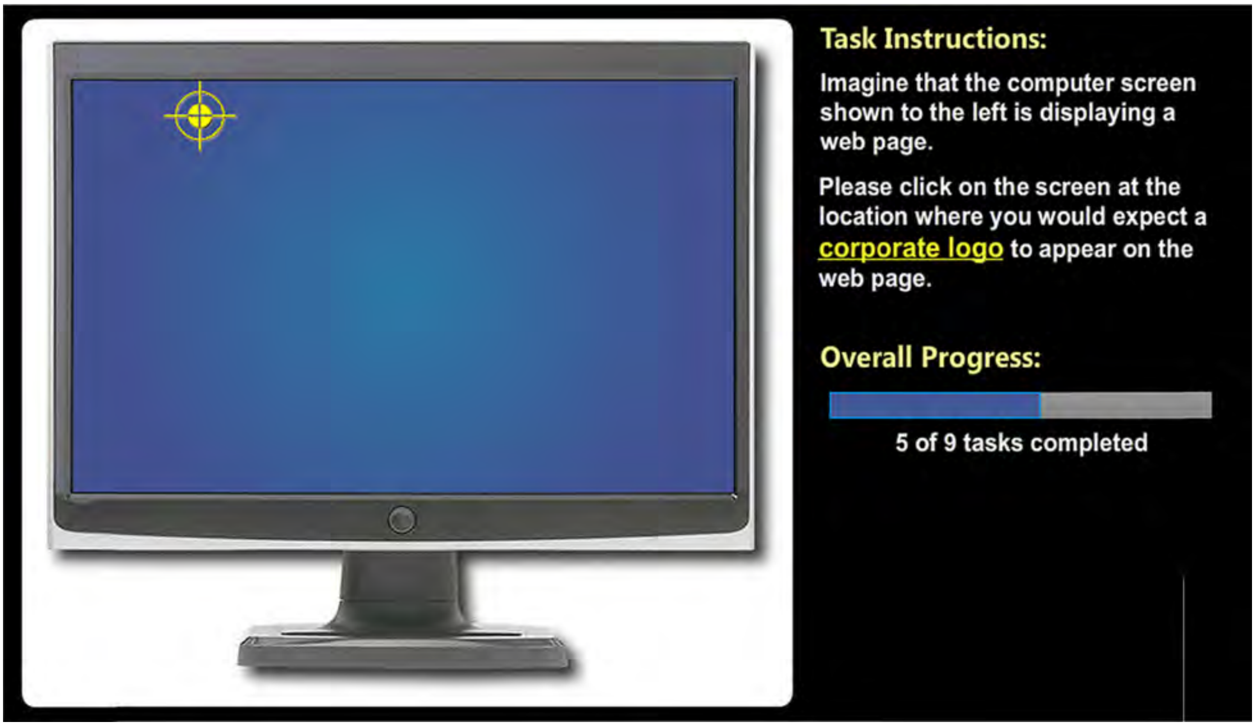

FIGURE 2. Screenshot illustrating the Blank Screen Method.

expectations about where interface elements should ideally appear. On the contrary, web users seem to expect to find each interface element in one of only a very small number of locations on a web page. Second, the heat maps show that each interface element appears to have one cluster which is strongly dominant over any others. In light of the wide diversity in age, gender, and web experience of the subjects who participated in the study, this degree of cohesion seems quite extraordinary. These results provided strong preliminary evidence for the existence of a general, shared mental model among web users.

A. CLUSTER ANALYSIS

Although the heat maps shown in Figure 3 suggest that people's mental models of web interface design are reasonably consistent and cohesive from person to person, it was necessary to perform a cluster analysis on the data in order to properly quantify the apparent consistency and cohesiveness. Table 1 thus reports the number of major clusters for each web interface element as obtained using average linkage-based hierarchical clustering [26]. The table also provides the number and percentage of observations in each cluster, as well as the centroid coordinates of each cluster (as proportions of the width and height of the display screen).

