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Attention Affordances: Applying Attention Theory to the Design of Complex Visual Interfaces

Emil Andersen[1], Kosa Goucher-Lambert[2], Jonathan Cagan[3], and Anja Maier[1]
[1] Department of Technology, Management and Economics, DTU—Technical University of Denmark
[2] Department of Mechanical Engineering, University of California
[3] Department of Mechanical Engineering, Carnegie Mellon University

The design of visual interfaces plays a crucial role in ensuring swift and accurate information search for operators, who use procedures and information tables to cope with problems arising during emergencies. The primary cognitive mechanism involved in information search is visual attention. However, design of interfaces is seldom done through applying predictions of theories of attention. Conversely, theories of attention are seldom tested in applied contexts. Combining application and attention research thus stands to benefit both fields. Therefore, this study tested three theories of visual attention that are especially relevant for information processing in emergencies—Load Theory, Feature Integration Theory, and Dilution Theory—as well as predictions about attentional guidance and capture of color in a complex visual interface. Evidence was found for several predictions from theory, especially from Feature Integration Theory. Implications for design practice and attention research are discussed.

Public Significance Statement
The success of visual interface designs for emergencies depends on proper guidance of attention. To enable this, the present paper tests insights from attention research to evaluate their potential for application outside the laboratory.

Keywords: visual attention, affordances, cognitive and visual load, color, human-centered design

In complex socio-technical environments, the performance of human operators heavily depends on the design of the visual aids at their disposal. For example, nuclear power plant operators depend on critical information presented in several complex interfaces to inform their decisions (Braseth & Øritsland, 2013; Lau et al., 2008). If information search is slow due to suboptimal design, decision-making may suffer and cause severe adverse effects. Similar practice areas include aviation and military strategy, where operators must also quickly find the correct information needed in complex visual interfaces (Burian, 2006; Cook & Smallman, 2008; Steelman et al., 2013).

The visual interfaces used in these areas must therefore be designed to allow the correct actions to be performed rapidly. To achieve this, the possible actions an interface allows, commonly referred to as affordances (Gibson, 1978; Norman, 1988), must thus be managed by the designer to increase the likelihood of the correct actions being performed.

To this end, user studies represent a useful tool, which improve design through increased knowledge of the potential user (Crilly et al., 2009), and thus better knowledge of how to manage affordances. For example, previous research has provided guidelines that help practitioners improve performance of products by changing their visual characteristics, such as their general aesthetic appeal (Blijlevens et al., 2013; Choi et al., 2016; Crilly et al., 2004; Orsborn et al., 2009), investigation of specific product tests, and user evaluation studies (Braseth & Øritsland, 2013; Karlsson, 2007; Lau et al., 2008; Na & Suk, 2014; Ranscombe et al., 2012; Weyer et al., 2010). However, such studies seldom relate or base their findings to the underlying cognitive mechanisms or to testing established theories of the cognitive mechanisms behind the interactions, making it harder to generalize across design cases. Conversely, while theories from the field of experimental psychology and related fields robustly predict the allocation of attention in highly controlled contexts, and thus could potentially serve as guidance for designers in managing affordances, they seldom have been tested in concrete use-cases. This paper attempts to address this gap by investigating how participants perform when searching for information in a display that simultaneously mimics a complex visual interface used in nuclear control rooms and the interfaces used in experimental psychology to allow for predictions about attention allocation.

Anja Maier https://orcid.org/0000-0002-3890-6452
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Correspondence concerning this article should be addressed to Emil Andersen, Department of Technology, Management and Economics, DTU—Technical University of Denmark, Akademivej, Building 358, DK-2800 Kgs, Lyngby, Denmark. Email: emil@summaseminars.com

This paper first reviews research and frameworks from ecological psychology and design research that are useful for understanding how interfaces are used. It is argued that designers create interfaces with certain actions in mind by creating products that afford those types of actions, and that user studies may lead to better understand which design options afford specific actions. Second, research on visual attention is outlined that provides insights into which visual components afford certain types of attention allocation. The focus is on theories that have relevance for the high visual and cognitive load conditions present of emergencies. Third, two visual search experiments are conducted that test multiple hypotheses from the attention literature in a complex visual interface that mimics those used in nuclear power plant control rooms. Fourth and finally, the results and their implications for design practice and attention research are discussed. The following sections show the relation between user studies and improved design, as illustrated by the alignment of intended and actual affordances. In relation to this, Load Theory (Lavie et al., 2004; Lavie & Tsal, 1994), Feature Integration Theory (Treisman, 1998; Treisman & Gelade, 1980; Treisman & Sato, 1990) and Dilution Theory (Benoni & Tsal, 2010; Tsal & Benoni, 2010) are outlined due to their possible application to interface design for high load conditions.

Aligning Designer Intention and Actual Use

Previous research has shown that design is a communicative process, wherein designers attempt to tell the user *how* to use a product *through* the product (Crilly, Good, et al., 2008; Crilly, Maier, & Clarkson, 2008). This paper takes this design-as-communication approach as its basic assumption with regards to how to improve design. Under this assumption, an important way that designers can increase the likelihood of a device's intended use becoming its actual use is through manipulating the possible actions of the designed object. These possible actions are commonly referred to as *affordances* (usually referencing the original formulation by Gibson (1978) and/or the application to design by Norman (1988). Using this terminology, a product is considered to have a number of affordances for actions that each have a related likelihood of use (e.g., a chair more readily affords sitting on it than throwing it). A metric for success of a designed object thereby lies in the extent to which the action that was intended for the product is also the action that is most readily afforded by the item. Previous research has shown that designers can increase the likelihood of their intended affordances matching actual affordances by performing user studies (Crilly et al., 2009; Maier et al., 2009): A prototypical user study will elucidate the likelihood of specific affordances of a product pertaining to specific groups. Applying such user or group knowledge is sometimes referred to as user-entered design or human-centered design (e.g. Cagan & Vogel, 2001, for a recent review see Boy, 2017) and has provided insights in a number of research areas. Alternatively, designs can be improved by relying on findings that are common to all humans due to our shared phylogenetic heritage, or broad cultural groups (Aslam, 2006; Leder et al., 2007; Lugo et al., 2016; Nørager, 2009). Together, these studies represent an increasing body of knowledge on the affordances of specific design properties. While the original definition of affordances is unconstrained, previous research has mostly considered the concept with regards to concrete actions (e.g., the above chair example), aesthetics (Xenakis & Arnellos, 2013), semantics (You & Chen, 2007), tool usage (Wagman & Carello, 2003), interface design (Stefanucci et al., 2015), or to fields such as engineering design (Ciavola & Gershenson, 2016) or design and architecture (Maier et al., 2009). Recently, however, Still and Dark (2013) proposed that affordances can represent any automatic cognitive process that is evoked when viewing an object, and that the relationships can be both evolutionary and culturally acquired. They conclude by speculating that in the presence of several perceived affordances, designers may benefit from models of basic cognitive mechanisms (e.g., the biased competition model of Desimone & Duncan, 1995) to inform their designs.

