Abstract

CREAGER, JAMES H. Understanding the Findability and Perceived Clickability of Shaded and Flat Objects in Almost-flat Interfaces. (Under the direction of Dr. Douglas Gillan).

Prior usability studies have suggested that shading gradients may improve the findability and perceived clickability of objects in almost-flat graphical user interfaces. The present research investigates these claims with multiple types of shading gradients. A traditional visual search paradigm was implemented to examine the rate at which shaded and flat objects could be found in almost-flat environments, and perceived depth ratings were collected to examine the magnitude and direction of depth emergent from those objects. With respect to search, convex objects with medium and high contrast gradients had high findability and were not distracting when searching for a flat object in the display. Concave objects and convex objects with low contrast gradients had high findability, but made search difficult for flat objects. With respect to depth ratings, convex objects with medium and high contrast shading gradients were consistently perceived with a raised three-dimensional shape, while perceptions were mixed for concave objects and convex objects with low contrast gradients. Findings advocate the use of almost-flat design with medium and high contrast convex shading gradients. Design guidelines are provided and theoretical implications are discussed.
Understanding the Findability and Perceived Clickability of Shaded and Flat Objects in Almost-flat Interfaces

by
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A thesis submitted to the Graduate Faculty of North Carolina State University in partial fulfillment of the requirements for the degree of Master of Science Psychology

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Dedication

To my loving wife and family. Thank you for your support and encouragement.
Biography

James (Jim) Creager holds a B.S. in Computer Science from North Carolina State University. His research examines user behavior in software interfaces, integrates human factors methods into the design cycle, and psychologically validates design.
Acknowledgements

I would like to thank my advisor, committee, professors, and all department staff who helped get this thesis to completion. It takes a lot of work to run a graduate program. Your investment into my education, research, and career is greatly appreciated. This project would not have been possible without you.
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Introduction

In software interfaces, findability (the ease with which users can locate an object or feature they know exists) and perceived clickability (the degree to which actionable elements appear to be clickable) are fundamental components of usable systems. Efficiency, effectiveness, and satisfaction all suffer when interface elements necessary for task completion are difficult to locate and activate (Rogers & Preston, 2009; Rosenbaum, Glenton, & Cracknell, 2008).

Findability and perceived clickability are influenced by visual design because users must visually search through displays and choose to interact with interface elements that appear relevant to their task goals (Findlater & McGrenere, 2007; Morville, 2005). For example, the degree to which a registration button stands out from its surroundings and looks clickable determines the likelihood of someone directing their attention to that area of the screen and deciding to click that button when they are trying to get to a registration form.

Almost-flat design is a new style of visual design that aims to make key interface elements findable and clearly clickable by emphasizing them with depth cues, such as shading gradients, amidst an otherwise flat environment (Page, 2014). This style is an amalgamation of its predecessors, realistic and flat design, which embodied the extremes of completely three-dimensional and two-dimensional appearances, respectively. Almost-flat design addresses both cognitive load problems introduced by realistic design (by reserving depth cues for important objects) and usability problems introduced by flat design, such as
the lack of clickability cues (Burmistrov, Zlokazova, Izmalkova, & Leonova, 2015; Page, 2014). Many consumer products, such as Google web apps and Android applications, have already adopted almost-flat design as their standard visual style based on these ideas.

Designers and usability practitioners have both advocated the superior usability of almost-flat design (Debus, 2013; Loranger, 2015; Meyer, 2015; Moore, 2013; Sanchez, 2012), but only a handful of published research studies provide support for this claim. Most notably, usability studies have suggested that a raised appearance from shading gradients helps users find important items in an interface and thereby increases performance on navigation tasks, while a flat appearance often causes users to disregard actionable elements resulting in decreased performance (Nielsen, 1995, 2012; Usabilla, 2013).