As suggested by the heat maps, the results of the cluster analysis confirm that each web interface element contains a very small number of clusters, and with the exception of the login/logout feature each interface element has one cluster that clearly dominates the others. When considered together, we believe that these results provide strong evidence of the presence of a shared visuo-spatial model of web interface design among web users, and that this shared model can be characterized using the centroids of the dominant clusters for each interface element. By defining the shared mental model in this way, it became possible to compute the Euclidean distance between each subject's personal mental model and the proposed shared mental model. Since, generally speaking, mental models are often formed and refined on the basis of direct experience, and given that each person's experiences with the web are, in the aggregate, unique, each person's visuo-spatial mental model should be expected to diverge somewhat from a standard reference model. The relevant issue, then, is the extent of such divergence. We therefore calculated the Euclidean distance between the locations selected by subjects for each web interface element and the centroid of that element's corresponding dominant cluster. After performing all of these calculations, we determined that in terms of the size of the display screen, each individual's mental model of web interface design varied from the reference model by an average of only 1.85%. This degree of proximity provides powerful evidence for the presence of a general, shared mental model of interface design among web users.

B. STATISTICAL ANALYSIS

We next undertook a statistical analysis of the data using MANOVA [27]. Initial omnibus tests revealed that significant differences were present according to a web user's gender ($\lambda = 0.942$, $F = 1.740$, $p < 0.05$), age ($\lambda = 0.930$, $F = 2.126$, $p < 0.01$), and level of experience ($\lambda = 0.945$, $F = 1.661$, $p < 0.05$). Eta-squared (η^2) effect sizes for the