This paper takes this notion a step further, showing how affordances of a visual interface can be related to, and predicted through, the application of relevant theories of attention. Understanding the visual attention system is particularly important for predicting what information will receive attentional processing, or, in other words, what information visual interfaces most readily afford being processed. Drawing upon these insights thereby represents an important avenue for increasing the likelihood that the intended affordance of a display is also the most likely (Kozine, 2007; McCarley & Steelman, 2013). In the following sections, theories and findings from attention research are outlined that could be especially important for determining the attention affordances of visual interfaces for emergencies due to the high visual and cognitive load present in such situations. Following this, two experiments are presented that test these theories in a newly created visual search paradigm that more closely resembles a realistic visual interface, while also mimicking the study designs used in experimental psychology.

Visual Search Under Load

In everyday and emergency settings, users of visual interfaces are subject to varying degrees of cognitive load from their surroundings. Whether due to varying amounts of tasks, having to hold varying amounts of information in memory, or being exposed to varying amounts of multimodal stimulation (e.g., alarms), the cognitive load of users will vary depending on the situation. The Load Theory of Selective Attention and Cognitive Control (henceforth Load Theory, Lavie, 2005, 2006, 2010; Lavie et al., 2004; Lavie & Tsal, 1994) predicts that when cognitive load goes up, the ability to ignore distracting stimuli goes down, due to a decrease in available cognitive inhibitory resources. Given the natural variations in cognitive load outlined above, these predictions, if they generalize to a more realistic interface, could provide highly relevant information for designers on the way how visual interfaces afford distractions.

In addition to cognitive load induced from their surroundings, users can be subject to varying levels of load from the interface itself. In attention research, load induced by the amount and characteristics of the objects in the visual scene is most commonly referred to as visual load, again usually with reference to Load Theory (Lavie et al., 2004; Lavie & Tsal, 1994). The most commonly referred examples of high and low visual load stem from the experiments that formed the basis of Feature Integration Theory (Treisman, 1998; Treisman & Gelade, 1980; Treisman & Sato, 1990). In a classic low visual load display, the target is separable from the distractors by a single feature, for example, shape. In such situations, a high-capacity pre-attentive processing stage can aid the visual search, leading to a fast, parallel search that is only marginally affected by the number of distracting objects in the display. In a classic high visual load display, the target can only be determined using the conjunction of two features, for example, shape and color. In such situations, the pre-attentive processing is not sufficient for attention allocation, and the observer must inspect each element in a slow, serial search. These findings, based on the predictions of Feature Integration Theory, have been highly influential in determining visual search performance in highly controlled experimental settings. They have furthermore shown promise in real life applications, such as for predicting visual search performance for targets in color-coded and intensity-coded displays (Yamani & McCarley, 2010).

Adding to this, the effect of visual load has been shown to extend to how distractors are processed. According to Load Theory, higher visual load will reduce the processing of distractors, as all capacity will be occupied by target-relevant objects. Conversely, low visual load affords spare processing capacity to spill over to irrelevant objects, leading to higher processing of distractors (Lavie et al., 2004; Lavie & Tsal, 1994). This finding has been shown to extend to irrelevant, real-life objects cartoon characters (Forster & Lavie, 2008), but the effects have recently been shown to be limited in their generalizability (Lleras et al., 2017).

As a competing theory to Load Theory, Dilution theory (Benoni & Tsal, 2010; Tsal & Benoni, 2010; Wilson et al., 2011) instead proposes that distractor processing depends on the total number of objects in the display: If there are more objects, then distractors will have lower influence because their effect is diluted by even entirely irrelevant objects. This effect has similarly been explained as a lowered probability of attention being allocated to any given object, thereby reducing the likelihood that a distractor is selected (Kyllingsbæk et al., 2011). While distractors may still have a larger probability than an irrelevant distractor, the dilution effect results in overall lower probability of it being selected. Based on this, while Dilution Theory does not address whether irrelevant objects will influence processing speed overall, the theory predicts that distractors should have a lower effect with more irrelevant objects. The predictions of this theory thus could be highly influential for understanding how easily a user is distracted by irrelevant objects in a complex display. Given the operators rely on highly complex visual interfaces to respond to emergencies, knowing how the visual load of these displays affords attentional allocation, could provide valuable input to designers as well.

Taken together, Load Theory, Feature Integration Theory, and Dilution theory make highly relevant predictions with regards to how users search for information in complex displays under load—whether from the surroundings or the visual interface. Despite this, their hypotheses have only seldom been tested outside of highly controlled environments. To alleviate this gap, the present study tests the predictions from all three theories in visual display that mimics those used by nuclear control room operators, to test whether these predictions could inform designers about how their display designs afford attentional allocation.

Color Guidance

In the sections above, it was shown how visual load influences attentional allocation. However, designers already often make efforts to reduce visual load in interface designs. Notably, the use of color is a common and useful tool for distinguishing between objects in complex visual displays (Jameson et al., 2001; Spence & Efendov, 2001; Spence et al., 1999; Vazquez et al., 2010; Ware, 2008). The use of color to guide visual search is in concordance with previous research on attention, which has repeatedly shown that color can both guide (Wolfe, 2007; Wolfe & Horowitz, 2017) and capture attention (Nordfang et al., 2013; Theeuwes, 1992, 1994). Critically for emergency settings, it was recently shown that the color guidance depends on visual load (Biggs et al., 2015), and that this interaction is different for individual colors (Andersen & Maier, 2019). Previous research has also shown that search in visual displays using colors to distinguish between objects depend heavily on the combination of the individual colors (Francis et al., 2010; Müller et al., 2009; Shive & Francis, 2013; Starke & Baber, 2018). However, the specific performance of individual colors in complex displays has seldom been investigated. Furthermore, it has, to our knowledge, not been investigated how this performance relates to the visual and cognitive load that characterizes emergencies. To this end, the present study investigated the performance of individual colors under the conditions of high cognitive and visual load, in addition to the hypotheses tested from Load Theory, Feature Integration Theory and Dilution Theory.