The aforementioned findings indicate the presence of an interesting phenomenon but leave many questions unanswered about its exact nature. Those studies did not separate the task of finding something on a page from the decision to click, nor did they verify that observed differences in performance were attributable to psychological differences in perception of shaded items. In particular, the studied interfaces lacked the control necessary to sufficiently demonstrate that shading gradients explained performance differences, rather than other aspects of modern design that often accompany almost-flat design, such as a more spacious page layout, fewer elements on a page, and larger page elements (Burmistrov et al., 2015).
The present research begins the process of validating the benefits of almost-flat design identified in previous usability studies through the use of more tightly controlled shaded stimuli and connections to established psychological theory. The present research also begins to investigate some of the potential consequences from overusing shading gradients and applying insufficient contrast to shading gradients in almost-flat environments. The hope is that through a detailed understanding of the instrumental perceptual processes involved in the use of almost-flat interfaces, design guidelines will be formed and guidance will be provided for future theoretical and computational modeling in almost-flat contexts.

**Visual Search Theory**

When a user tries to find a particular interface item (the target), they engage in a process of visual search. Guided Search Theory (GST) – one of the most widely accepted psychological models of visual search – describes the process as a progression between two phases (Wolfe, 1994, 2007; Wolfe, Cave, & Franzel, 1989; Wolfe, Horowitz, Palmer, Michod, & Van Wert, 2010; Wolfe & Gancarz, 1997). In the first phase, low-level visual features, such as colors and shapes, are parsed out of the environment rapidly and in parallel. In the second phase, guidance processes use a combination of top-down and bottom-up information, including known target characteristics and feature salience, to generate activation matrices, designate locations of interest (LOIs), and serially deploy focused attention to those locations in order of decreasing activation. While at each location, focused
attention binds features together and sends them to object recognition processes so objects can be compared to the target.

Search efficiency, measured as search time per object in the environment, is dependent on the detection of LOIs and the amount of activation at each LOI. If no LOIs are detected, then a target can be deemed absent without having to deploy attention, so search terminates very efficiently. If LOIs are detected, then attention must deploy to the LOIs, one at a time, until either the target is found or the target is deemed absent due to a quitting rule such as searching all LOIs. In the most efficient case, the LOI with the highest activation is at the target’s location; attention deploys to that location first; and the target can be deemed present without having to examine other objects (distractors) in the environment. In the least efficient case, the LOI with the lowest activation is at the target’s location, and attention deploys to the target last. Between lies an efficiency continuum depending on how many LOIs are examined before the target is found or can be deemed absent.

From an interface design perspective, the effectiveness of guidance is determined by the visual features of the target, relative to the visual features of distractors in the surrounding interface. A designer can craft a pro-search environment by emphasizing important objects with a unique visual feature while balancing salience across the environment (Treisman, 1977; Treisman & Souther, 1985; Wolfe, 2007). Then, when a targeted object is present, top-down guidance processes will detect the target’s unique feature resulting in high activation at the target’s location; bottom-up guidance processes will detect evenly
distributed salience resulting in balanced activation across the scene; and attention will be deployed to target’s location first due to its large aggregated activation. When the target is absent, few (if any) LOIs will be detected, and the target’s absence will be detected quickly, since the target’s unique feature is missing and salience is evenly distributed.

Unfortunately, feature selection is not always straightforward, and multiple considerations must be taken into account. First, not all visual features provide guidance during the second phase of search (Treisman & Gelade, 1980; Wolfe & Horowitz, 2004). Volumetric geons and line intersections are examples (Brown, Weisstein, & May, 1992; Pilon & Friedman, 1998; Wolfe & DiMase, 2003). Second, features that do provide guidance must be discriminable from features in the surrounding environment, because search efficiency decreases as similarity between the target and distractors increases (Duncan & Humphreys, 1989; Nagy & Sanchez, 1992; Treisman & Gormican, 1988). Third, many of the features that provide guidance exist on dimensions that inevitably vary in salience (Nagy & Sanchez, 1992; Treisman & Gormican, 1988; Wolfe, 2007). Variance in salience can create imbalance across the environment and be detrimental to search, because search efficiency decreases as the environment becomes more salient than the target. This is especially relevant to interface design, because users may search for an object which has not been emphasized. If the feature used for emphasis is highly salient, it will make search for the non-emphasized object more difficult.
The best way to know how a set of features influence guidance is to empirically test the features in relevant, controlled contexts (Treisman & Gelade, 1980; Wolfe, 2007). This warrants a systematic analysis of the visual features in almost-flat interfaces and subsequent controlled experiments to assess the guidance provided by those features in visual search.