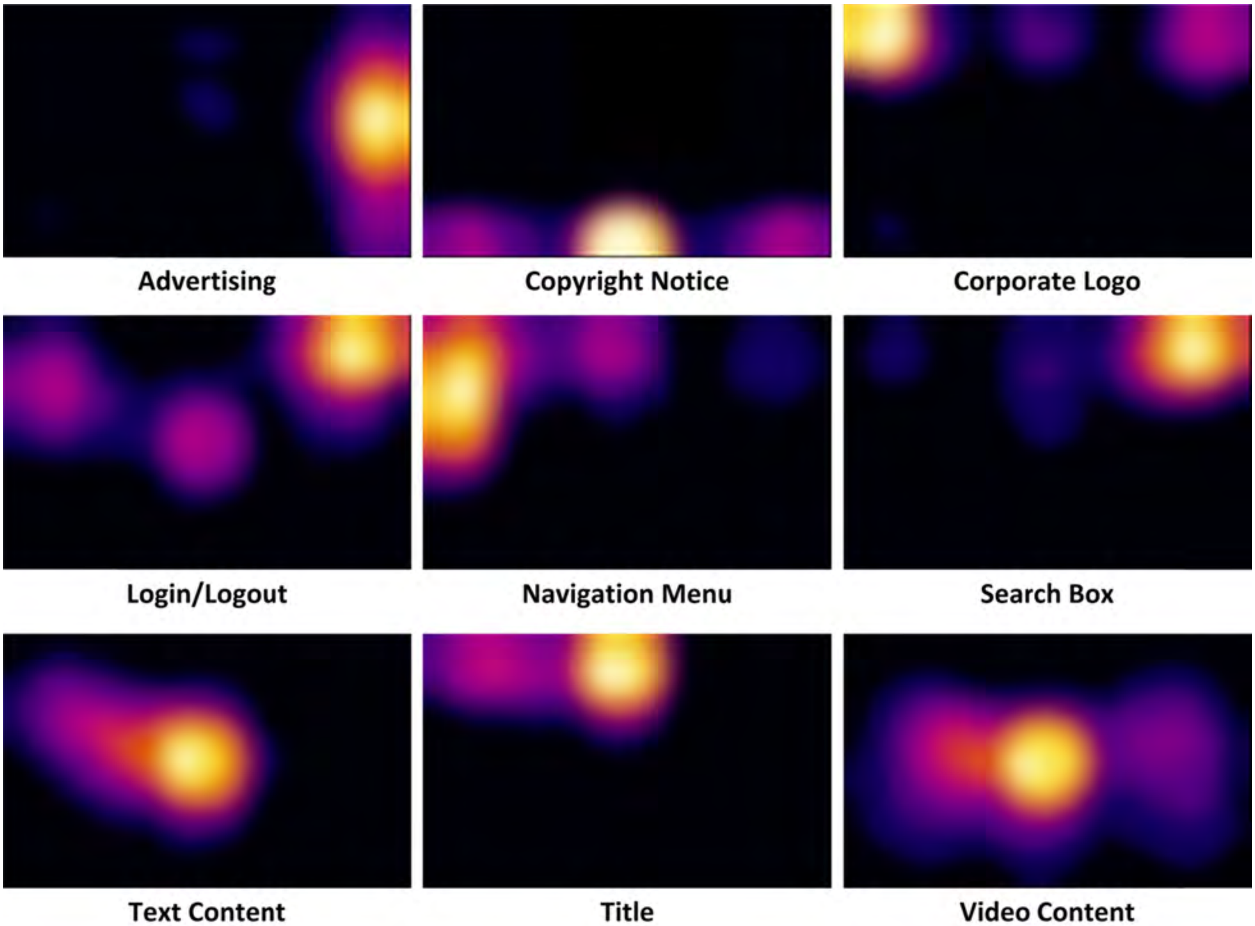

FIGURE 3. Heat maps depicting mental models of website design.

observed differences in expectations about interface element locations according to a subject's gender, age, and level of experience were 0.058, 0.069, and 0.055, respectively, indicating that the observed effects, though significant, were quite small. Nevertheless, the significance of the observed effects called for a more granular investigation. Further analyses were hence duly undertaken, the results of which are depicted in Figure 4 below.

As shown in the figure, only the location of video content varied significantly by gender, revealing that men and women have slightly different perceptions regarding where video content is expected to appear on a web page. Specifically, in terms of the width and height of the display screen, women tend to expect video content to appear approximately 3.5% to the left and 4.3% lower on the screen than do men. With respect to age, significant differences were detected in the locations of a web page's text content and navigation menu. These differences were revealed to be almost entirely attributable to the expectations of the older subjects in the study. Those subjects who were at least 60 years old expected a web page's text content to appear approximately 7.4% of the screen height closer to the top than younger web users. These older subjects also expected the navigation menu to appear approximately 9.2% of the screen width farther to the right and 10.5% of the screen height closer to the top when compared to younger web users. Finally, the expected locations of an advertisement, a login/logout feature, and the navigation menu varied significantly according to a user's level of web experience. These differences were due almost entirely to the expectations of the least experienced web users. Again in terms of the width and height of the display screen, the least experienced users expected advertisements to appear approximately 7.9% farther to the left and 3.9% higher than a user of average experience. Notably, the least experienced users also expected the login/logout feature to appear 54.1% farther to the left and 9.9% higher than a typical web user, while expecting the navigation menu to appear 65.9% farther to the right and 9.3% higher on the screen. In congruence with mental models theory, these observations suggest that visuo-spatial mental models of web interface design evolve over time as users accumulate more experience.

C. HUMAN VISUAL PHYSIOLOGY AND WEB INTERFACE DESIGN

Although exploring the minutiae of the individual elements which together comprise a visuo-spatial mental model of web

TABLE 1. Cluster analysis of web interface mental models data.