Current Study: Testing Attention Affordances

The purpose of the current study is to test hypotheses from the theories and findings outlined above, to determine attention affordances that are of particular use for visual interfaces for emergencies. Specifically, five hypotheses are tested, of which two (2a and 2b) represent conflicting accounts of how distracting objects will interfere with search performance:

> *Hypothesis 1*: Based on the hypotheses of Feature Integration Theory, high visual load is expected to result in slow, serial search, whereas low load is expected to result in rapid, parallel search.

> *Hypothesis 2a*: Based on the hypotheses of Load Theory, higher visual load is expected to decrease distractor interference.

> *Hypothesis 2b*: Based on the hypotheses of Dilution Theory, visual load is not expected to interact with distractor interference. Instead, distractor interference is expected to depend on the total number of objects in the display.

> *Hypothesis 3*: Based on the hypotheses of Load Theory, high cognitive load is expected to increase distractor interference.

> *Hypothesis 4*: Based on the findings on color guidance, color is expected to guide and capture attention, and this effect is expected to be different for individual colors, particularly under high visual load.

To test these hypotheses, a novel experimental paradigm was created that mimics a simplified nuclear control room interface (based on the illustrations of Braseth & Øritsland, 2013), while simultaneously sharing enough characteristics with the displays used in the attention literature to allow for reliably testing the above hypotheses. Two experiments were conducted using the same display and study setup with one difference: In Experiment 1, participants knew the both the target number and color, whereas in Experiment 2 participants only knew the target. This difference between the two experiments served to test the role of guidance of color (Experiment 1) and capture of color (Experiment 2) respectively. The two experiments are outlined and discussed in the following sections. An overview of the experiment interface, including how the various manipulations relate to the five hypotheses, is given in Figure 1.

Experiment 1: Search With Known Target Color

To test the outlined hypotheses, a novel experimental paradigm was created, which featured variations of visual interfaces that mimic a simplified nuclear control room interface, based on the illustrations of Braseth and Øritsland (2013). In Experiment 1, participants searched for a barometer number and its associated color. Hypotheses from the included attention theories were tested by measuring visual search times for varying conditions as outlined in detail below.

Method

Participants

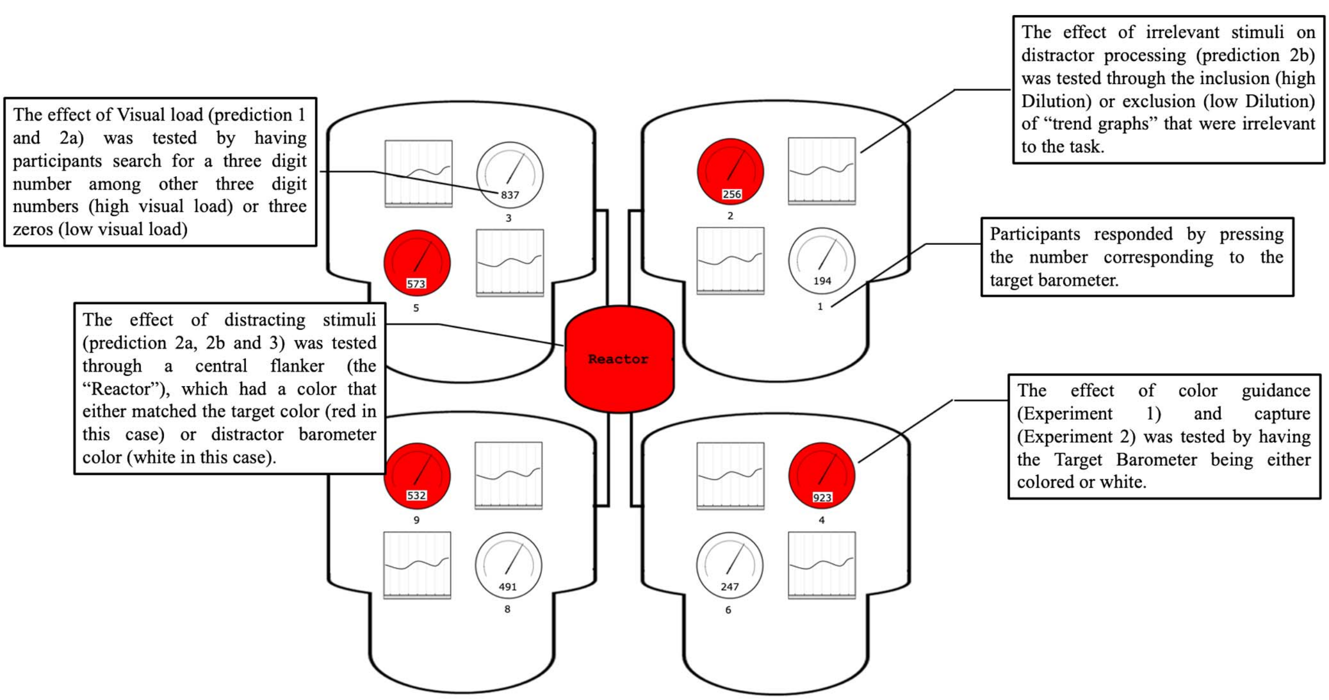
Twenty-five (19 female) students at Carnegie Mellon University and University of Pittsburgh participated in the experiment in exchange for monetary compensation. Participants were between 18 and 30 years old, and were required to have normal or corrected-to-normal vision, not be color blind, not suffer from ADHD or depression, or have a family history of ADHD or depression. Participants were pre-screened for color blindness prior to the experiment using an online version of the Ishihara 38 plates test (Color-blindness.com, n.d.). Consent from all participants was obtained at the start of experimental data collection in accordance with protocol approved by the Institutional Review Board at Carnegie Mellon University.

Materials

Visual interfaces were created based on the illustrations of Braseth and Øritsland (2013). Figure 1 shows an example interface with the various manipulations and their relation to theory. The interfaces were further created so that objects were equidistant from the center of the display. All interfaces contained a "Reactor" object (of varying color, see Figure 2), which measured 2.6° diagonally and 3.5° horizontally, connected to four "Steam Generators," which measured 8.7° horizontally at the widest point, 6.0° horizontally at the narrowest point and 6.9° diagonally. Each "Steam Generator" contained two contained two "Barometers." The "Barometers" varied in color (see Figure 2 for the various colors), measured 1.9° in diameter, and contained a white box with a three-digit identification number, which participants used for visual search. Below each barometer was a single digit for participants to report in the search task. This mimics the design of Theeuwes (1992) and Nordfang et al. (2013) in that that the target color was not part of the target number. In half of the interfaces, each "Steam Generator" also contained two "Trend Graphs," measuring 1.9° both horizontally and diagonally, to increase the visual dilution. "Barometers," "Reactors," "Steam Generators" and "Trend Graphs" were created in Microsoft PowerPoint 2010. Text objects were created in E-Prime and used the Courier New font. Colored objects used the "standard colors" Red,

Figure 1

An Example Target Search Display With Explanations for the Various Manipulations and Their Relation to Theory

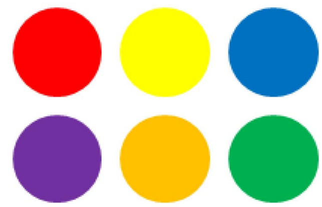


Note. See the online article for the color version of this figure.