**Features in Almost-flat Environments**

Almost-flat design permits a large number of visual features (e.g. colors, shapes, etc.), but the present research focuses on pictorial depth cues – specifically, shading gradients and flat luminance – which distinguish almost-flat design from its predecessor styles and have yet to be studied in a shared environment.

First, shading gradients are comprised of a vertical luminance gradient – the direction of which determines an implied three-dimensional shape (Figure 1). When the gradient transitions from light at the top to dark at the bottom, a convex (raised) appearance is implied, as if a light source shines from above. When the gradient transitions from dark at the top to light at the bottom, a concave (depressed) appearance is implied. Previous research has demonstrated that a concave target can be found efficiently among convex distractors due to its emergent depth, but the reverse search (a convex target among concave distractors) is inefficient (Aks & Enns, 1992; Kleffner & Ramachandran, 1992). These disparate findings evidence the need for context-specific empirical testing with regard to shading gradients.
Second, flat luminance refers to a consistent luminance value applied across the entire surface of an object (Figure 1). In a three-dimensional world, a consistent luminance implies a flattened shape that does not rise above or sink below the background. Previous research has shown that unique flat luminance values can be found efficiently among other flat luminance values, but only when guidance processes are able to discriminate the difference in luminance between target and distractors (Cavanagh, Arguin, & Treisman, 1990; Nagy & Sanchez, 1992; Treisman, 1982; Treisman & Gormican, 1988). These findings evidence the need for context-specific empirical testing with regard to contrast.

Figure 1. Flat and shaded interface elements. Example interface elements with different implied three-dimensional shapes: a button (convex), a toggle widget (concave), and an alert icon (flat) from left to right.

Shaded and flat objects form an interesting and unstudied combination of visual features. From a top-down perspective, convex, concave, and flat objects each have a unique three-dimensional shape that could stand out from the others during top-down guidance. From a bottom-up perspective, however, shaded objects are likely to be more salient than flat objects, because they have more depth (Ramachandran, 1988a; Treisman & Gormican, 1988; Treisman & Souther, 1985). In combination, top-down and bottom-up processes are likely to both highly activate the location of a shaded target, but they are likely to activate different
locations when searching for a flat target, which could make search inefficient. This is illustrated in Figure 2 with simple objects.

Figure 2. Illustrative activation matrices. Two displays are shown to the left: one containing a single shaded object among multiple flat objects (A) and another display containing a single flat object among multiple shaded objects (B). Illustrative top-down and bottom-up activation matrices are shown to the right of each display. Top-down matrices assume the target of search is the shaded object in (A) and the flat object in (B). In search for a shaded target among flat distractors (A), both top-down and bottom-up processes produce high activation at the location of the target and low activation at the locations of the distractors resulting in a single LOI. In search for a flat target among shaded distractors (B), top-down processes produce high activation at the location of the target and low activation at the location of the distractors, but bottom-up processes produce high activation at the location of distractors and low activation at the location of the target. When both top-down and bottom-up activations are taken into account, an LOI exists near every object in the display.

The influence of shading gradient contrast is also interesting and unstudied. As contrast decreases, three-dimensional shape becomes flatter with lower salience. Thus, when searching for a shaded target among flat distractors, both top-down and bottom-up processes
will likely produce less activation at the target’s location as the contrast across the target’s shading gradient decreases. This could make search inefficient at lower contrasts. Conversely, when searching for a flat target among low contrast gradients, top-down processes will activate distractors more, because they are more similar to the target, but bottom-up processes will activate distractors less, because they are less salient. This could make search more or less efficient, depending on the relative contribution of top-down and bottom-up processes.

In summary, predicting search efficiency in an almost-flat environment is not a trivial task. One type of process (top-down or bottom-up) could play a dominant role in guidance, or the processes could interact. Moreover, the contributions could vary when different gradient contrasts are involved. An empirical investigation is necessary to determine (a) the conditions in which shaded and flat objects are findable and (b) the conditions in which they are not findable, so design guidelines can be created.