Interface Element	Clusters	Cluster	Observations (%)	Centroid (x, y)
Advertising	3	1	413 (78%)	(0.912, 0.502)
		2	76 (14%)	(0.491, 0.440)
		3	44 (8%)	(0.093, 0.600)
Copyright Notice	3	1	392 (74%)	(0.395, 0.955)
		2	128 (24%)	(0.844, 0.824)
		3	13 (2%)	(0.199, 0.309)
Corporate Logo	2	1	330 (62%)	(0.112, 0.199)
		2	203 (38%)	(0.775, 0.229)
Login/Logout	2	1	279 (52%)	(0.855, 0.163)
		2	254 (48%)	(0.315, 0.372)
Navigation Menu	3	1	475 (89%)	(0.186, 0.258)
		2	50 (9%)	(0.872, 0.268)
		3	8 (2%)	(0.166, 0.940)
Search Box	2	1	524 (98%)	(0.728, 0.163)
		2	9 (2%)	(0.081, 0.852)
Text Content	2	1	512 (96%)	(0.375, 0.454)
		2	21 (4%)	(0.790, 0.403)
Title	2	1	517 (97%)	(0.369, 0.135)
		2	16 (3%)	(0.791, 0.337)
Video Content	3	1	256 (48%)	(0.518, 0.285)
		2	165 (31%)	(0.236, 0.483)
		3	112 (21%)	(0.819, 0.526)

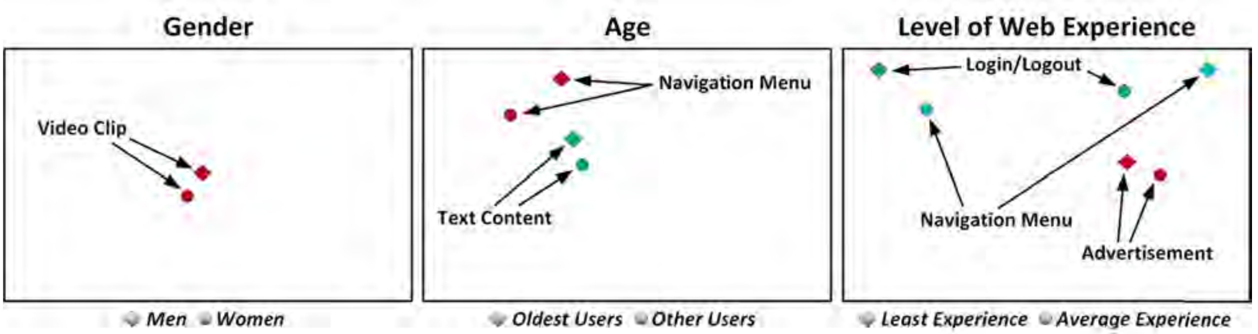

FIGURE 4. Demographic differences in interface element location expectations.

interface design can certainly yield interesting insights, it was also important to consider the influence of human visual physiology on the nature of the general, shared mental model described above. As noted previously, the physiological capabilities and constraints of the human visual system imply that the primary content of a webpage should be centrally located in a user's mental model of web interface design, with the locations of less important visual interface elements being relegated to the periphery. With a view toward assessing this prediction, we merged all of the data gathered in the study into two large bins – one containing elements which comprise a web page's primary content (i.e., video content or the page's text content), and the other containing all of the remaining non-content interface elements (e.g., the navigation menu, advertisements, etc.). The results of this process are depicted visually in Figure 5 below.

In considering the figure above, one cannot help but be struck by the obvious contrast between the two heat maps. The aggregated mental models data clearly suggest that people expect to find a web page's primary content near the center of the screen, while all of the other non-content elements are expected to be located at the periphery. These results provide strong evidence in support of the theoretical link between human visual physiology and a user's visuo-spatial model of web interface design. What is perhaps most fascinating about this finding is that the way in which human beings organize and arrange information for web-based visual consumption does not appear to be arbitrary or linked solely to experience. On the contrary, our expectations regarding how websites should be designed are, at least in part, rooted in the ancient physiology of the human visual system.