Figure 2

Color Codes, Contrast Scores, Luminance Scores, and Visual Representation of the Used Colors

Colour	R	G	B	Contrast	Luminance
Red	255	0	0	4	29
Yellow	255	255	0	1.1	106
Green	0	176	80	2.9	33
Blue	0	112	192	5.1	15
Orange	255	192	0	1.6	66
Purple	112	48	160	8	7



Note. See the online article for the color version of this figure.

Light Blue, Light Green, Yellow, Orange and Purple from Microsoft PowerPoint 2010 in concordance with (Andersen & Maier, 2017, 2019). All text objects used the Courier New font and were created in E-Studio version 2 for Windows.

Visual Load

Visual load was manipulated through conditions that allowed participants to search in parallel or serially for the number target, to see the effect on overall reaction time (RT) and distractor processing. In the high load condition, all eight barometers had a sequence of three random numbers (e.g., 957). In the low load condition, the target was the same as in the high load condition, but all other barometers had three zeros (000) as their number sequence. The experiment thus mimiced the common methodology for studying the effect of visual load (e.g., Biggs et al., 2015; Lavie et al., 2004; Lavie & Tsal, 1994). In concordance with Feature Integration Theory, higher visual load was expected to lead to higher RTs (Hypothesis 1).

The effect of distractor interference under high visual load was tested by varying the color of the central “Reactor Object” to be either congruent (i.e., the same as the target) or incongruent (i.e., white, the color of the non-target barometers) with the target color. Participants were told to ignore the distractor in all cases. This experiment thus mimicked the flanker response-competition task (Eriksen & Eriksen, 1974), with a central flanker (Beck & Lavie, 2005; Wilson et al., 2011). Differences in response times between the congruent and incongruent conditions were considered to indicate distractor interference. In concordance with Load Theory, lower distractor interference was expected in the high load condition (Hypothesis 2a). Furthermore, in concordance with Biggs et al. (2015) and Andersen and Maier (2019) larger effects of guidance and capture of color under higher visual load were anticipated (Hypothesis 4).

Visual Dilution

Visual dilution was manipulated through the inclusion (high dilution) or exclusion (low dilution) of irrelevant “Trend Graphs” in the “Steam Generators.” Participants were instructed to ignore them whenever they appeared. In concordance with the Dilution (Benoni & Tsal, 2010; Tsal & Benoni, 2010; Wilson et al., 2011) account and Theory of Visual Attention (TVA; Kyllingsbæk et al., 2011), lower distractor interference was expected under higher visual dilution (Hypothesis 2b), meaning when the irrelevant “Trend Graphs” were present.

Cognitive Load

Cognitive load was manipulated through a modified version of the dual task paradigm of Lavie et al. (2004), which uses a reduced version of Sternberg’s (1966) short-term recognition task to manipulate cognitive load while participants perform a search task. This experiment varied in that participants remembered letters and searched for numbers (whereas the converse was used by Lavie et al., 2004). Participants were asked to remember a letter sequence of one (low cognitive load) or five (high cognitive load) letters. Letters were consonants (y was considered a vowel) to avoid reduced load from chunking. The sequence was presented for 500 ms in the low load condition and 2,000 ms in the high load condition similar as in Lavie et al. (2004). After this, the participants performed the search task, and were then presented with a single letter probe, which they determined to be part of the memory sequence or not. There was a 50–50 chance that the presented probe was present or absent. Participants pressed the CTRL key if the target was present and the ALT key if the target was absent. For each trial, participants were given feedback on their performance on the memory task in that specific trial, as well as all trials so far (excluding practice). In concordance with Load Theory, higher overall RTs for the search task were expected under higher cognitive load due to larger distractor interference (Hypothesis 3).

Placement

The possible effect of reading order was controlled for by randomizing the placement of both target and distractor objects across participants. In concordance with previous findings (Buscher et al., 2009, 2010; Cutrell & Guan, 2007) participants were expected to find targets faster in the top-left quadrant of the display due overtraining for the left-to-right reading order.

Apparatus

The experiment was conducted on a laptop computer with an externally connected screen and keyboard. Stimuli were displayed using E-Studio version 2 for Windows.

Experiment Procedure

Each participant completed one training block (20 trials) and three experiment blocks (102 trials each for 306 trials total). Each trial proceeded as follows: First, a screen appeared for 2,000 ms or 500 ms (see the above section on Cognitive Load for details), which showed the letter sequence to be remembered, followed by a 30 ms visual mask. Second, the target barometer, including color and barometer number, was shown for 2,000 ms followed by a 30 ms visual mask. Third, a fixation cross appeared in the middle of the screen for 500 ms to ensure that participants were focused in the middle of the display at the start of each search task. Fourth, the search display (see Figure 1 for an overview of the variations) appeared until the participant responded with the corresponding number using the numpad (maximum response time allowed was 8,000 ms based on pilot tests) had passed. Fifth, participants were shown a letter probe, and pressed CTRL if the number was present in the memory sequence or ALT if the number was absent (see Section 3.1.4 for details) (maximum response time allowed was 6,000 ms based on pilot tests). Sixth and final, participants were given feedback on their performance in the memory task for 1,000 ms. Figure 3 shows the experiment procedure.

Analysis and Design

Analysis and graphical illustration were created using base R (R Core Team, 2017) and the nlme package (Pinheiro et al., 2019), ggplot2 (Wickham et al., 2018), and tidyr (Wickham et al., 2019) packages for R.