**Perception of Three-dimensional Shape**

Following the need for findability is the need for perceived clickability. Once users find an interface element that seems like it might take them to a piece of helpful content, they assess the element for clickability. If the element does not appear actionable, users are likely to disregard it and subsequently search for an alternative path to their desired content (Nielsen, 1995, 2012; Usabilla, 2013).
The exact nature of clickability cues has not been widely studied, perhaps because many of the cues are a product of convention and experience, such as blue underlined text indicating a hyperlink, rather than physical metaphors. However, there is general theoretical agreement that a raised three-dimensional appearance offers affordances to clickability which should be perceived by both novice and expert users (Gaver, 1991; Norman, 2013).

Previous research has demonstrated that vertical luminance gradients can be effective cues to three-dimensional shape during deliberate processing and decision making. Specifically, people tend to perceive a convex (raised) shape when an object has a gradient that transitions from light at the top to dark at the bottom, as if a light source were shining from above (Ramachandran, 1988a, 1988b). But when the gradient is reversed (dark at the top to light at the bottom) perceptions become less consistent. Some people perceive a concave (depressed) shape while others perceive a convex shape (Liu & Todd, 2004).

Unfortunately, these aforementioned studies focused on either highly unusual objects or hyper-realistic shading, so it is unclear whether the aforementioned findings will hold for simple shading gradients on objects commonly used in almost-flat design.

**Research Questions**

The following research questions emerged for search and shape perception in almost-flat environments:

**RQ1** How efficiently are shaded objects found among flat objects? And how efficiently are flat objects found among shaded objects? The former question
addresses the search benefits from emphasizing a key interface element with shading, and the latter addresses consequences against search for non-emphasized items.

**RQ2** What search efficiency patterns emerge across the aforementioned search conditions? And what do the patterns reveal about the influence of features on guidance processes? These questions address the relative contribution of top-down and bottom-up processes underlying search.

**RQ3** How are shaded and non-shaded objects perceived in depth? And how consistent are those perceptions between people? These questions address the quality of clickability signifiers provided by different objects.

**RQ4** How does the level of contrast across a shading gradient influence findability and shape perception? This addresses the discrimination capabilities of guidance processes in search and changes in clickability signifiers between different degrees of shading.

The present research addressed these questions through two experiments. Experiment 1 investigated RQ1, RQ2, and RQ3 with high contrast shaded stimuli. This experiment was previously published in a proceedings article (Creager & Gillan, 2016) but is reported again to reframe the results into Guided Search Theory and expand on its theoretical impact in lieu of results from the second experiment. Experiment 2 replicated high contrast conditions from Experiment 1 and also investigated RQ4 with low and medium contrast shaded stimuli.
Together, these experiments yielded new theoretical insights and new design guidelines for almost-flat design. The subsequent sections of this paper report the details, results, and a brief discussion of each experiment followed by an integrated discussion and conclusion.

**Experiment 1**

Experiment 1 investigated the search efficiency and perceived depth of convex, concave, and flat objects in a traditional visual search task and a traditional depth rating task. With respect to visual search, it was hypothesized that both convex and concave targets (present or absent) would be found efficiently among flat distractors, because shaded objects would have a unique and highly salient depth, relative to flat objects. It was also hypothesized that flat targets (present or absent) would be processed inefficiently among shaded distractors, because shaded objects would be highly salient and distracting. With respect to depth, it was hypothesized that there would be a significant difference in perceived depth between each stimulus type.

**Method**

**Participants.** Seventeen undergraduate students (6 female) participated in a single 30-minute session for course credit. All participants self-reported either normal (11) or corrected-normal (6) vision. All participants completed every trial of the experiment, and 16 participants finished the visual search task with a mean accuracy above 90%. The remaining participant, who responded correctly to only 78% of the trials, was not included in subsequent analyses.
**Setup and materials.** Participants were seated approximately 0.7 meters away from an eye-level, 17-inch computer monitor and were asked to maintain a consistent posture and viewing angle throughout the experiment. Tasks were completed in a local PsychoPy application designed with hardware acceleration for precise response time measurements (Peirce, 2007).

**Stimuli and displays.** Three types of target and distractor stimuli were used (Figure 3), each a circle subtending 1° of visual angle (assuming a 0.7m viewing distance). A convex stimulus was formed by a vertical luminance gradient ranging from 147 cd/m² (very light grey) at the top to 12 cd/m² (very dark grey) at the bottom. A concave stimulus was formed by rotating the convex stimulus 180°. And a flat stimulus was formed by an evenly distributed luminance value of 68 cd/m² (medium grey), which was the average luminance of the shading gradients. Notably, high contrast gradients were used to ensure discriminability between flat and shaded stimuli.