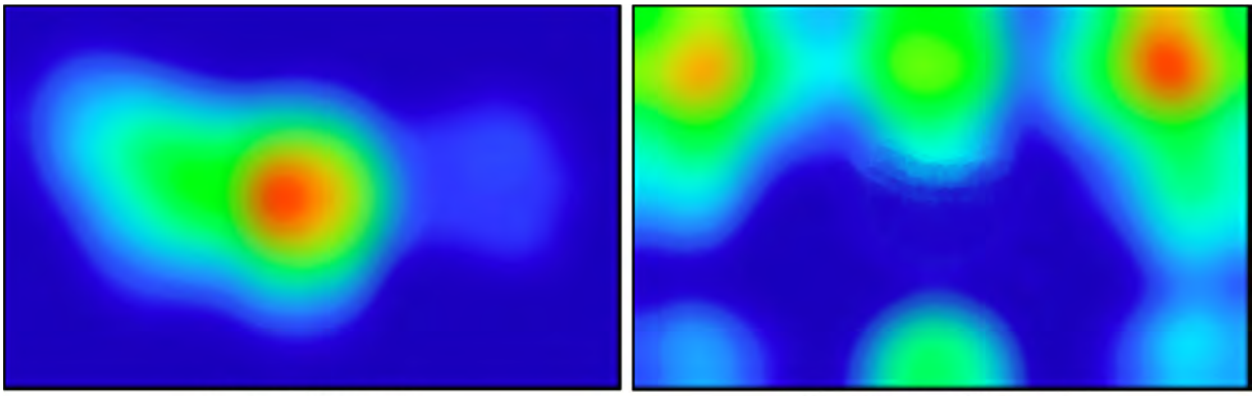

FIGURE 5. Content vs. non-content interface elements.

V. IMPLICATIONS AND RECOMMENDATIONS

In this study, we (1) developed a comprehensive theoretical model of the antecedents and impacts of visuo-spatial mental models of web interface design, (2) empirically identified the nature of people's mental models of web interface design, and (3) demonstrated that people possess a shared mental model of web interface design. These activities carry several important implications for both practice and future scientific research.

A. PRACTICAL IMPLICATIONS

One of the key contributions of this work was to establish and mathematically describe the geometric nature of people's shared mental model of web interface design. Both managers and web designers alike can (and should) use this information to evaluate the extent to which their current or proposed web interface designs conform to the standard reference model. This is not to say that every organizational website should look exactly the same; indeed, just as the individual characteristics that distinguish one human being from another vary from person to person, colors, fonts, multimedia elements, and page content serve to establish a website's unique identity, and should be expected to vary from one website to the next. It is instead the *arrangement* of these interface elements that should conform as closely as possible to a user's mental model of web interface design. The reasons for this recommendation can be found in the integrated theoretical framework described earlier in this paper. Specifically, the theoretical model shows how users' expectations about interface design emerge from their mental models, and that users evaluate the actual design of a web interface against their expectations in order to arrive at conclusions about quality and usability, which ultimately determine the extent to which a user is satisfied with the web interface. This is critically important because a website commonly serves as the public face of an organization, and dissatisfaction with an organization's website can lead not only to frustration [5], but also to disloyalty, loss of trust, and a general decline in the opinion of users toward the underlying organization [6], [7].

B. IMPLICATIONS FOR FUTURE RESEARCH

Much remains to be learned about the connections between mental models, expectations, and user satisfaction, and the geometric properties of the shared mental model of web interface design and the integrated theoretical framework described in this paper can serve as important foundation stones upon which future scientific research in this area can be built. The work described herein is, to the best of our knowledge, the first to establish concrete theoretical links between mental models and user satisfaction in the context of web interface design. What remains unknown, however, is the precise extent to which divergence from the general, shared mental model of interface design impacts user perceptions about the quality and usability of a web interface, and the extent to which such perceptions ultimately affect user satisfaction. Fortunately, the geometric approach for eliciting and describing visuo-spatial mental models presented in this paper can serve as a viable inroad for inquiring into these empirical questions. Specifically, the methods and mathematical framework described above can be used to reliably measure the degree of divergence between existing or proposed web interfaces and the standard reference model, and when coupled with instruments designed to measure interface quality, usability, and satisfaction, this framework can help to reveal powerful scientific insights into web interface design that might otherwise remain shrouded in uncertainty.