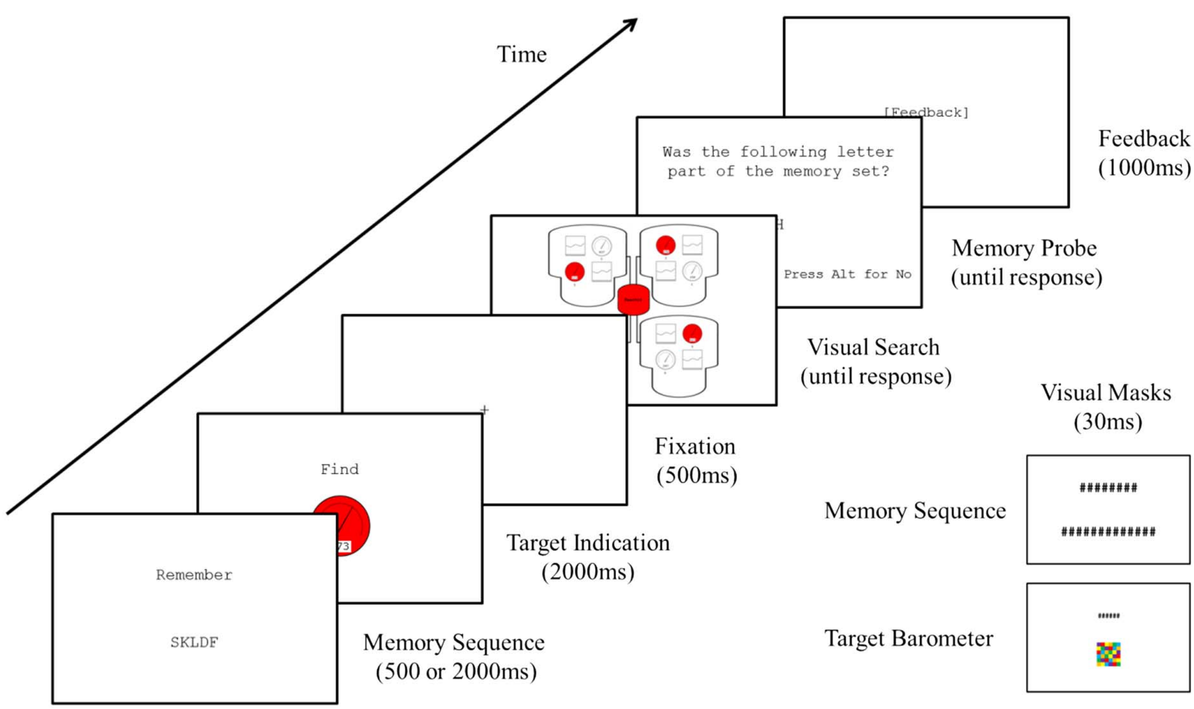
The dependent variable was RT for the visual search task. The independent variables were target color (seven levels: white, red, blue, yellow, green, orange, purple), distractor color (seven levels: white, red, blue, yellow, green, orange, purple), distractor interference measured as the difference between distractor types (congruent or incongruent distractor color), cognitive load (high or low), visual load (high or low), visual dilution (high or low). Placement of targets (eight possible positions, randomized across trials) was included as a control variable as noted above. A linear mixed effects model was fitted to the data with Subject as random factor. Main effects were evaluated using a Repeated-Measures ANOVA model.

Based on a high overall accuracy of 97.6%, only accurate trials were analyzed. Furthermore, trials were removed as outliers if the RT for the search task was 3 standard deviations above or below the mean response time, or if no response were given. RTs were log-transformed prior to analysis to better fit the assumption of normal distribution of the residuals. An overview of the results is given in Table 1.

Results and Discussion

Experiment 1 tested hypotheses from relevant theories of attention in a newly created experimental paradigm wherein participants searched for three-digit numbers that were located in barometers that participants knew the color of. The results, outlined in Table 1, show both congruence and incongruence with the hypotheses of the included theories. Notably, the results supported Hypothesis 1, which was derived from Feature Integration Theory (Treisman & Gelade, 1980), as participants were faster when they were able to use a single feature to filter out irrelevant objects, as reflected in a significant effect of visual load. In concordance with Feature Integration Theory, this indicated that participants were faster when they only needed one feature, that is, the shape of the number, rather than the specific number identity, to find the target. Furthermore, the presence of the irrelevant trend graphs had no significant on overall search time, which further supports the hypotheses of Feature Integration Theory, given that the theory predicts that irrelevant objects should be filtered

Figure 3
The Experiment Procedure



Note. See the online article for the color version of this figure.

Table 1
Results of Mixed Effects Linear Model for Experiment 1

Simple effects	Basic LME-model Estimate	Basic LME-model p	Full LME-model Estimate	Full LME-model p	ANOVA F	ANOVA p
Target color[a]						
Green	1.01	.39	1.03	.12		
Orange	1.00	.80	1.00	.92	72.61	<.0001
Purple	.99	.45	.98	.26		
Red	.99	.44	.98	.33		
White	1.13	<.0001	1.11	<.0001		
Yellow	.98	.2888	.97	.11		
Distractor color[b]						
Green	.99	.68	.99	.69		
Orange	.99	.64	.99	.66	1.71	.11
Purple	.99	.60	.99	.61		
Red	.99	.73	.99	.73		
White	.98	.20	.98	.21		
Yellow	1.00	.94	1.00	.95		
Distractor type[c]	1.02	<.01	1.00	.80	4.66	.03
Cognitive load[d]	1.03	<.0001	1.04	<.0001	32.02	<.0001
Visual load[e]	.94	<.0001	.93	.0001	102.85	<.0001
Visual dilution[f]	1.00	.48	.98	.03	.12	.73
Target position[g]						
1 o'clock	.83	<.0001	.83	<.0001		
2 o'clock	.91	<.0001	.91	<.0001	269.07	<.0001
4 o'clock	1.07	<.0001	1.07	<.0001		
5 o'clock	1.07	<.0001	1.07	<.0001		
7 o'clock	1.04	<.001	1.04	.002		
10 o'clock	.84	<.0001	.81	<.0001		
11 o'clock	.74	<.0001	.74	<.0001		
Target color × Visual load[h]						
Green			.96	.15		
Orange			1.00	.90	1.87	.08
Purple			1.02	.38		
Red			1.02	.55		
White			1.03	.24		
Yellow			1.03	.21		
Distractor type × Visual load[i]			1.01	.58	.30	.58
Distractor type × Cognitive load[j]			.99	.66	.19	.66
Distractor type × Visual dilution[k]			1.03	.02	5.36	.02