Stimuli were grouped into four target-distractor pairs (convex-flat, flat-convex, concave-flat, flat-concave) and stimuli from each pair were arranged on a white background (159 cd/m²) to form different displays. Displays were generated with one of three numbers of items: 1, 6, and 12, with items placed randomly in a 7° x 7° region without overlap. In half of the displays, one of the items was a target and the remaining items were homogenous distractors. In the remaining half of the displays, all items were homogeneous distractors. This made target detection in a display size of 1 akin to a traditional choice reaction time test,
whereas larger display sizes required more complex search processing. Examples of the two target presence conditions (present, absent) are shown in Figure 4.

![Figure 3. Experiment 1 stimuli. The three types of target and distractor stimuli: flat, convex, and concave from left to right.](image)

![Figure 4. Experiment 1 example displays. An example target present display (left) and target absent display (right) for the convex-flat target-distractor pair.](image)

**Procedure.** All participants completed the visual search task first, followed by the depth rating task.

**Visual search task.** Participants first completed the visual search task. Each trial began with a fixation symbol displayed in the center of the screen for one second. This was followed by a stimulus display to which the participant would respond either target present (left Ctrl key) or target absent (right Ctrl key). The stimulus display was visible until either the participant responded or three seconds elapsed, and then a feedback message of “correct” or “incorrect” was displayed in the center of the screen for one second. If a response was not
received within three seconds, the trial was marked incorrect. Response time and accuracy were recorded.

Trials were blocked by the four target-distractor pairs (convex-flat, flat-convex, concave-flat, flat-concave), and blocks were presented in random order within-subject. Within each block, displays were presented in random order without replacement until every combination of display size (1, 6, 12) and target presence (present, absent) had been seen. This was repeated 15 times in each block for a total of 90 trials per block (3 display sizes x 2 target presence x 15 repetitions) for 360 trials over all four target-distractor pairs.

At the beginning of each block, participants were shown the upcoming target and distractor stimuli and given six practice trials, one for each combination of display size and target presence for the block. Participants were instructed to look at the fixation symbol and respond as quickly and accurately as possible once the stimulus display appeared.

**Depth ratings.** After completing the visual search task, participants were shown each of the convex, concave, and flat stimuli – one at a time – and asked to rate the apparent depth of each stimulus on a scale of -10 to 10. Participants were instructed that a negative value indicated the stimulus appeared depressed into the screen, a value of zero indicated the stimulus appeared flat, and a positive value indicated the stimulus appeared raised out of the screen.
Results and Discussion

**Visual search.** Mean response times for correct trials in each display condition are shown in Figure 5, and the corresponding slopes (computed via method of least squares) are shown in Table 1. Significant departures of slope from zero are indicated by asterisks, as determined by a one sample t-test.

![Figure 5. Experim](image)

Figure 5. Experiment 1 response time graphs. Mean response times are shown for correct responses in the four target-distractor conditions: search for a convex target among flat distractors (top left), flat target among convex distractors (bottom left), concave target among flat distractors (top right), and flat target among concave distractors (bottom right). Target present and target absent conditions are plotted separately.
Table 1. Experiment 1 response time slopes.

<table>
<thead>
<tr>
<th>Target-distractor</th>
<th>Slope (ms/item)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Target present</td>
</tr>
<tr>
<td>Convex-flat</td>
<td>0</td>
</tr>
<tr>
<td>Concave-flat</td>
<td>4</td>
</tr>
<tr>
<td>Flat-convex</td>
<td>6 *</td>
</tr>
<tr>
<td>Flat-concave</td>
<td>19 *</td>
</tr>
</tbody>
</table>

Note. * = p < .05 (significantly different from zero)

A two-way repeated measures ANOVA was performed to examine the effects of target-distractor pair and target presence on the slope of reaction time over display size. There were significant main effects of target-distractor pair, $F(3, 45) = 32.26, p < .001, \eta^2 = .47$, and target presence, $F(1, 15) = 14.81, p < .001, \eta^2 = .10$. There was also a significant two-way interaction of target-distractor pair and target presence, $F(3, 45) = 17.30, p < .001, \eta^2 = .17$.