VI. LIMITATIONS AND CONCLUDING REMARKS

There are, of course, several limitations to our work that must be acknowledged. First, our findings were derived only from the responses of adult web users. It is conceivable that children's mental models may differ from those of adults, and investigating children's visuo-spatial mental models of website design may be a fruitful area for future research. Similarly, our results were derived only from English-speaking web users. This is important because the English language is written from left-to-right, and mental models of the locations of peripheral interface elements such as a navigation menu, advertisement, or corporate logo might reasonably be expected to differ among web users who speak Hebrew, Arabic, or Farsi, which are written from right-to-left. Our work is also limited inasmuch as we intentionally avoided asking subjects to focus on any particular type or category of website while participating in the experiment. Given the human brain's proclivity for generating mental models, it stands to reason that people have likely developed sub-models for specific types of websites (search engines, social networking sites, news sites, etc.). Exploring such sub-models may also be fertile ground for future inquiry.

The limitations noted above notwithstanding, there are two key points which we would like to bring to the fore: First, our findings suggest not only that people possess a shared visuo-spatial mental model of website design, but also that this shared model is remarkably cohesive and consistent from person to person. Second, people's mental models of how websites should be designed are not rooted solely in experience, but also appear to be linked to the physiology of the human visual system. When considered together, these observations point toward a new paradigm of thought about how users judge website quality and usability. Given that people's visuo-spatial mental models reflect their expectations about how a website should be designed, the integrated theoretical framework described in this paper suggests that the degree of discomfort and frustration that web users feel when interacting with a website is linked to the degree of misalignment between the website's interface and the user's mental model. This theoretical proposition will, of course, need to be empirically tested by future research, but if it proves to be sound, then organizations could improve the satisfaction of their web users – and by extension, users' perceptions of and confidence in the underlying organization – simply by taking steps to ensure that their web interfaces are properly aligned with users' mental models of website design.

REFERENCES

[1] A. LaFrance, *How Many Websites Are There?* Washington, DC, USA: The Atlantic, 2015.

[2] A. Binstock, *Interview With Alan Kay*. London, U.K.: InformationWeek, 2012.

[3] R. E. Nisbett, *Mindware: Tools for Smart Thinking*. New York, NY, USA: Farrar, Straus and Giroux, 2016.

[4] J. W. Palmer, "Web site usability, design, and performance metrics," *Inf. Syst. Res.*, vol. 13, no. 2, pp. 151–167, Jun. 2002.

[5] S. Nadkarni and R. Gupta, "A task-based model of perceived website complexity," *MIS Quart.*, vol. 31, no. 3, pp. 501–524, Sep. 2007.

[6] C. Flavián *et al.*, "The role played by perceived usability, satisfaction and consumer trust on website loyalty," *Inf. Manage.*, vol. 43, no. 1, pp. 1–14, Jan. 2006.

[7] R. Agarwal and V. Venkatesh, "Assessing a firm's Web presence: A heuristic evaluation procedure for the measurement of usability," *Inf. Syst. Res.*, vol. 13, no. 2, pp. 168–186, 2001.

[8] A. AlTaboli and M. R. Abou-Zeid, "Effect of physical consistency of Web interface design on users' performance and satisfaction," in *Human-Computer Interaction. HCI Applications and Services*. Berlin: Springer, 2007, pp. 849–858.

[9] D. A. Norman, "Some observations on mental models," in *Mental Models*, D. Gentner and A. L. Stevens, Eds., Hillsdale, NJ, USA: Lawrence Erlbaum Associates, 1983, pp. 7–14.

[10] P. N. Johnson-Laird, *Mental Models: Towards a Cognitive Science of Language, Inference, and Consciousness*. Cambridge, U.K.: Cambridge Univ. Press, 1983.

[11] P. N. Johnson-Laird, "Imagery, visualization, and thinking," in *Perception and Cognition at Century's End*, J. Hochberg, Ed. San Diego, CA, USA: Academic, 1998, pp. 441–467.

[12] M. Knauff and P. N. Johnson-Laird, "Visual imagery can impede reasoning," *Memory Cognit.*, vol. 30, no. 3, pp. 363–371, Apr. 2002.