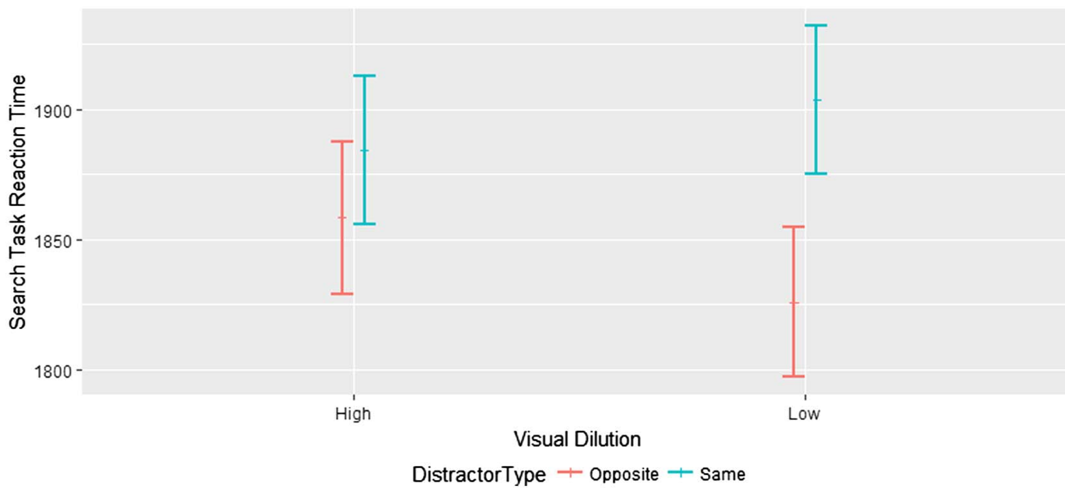
Note. The ANOVA were computed from the full Linear Mixed-Effects (LME) model. Estimates for both LME models are untransformed (exp(b)), representing percentage change in the dependent variable (RT), (e.g., 1.03 represents 3% change in RT).
[a] 0 = blue.
[b] 0 = blue.
[c] 0 = distractor color different from target color, 1 = distractor color same as target color.
[d] 0 = high, 1 = low.
[e] 0 = low, 1 = high.
[f] 0 = high, 1 = low.
[g] 0 = 8 o'clock.
[h] 0 = Blue × Low visual load.
[i] 0 = distractor color same as Target × Low visual load.
[j] Distractor color same as Target color × Low cognitive load.
[k] Distractor color same as Target color × Low visual dilution.

during pre-attentive processing as a result of the difference in shape. This, perhaps surprising, result thus indicates that a cluttered visual display will not be harder to navigate if targets are sufficiently distinguishable from each other through, for example, shape.

In contrast to the successful predictions of Feature Integration Theory, the hypotheses of Load Theory (Hypotheses 2a and 3) were not supported, as shown by the lack significant interactions between cognitive load and distractor interference and between visual load and distractor interference. Instead, as shown in Figure 4, the results showed that there was only an effect of the salient distractor object (the reactor in the middle of the display) when Visual Dilution was low (i.e., when the irrelevant graphs were not present), which is consistent with the hypotheses of the competing Dilution Theory (Hypothesis 2b), and inconsistent with Load Theory (prediction 2a). The results of Experiment 1 thus corroborates the claims of proponents of Dilution theory, suggesting that the interaction between Load and distractor processing are attributable to Visual Dilution rather than Visual Load (Benoni & Tsal, 2010). In addition to this finding, while Visual Dilution (i.e., the presence of the irrelevant trend graphs) did not slow the average search time, the higher visual

Figure 4

The Interaction Between Visual Dilution and Distractor Interference



Note. When the diluting graphs are present, the color of the distracting reactor object has no significant effect. When the diluting graphs are absent, the color of the distracting reactor object significantly slows search if it matches the target color. Error bars indicate 95% confidence intervals. See the online article for the color version of this figure.

amount of objects nevertheless reduced the effect of a salient distractor, further supporting the counter-intuitive finding that more complex displays may not be harder to navigate if the target characteristics are highly distinguishable.

The hypotheses pertaining to the attentional guidance of color (Hypothesis 4) showed mixed results: The hypothesis of an overall guidance of color (Nordfang et al., 2013; Theeuwes, 1992, 1994; Wolfe, 2007; Wolfe & Horowitz, 2017) was supported as reflected in faster RTs for non-white targets compared to white targets. However, in opposition to the previous results of Andersen and Maier (2019), no significant difference was found difference between individual non-white colors. Furthermore, there was no significant interaction between individual colors and Visual Load, which stands in opposition to previous finding (Andersen & Maier, 2019; Biggs et al., 2015).

Finally, the results showed a counter-intuitive effect of cognitive load, as higher cognitive load was associated with faster search speed, in contrast to the hypothesis of Load Theory (Hypothesis 3). Post-hoc test revealed that this may have been due to a small (~1.5%), but statistically significant ($F = 14.9, p < .0001$), difference in accuracy. As such, when working memory was beyond the normal maximum capacity, participants were able to find the targets faster at a slight cost of accuracy. A non-significant interaction effect between cognitive load and the distractor type indicates that the faster search speed was not due to lower distractor processing. As this effect was counter to the predicted, further research is needed to clarify this effect

Experiment 2: Search With Unknown Target Color

Experiment 1 showed some support for Hypothesis 4, showing of an overall attentional guidance from color, but no difference between individual colors. These results may reflect that participants were aided in their search by knowing the target color in advance. However, in real life use of visual interfaces the target color may not always be known in advance. Therefore, a second experiment was conducted where participants did not know the target barometer color, to test the effect of color on search performance when the target color was unknown.

Method

Participants

A new sample of 25 (16 female) students at Carnegie Mellon University and University of Pittsburgh participated in the experiment. Inclusion criteria and compensation were identical to Experiment 1. Consent from all participants was obtained at the start of experimental data collection in accordance with protocol approved by the Institutional Review Board at Carnegie Mellon University.

Method, Analysis and Design

The methods, analysis and design for Experiment 2 were identical to Experiment 1 in all aspects except that participants were only instructed in the target number, as opposed to both the target color and target number in Experiment 1. Given that participants had no knowledge of the target color, distractor interference was measured across colors. As for Experiment 1, there was a high overall accuracy of 98.2%, and as such only RTs for accurate trials were analyzed.

Results and Discussion

Experiment 2 studied visual search performance in a complex display, when participants did not know the target color. As in Experiment 1, the results, outlined in Table 2, showed both congruence and incongruence with the predictions from the included theories of attention, but notably the congruencies and incongruencies differed from those in Experiment 1.