Bonferroni post hoc tests revealed the slopes of target present and target absent searches were significantly different when searching for a flat target among convex distractors ($p = .003$) and when searching for a flat target among concave distractors ($p < .001$). However, the slopes of target present and target absent searches showed non-significant differences when searching for a convex target among flat distractors ($p = 1.00$) and a concave target among flat distractors ($p = 1.00$).

In summary, both convex and concave targets yielded efficient response time slopes in target present and target absent conditions. These results supported the hypothesis that convex and concave stimuli could be processed efficiently and suggested shading gradients
could be used to increase the findability of key elements in an almost-flat interface. When the target was flat, however, efficiency varied by distractor type. Results supported the hypothesis that flat targets would be processed inefficiently among concave distractors, but they did not support the hypothesis that flat targets would be processed inefficiently among convex distractors, because target present search was efficient. This suggested concave shading had the consequence of preventing attention from deploying to flat targets efficiently, but convex shading seemed to avoid those consequences in the target present condition. Thus, the findability of non-emphasized, flat elements was better in an environment with convex objects, compared to concave objects.

**Depth ratings.** Mean depth ratings for each stimulus are shown in Figure 6. The impact of stimulus type on depth ratings was analyzed with a one-way repeated measures ANOVA. Overall, stimulus type had a significant impact on depth ratings, $F(2, 30) = 10.45$, $p < .001$, $\eta^2 = .37$. Bonferroni post hoc tests revealed depth ratings for the convex stimulus were significantly different from both the flat stimulus ($p < .001$) and the concave stimulus ($p = .01$). However, the difference in depth ratings between the concave stimulus and flat stimulus was non-significant ($p = .52$).

These results partially supported the hypothesis that perceived depth would significantly different between each stimulus type, but indicated the concave stimulus was perceived more similar to the flat stimulus than expected. Given that the concave stimulus was designed to be the exact opposite of the convex stimulus, average depth ratings for the
A concave stimulus were expected to be approximately the inverse of the convex stimuli. One potential explanation for the unexpected result was that some people could have perceived a concave shape while others perceived a convex shape (similar to Liu & Todd, 2004). This would produce a mix of positive and negative depth ratings that would average to a value closer to zero.

![Figure 6. Experiment 1 depth rating graph. Mean depth ratings are shown for each stimulus type.](image)

To examine this possibility, depth ratings were categorized by the perceived shape specified in the depth rating task instructions. Stimuli given a zero depth rating were categorized as flat. Stimuli given a positive depth rating were categorized as convex. And stimuli given a negative depth rating were categorized as concave.
Counts and mean depth ratings for each combination of stimulus and perceived shape are shown in Table 2. All participants perceived the flat stimulus to be flat in shape, and all but two participants perceived the convex stimulus as convex. However, the concave stimulus was not consistently perceived as concave. A large number of convex perceptions brought the overall mean for the concave stimulus closer to zero.

Table 2. Experiment 1 frequency and depth of perceived shape.

<table>
<thead>
<tr>
<th>Stimulus</th>
<th>Perceived Shape</th>
<th>N</th>
<th>Perceived Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat</td>
<td>Flat</td>
<td>16</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>Convex</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Concave</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Convex</td>
<td>Flat</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Convex</td>
<td>14</td>
<td>5.36</td>
</tr>
<tr>
<td></td>
<td>Concave</td>
<td>2</td>
<td>-3.00</td>
</tr>
<tr>
<td>Concave</td>
<td>Flat</td>
<td>1</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>Convex</td>
<td>6</td>
<td>3.83</td>
</tr>
<tr>
<td></td>
<td>Concave</td>
<td>9</td>
<td>-5.67</td>
</tr>
</tbody>
</table>

Note. A dash indicates no participants were in that group.

In summary, participants tended to perceive convex and concave stimuli as having depth, relative to the background, and flat stimuli as having no depth. This confirmed an emergent sense of depth differentiated concave and convex stimuli from flat stimuli. However, a large number of participants interpreted the depth of the concave stimulus opposite the intended direction. These results indicated convex stimuli would be better for
affordances and perceived clickability due to a consistent interpretation of a raised three-dimensional shape.