[13] D. Gentner and A. L. Stevens, *Mental Models*. Hillsdale, NJ, USA: Lawrence Erlbaum Associates, 1983.

[14] R. L. Oliver, "Effect of expectation and disconfirmation on postexposure product evaluations: An alternative interpretation," *J. Appl. Psychol.*, vol. 62, no. 4, pp. 480–486, 1977.

[15] R. L. Oliver, "A cognitive model of the antecedents and consequences of satisfaction decisions," *J. Marketing Res.*, vol. 17, no. 4, pp. 460–469, Nov. 1980.

[16] S. H. Schwartz, *Geometrical and Visual Optics*, 2nd ed. New York, NY, USA: McGraw-Hill, 2013.

[17] L. A. Remington, *Clinical Anatomy and Physiology of the Visual System*, 3rd ed. St. Louis, MO, USA: Elsevier, 2012.

[18] S. Anderson, K. T. Mullen, and R. F. Hess, "Human peripheral spatial resolution for achromatic and chromatic stimuli: Limits imposed by optical and retinal factors," *J. Physiol.*, vol. 442, no. 1, pp. 47–64, Oct. 1991.

[19] L. A. Isbell, "Snakes as agents of evolutionary change in primate brains," *J. Human Evol.*, vol. 51, no. 1, pp. 1–35, Jul. 2006.

[20] T. Isa, "Intrinsic processing in the mammalian superior colliculus," *Current Opinion Neurobiol.*, vol. 12, no. 6, pp. 668–677, Dec. 2002.

[21] T. P. Doubell, I. Skaliora, J. Baron, and A. J. King, "Functional connectivity between the superficial and deeper layers of the superior colliculus: An anatomical substrate for sensorimotor integration," *J. Neurosci.*, vol. 23, no. 16, pp. 6596–6607, Jul. 2003.

[22] D. M. Steiger and N. M. Steiger, "Instance-based cognitive mapping: A process for discovering a knowledge worker's tacit mental model," *Knowl. Manage. Res. Pract.*, vol. 6, no. 4, pp. 312–321, 2008.

[23] W. E. Saris and I. N. Gallhofer, *Design, Evaluation, and Analysis of Questionnaires for Survey Research*. Hoboken, NJ, USA: Wiley, 2007.

[24] Pew Research Center, *Internet User Demographics*. Washington, DC, USA: Internet & American Life Project, 2012.

[25] R. L. Ling, "A computer generated aid for cluster analysis," *Commun. ACM*, vol. 16, no. 6, pp. 355–361, Jun. 1973.

[26] L. Rokach, "A survey of clustering algorithms," in *Data Mining and Knowledge Discovery Handbook*, L. Rokach and O. Maimon, Eds., 2nd ed. New York, NY, USA: Springer, 2010, pp. 269–288.

[27] K. A. Pituch and J. P. Stevens, *Applied Multivariate Statistics for the Social Sciences*, 6th ed. London, U.K.: Routledge, 2015.

DANIEL S. SOPER is an Associate Professor of Information Systems and Decision Sciences with the Mihaylo College of Business and Economics, California State University, Fullerton, Fullerton, CA, USA. His current research interests lie in the realms of human cognition, interface design, innovative applications of computational linguistics. His research has appeared in a wide variety of leading information systems and computer science journals and conference proceedings.

SINJINI MITRA was a Post-Doctoral Research Associate with the Information Sciences Institute, University of Southern California. She was a Post-Doctoral Research Associate with the Department of Statistics and CyLab, Carnegie Mellon University. She is currently an Assistant Professor of Information Systems and Decision Sciences with the Mihaylo College of Business and Economics, California State University, Fullerton, (CSUF), Fullerton, CA, USA. She is an Associate Director of the Center for Information Technology and Business Analytics, CSUF. She is also a Faculty Associate of the ECS Center for Cybersecurity, CSUF. Her research interests include data mining and business analytics, security and biometric authentication, and statistical modeling applications in education, healthcare, and information systems.