As in Experiment 1, the results of Experiment 2 showed no effect of Visual Dilution (i.e., the presence of irrelevant graphs), but that visual load slowed search (Hypothesis 1). These findings thus give further support Hypothesis 1, derived from Feature Integration

Theory, that participants were able to ignore irrelevant stimuli by only scanning for barometer-like objects, and non-000 target numbers when applicable. Furthermore, as in Experiment 1 cognitive load improved search speed (which was counter to Hypothesis 3). The results thus further underline a need for conducting additional research to elucidate the effect of cognitive load on performance, although, as was the case in Experiment 1, post-hoc analysis showed that the difference in speed as a function of cognitive load may have been due to a small (~1.5%), but statistically significant ($F = 39.72$, $p < .0001$), difference in accuracy.

However, unlike Experiment 1, the results of Experiment 2 showed a significant difference between individual target and distractor colors (Hypothesis 4). The difference between individual colors was furthermore increased at high visual load (see Figure 5), thus supporting Hypothesis 4, which was derived from the findings of Andersen and Maier (2019) and Biggs et al. (2015). Post-hoc tests revealed that the difference between target colors was caused by white targets being found significantly slower than all colored targets except red, whereas red and purple were found significantly slower than yellow ($p < .001$), orange ($p < .01$) and blue targets ($p < .001$).

Further post-hoc test revealed that the difference between distractors colors was caused by red distractors capturing significantly more attention than blue ($p = .02$), orange ($p = .034$) and white ($p < .0001$) distractors, and purple distractors capturing

Table 2

Results of Mixed Effects Linear Model for Experiment 2

	Basic LME-model		Full LME-model		ANOVA	
Simple effects	Estimate	*p*	Estimate	*p*	*F*	*p*
Target color[a]						
Green	1.02	.36	1.03	.18	19.79	<.0001
Orange	1.02	.28	1.01	.77		
Purple	1.04	.03	1.05	.04		
Red	1.03	.06	1.07	.01		
White	1.08	<.0001	1.09	<.0001		
Yellow	.98	.34	0.98	.35		
Distractor color[b]						
Green	1.01	.58	1.04	.23	4.04	.0005
Orange	1.00	.95	1.03	.41		
Purple	1.01	.72	1	.91		
Red	1.02	.34	1.04	.23		
White	.99	.34	1.01	.75		
Yellow	1.02	.24	1.06	.10		
Distractor type[c]	1.01	.26	1.01	.26	3.12	.08
Cognitive load[d]	1.02	.01	1.05	.04	1.96	.0009
Visual load[e]	.93	<.0001	0.95	.02	136.71	<.0001
Visual dilution[f]	.99	.26	1	.98	1.26	.26
Target position[g]						
1 o'clock	.89	<.0001	0.89	<.0001	263.04	<.0001
2 o'clock	.95	<.0001	0.94	<.0001		
4 o'clock	1.02	.12	1.02	.12		
5 o'clock	1.04	<.001	1.04	<.001		
7 o'clock	1.02	.06	1.02	.06		
10 o'clock	.77	<.0001	0.77	<.0001		
11 o'clock	.71	<.0001	.71	<.0001		
Target color × Visual load[h]						
Green			0.97	.32	2.48	.02
Orange			1.02	.53		
Purple			0.98	.46		
Red			0.93	.04		
White			0.98	.53		
Yellow			1.01	.70		
Distractor type × Visual load[i]						
Green			1.00	.93	0.15	.99
Orange			1.00	.89		
Purple			0.99	.77		
Red			1.00	.96		
White			1.00	.90		
Yellow			0.97	.50		
Distractor type × Cognitive load[j]						
Green			0.97	.30	0.35	.91
Orange			0.96	.20		
Purple			0.97	.30		
Red			0.97	.33		
White			0.97	.19		
Yellow			0.97	.41		

(*table continues*)

Table 2 (*continued*)

Simple effects	Basic LME-model Estimate	*p*	Full LME-model Estimate	*p*	ANOVA *F*	*p*
Distractor type × Visual dilution[k]						
Green			0.97	.36	1.50	.17
Orange			0.98	.51		
Purple			1.05	.11		
Red			0.98	.52		
White			0.99	.72		
Yellow			0.98	.51		

Note. The ANOVA were computed from the full Linear Mixed-Effects (LME) model. Estimates for both LME models are untransformed (exp(*b*)), representing percentage change in the dependent variable (reaction time, RT), (e.g., 1.03 represents 3% change in RT).
[a] 0 = blue.
[b] 0 = blue.
[c] 0 = distractor color different from target color, 1 = distractor color same as target color.
[d] 0 = high, 1 = low.
[e] 0 = low, 1 = high.
[f] 0 = high, 1 = low.
[g] 0 = 8 o'clock.
[h] 0 = Blue × Low visual load.
[i] 0 = distractor color same as Target × Low visual load.
[j] Distractor color same as Target color × Low cognitive load.
[k] Distractor color same as Target color × Low visual dilution.

significantly lower attention than white distractors ($p < .001$). Furthermore, the difference between distracting colors was not affected by visual load, in concurrence with Hypothesis 4 and the findings of Andersen and Maier (2019).

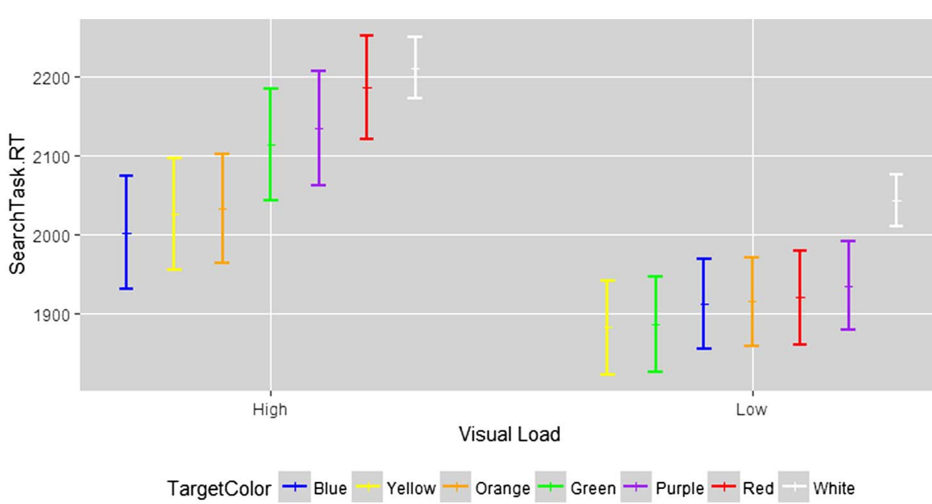
These results thus indicate that individual colors of both target and distractor objects have individual effects on attention when the target color is unknown. Therefore, when users are expected to be naïve to the expected color scheme (e.g., due to a lack of training opportunities or infrequent exposure to the display) the exact colors used may have a significant effect on attention allocation, whereas this was not the case for interfaces where the target color was known.

General Discussion

Two experiments were conducted in order to test predictions from theories of attention, which were particularly relevant for predicting how complex visual displays afford the allocation of attention in conditions of varying load. This was done using variations of a display that simultaneously mimicked the interfaces used in nuclear

Figure 5

The Interaction Between Visual Load and the Difference Between Individual Target Colors



Note. At high load, the individual difference between colors is larger, but the difference between red and white is smaller. At low load, the difference between non-white colors is smaller, but the difference between non-white and white targets is larger. Error bars indicate 95% confidence intervals. See the online article for the color version of this figure.

control rooms and those used in experimental psychology. Specifically, it was investigated whether the selected theories of attention could predict the attention affordances of visual and cognitive load, visual dilution, target and distractor color, and distractor interference when their insights were transferred from a highly specific and controlled environment to a complex display where all these aspects of attention were required at once. In both experiments, participants searched for a number sequence in an interface that varied to allow testing the effect of the individual attention affordances. In Experiment 1, participants knew the target color, whereas in Experiment 2 they did not. The results for each experiment were discussed in detail above. This section draws together these results and discusses the findings of both experiments with regards to their implication for design research, design application and attention research.

Implications for Attention Research

The presented experiments tested four hypotheses from theories of attention that were relevant for predicting the afforded attention allocation of a complex display that mimicked those used in a nuclear control room. While the hypotheses have proven to be robust within the tightly controlled experimental conditions, they should also generalize to real world settings if they truly reflect insights about human nature. Therefore, the experiments presented in this paper have implications for attention research, as they test of the robustness of the hypotheses in a complex visual interface.

The most robust finding was that the experiments consistently showed the utility of the seminal theory of Treisman and Gelade (1980), reflected in Hypothesis 1, for predicting participants' ability to filter out irrelevant information. In both experiments, results showed that participants were able to filter out the irrelevant graph objects, as predicted by the theory. Furthermore, overall RT depended on whether participants used feature- or conjunction search to find the target.

The second line of findings relates to two theories regarding the effect of visual load on distractor processing: Load Theory and Dilution Theory. Experiment 1, where participants knew the target color and thus could be distracted by a matching color of the central reactor object, showed that higher visual load had no effect on distractor processing, counter to the prediction of Load Theory. Conversely, the presence of irrelevant graphs affected distractor processing in concordance with Dilution Theory (Benoni & Tsal, 2010; Tsal & Benoni, 2010). Despite the larger prominence of Load theory, the findings in the present paper agree thus better with the more recent Dilution account. This was reflected in that Hypothesis 2b was generally supported, whereas there was either no evidence or countering evidence for Hypotheses 2a and 3. The results presented here thus offer some cadence to the claims of Benoni and Tsal (2010; Tsal & Benoni, 2010) and others (Kyllingsbæk et al., 2011; Wilson et al., 2011) that predictions from Load Theory can more accurately be explained by a dilution account of distractor processing. Furthermore, our results corroborate the findings and suggestions of Lleras et al. (2017) that Load Theory may have limited generalizability to applied contexts. This is further corroborated by the fact that the present paper presents results that conflict with Load Theory's predicted interaction between cognitive load and distractor processing: Experiment 1 showed no interaction effect between distractor processing and visual or cognitive load, as proposed in Hypothesis 3—in fact, both Experiments 1 and 2 showed faster RTs under high cognitive load.

In sum, the studies show evidence that Feature Integration Theory and Dilution Theory may be sufficiently robust to generalize to an applied context, whereas Load Theory was not supported in this manner.

Implications for Design Practice

The experiments presented in this paper studied distinct hypotheses with regards to the afforded allocation of attention to varying parts of a complex display. While the presented display was designed to mimic the interfaces used in a nuclear power plant control room (based on Braseth & Øritsland, 2013), the results should generalize to complex displays in general, given that all findings were related to predicted affordances that were derived from attention theory (which considers attention in a broad manner) and that the included variables should be present in a variety of contexts. Notably, the study manipulated cognitive load and visual load, thereby giving designers insights on how attention is allocated in wide variety of use cases and complexities. Based on this, a number of design guidelines can be derived based on the findings of the present study.

As the most consistent findings, the experiments showed the importance of reading order in predicting the afforded attention allocation in a complex visual interface. Assuming these results do indeed generalize, high priority items would thus benefit from being presented in the top-left corner of the screen in visual interfaces like the ones presented used in the experiments.

Furthermore, the experiments consistently showed that additional irrelevant objects were effectively filtered out and did not afford attention allocation. These results thus indicate that additional cluttering objects do not hinder search in complex visual displays if they are easily distinguishable from the targets users are looking for. In fact, the results of Experiment 1 showed that the irrelevant reactor object had a lower distracting effect when irrelevant graphs were present. These results indicate, perhaps counter-intuitively, that more visual clutter will reduce the effect of a salient distracting object.

As the final consistent finding, both experiments showed, that higher cognitive load improved speed at a slight cost of accuracy. While further research is needed to elucidate the mechanism behind these findings, the results thus suggest that high cognitive load may be facilitating parts of performance (i.e., RT) while hindering others (i.e., accuracy) while using complex visual interfaces.

Finally, the experiments showed that the affordances of individual color for attention allocation varies depending on the context: In the high complexity environment of Experiment 1 and 2, the effect of individual colors was only observed when participants had no knowledge of the target color. The results presented here thus represent two different cases for how designers should apply colors in their visual interfaces depending on the expected use case.

In sum, the present study may provide guidelines for designers on how visual displays afford the allocation of attention for varying degrees of cognitive and visual load, and for individual colors.

Conclusion

This paper presented two visual search experiments that tested predictions from theories of attention in a complex visual interface.

It was argued that attention theories can elucidate how attention allocation is afforded in complex visual displays, and that this can be used to improve how visual interfaces are designed by better aligning intended and actual use. Furthermore, the experiments acted as a test of whether the hypotheses of the selected theories of attention, which have proven robust in the highly controlled settings, also predict the attention allocation in more complex interfaces. Three prominent predictive theories—Feature-Integration Theory, Load Theory, and Dilution Theory—and standalone predictions on the attentional guidance and capture of color were tested simultaneously using a display that mimicked both the complex visual interfaces used in nuclear control rooms and the highly controlled displays used in experimental psychology. The results showed that several hypotheses from attention theories, most notably Feature-Integration Theory, could generalize to predict the afforded allocation of attention, and that the accuracy of the predictions related to the amount of knowledge participants had about the target.

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