**Experiment 2**

Based on the combined results of the visual search and depth rating tasks in Experiment 1, convex shading proved to be an effective visual treatment for improving the findability and perceived clickability of an object in an almost-flat interface. However, the convex stimulus used in Experiment 1 had a high contrast to maximize apparent depth, which was not representative of the wide array of shading gradients used in common practice, particularly those that are more subtle.

Since the appearance of a convex object approaches that of a flat object as gradient contrast decreases, a convex target with a subtle gradient would likely have less salience, be more similar to flat distractors, and have fewer affordances to clickability. If contrast were low enough, activation levels could become indiscriminable between target and distractors during guidance, and efficient searches documented in Experiment 1 could become inefficient. Similarly, clickability signifiers could be lost at lower contrasts due to decreased depth perception and/or inconsistent perception of three-dimensional shape.

To investigate the impact of gradient contrast on findability and perceived clickability, Experiment 2 used the same tasks from Experiment 1 with new convex stimuli that varied in contrast. With respect to visual search, it was hypothesized that search for medium and high contrast convex targets among flat distractors would be efficient in both
target present and target absent conditions (similar to Experiment 1), but search for low contrast convex targets would be inefficient due to poor discriminability during guidance. Also, it was hypothesized that search for a flat target among medium and high contrast convex distractors would follow a mixed search pattern wherein the target present search would be efficient and the target absent search would be inefficient (similar to Experiment 1), but search among low contrast convex distractors would be inefficient due to poor discriminability during guidance.

With respect to perceived depth, it was hypothesized that all stimuli (flat, low contrast, medium contrast, and high contrast) would differ significantly in depth. With respect to perceived shape, it was hypothesized that there would be a significant difference in the number of people who would perceive the low, medium, and high contrast stimuli as convex such that the low contrast stimulus would be perceived as non-convex more than the medium and high contrast stimuli.

Method

Participants. 28 undergraduate students (13 female) were recruited from an introductory psychology course and were compensated with course credit. All participants (12 with corrective lenses) had at least 20/20 visual acuity as measured by a Snellen test and had normal contrast sensitivity as measured by a Pelli-Robson test (Pelli, Robson, & Wilkins, 1988). Two participants showed signs of color deficiency (one with mild tritanopia; the other with moderate protanopia and deuteranopia) as measured by Waggoner’s ColorDx test
All participants completed all of the experimental tasks, but two participants, one of whom showed the aforementioned signs of tritanopia, had an accuracy below 90% and were removed from subsequent analyses. The participant with signs of protanopia and deuteranopia had results similar to normal color vision participants, so all of the remaining participants were analyzed together.

**Setup and materials.** Setup and materials were the same as Experiment 1.

**Stimuli and displays.** Four types of target and distractor stimuli were used (Figure 7), each a circle subtending 1° of visual angle as in Experiment 1: flat stimuli had an evenly distributed luminance value of 80 cd/m² (medium grey); low contrast stimuli were formed by a vertical convex luminance gradient ranging from 104 cd/m² (slightly light grey) at the top to 56 cd/m² (slightly dark grey) at the bottom; medium contrast stimuli were formed by a vertical convex luminance gradient ranging from 128 cd/m² (light grey) at the top to 32 cd/m² (dark grey) at the bottom; and high contrast stimuli were formed by a vertical convex luminance gradient ranging from 152 cd/m² (very light grey) at the top to 8 cd/m² (very dark grey) at the bottom. Notably, the difference in luminance across each gradient increased by a consistent 48 cd/m² between each level of contrast; the average luminance of all stimuli was 80 cd/m² - the luminance of the flat stimuli; and flat and high contrast stimuli were the same as the flat and convex stimuli in Experiment 1.
Stimuli were grouped into six target-distractor display conditions based on target-distractor type (convex-flat or flat-convex) and contrast of the convex stimuli (low, medium, or high): low-flat, medium-flat, high-flat, flat-low, flat-medium, and flat-high. Distractors were homogeneous and displays were generated in the same way as Experiment 1. Notably, the high-flat and flat-high conditions replicated the convex-flat and flat-convex conditions in Experiment 1.

![Stimuli](image)

Figure 7. Experiment 2 stimuli. Flat, low contrast convex, medium contrast convex, and high contrast convex from left to right. The flat and high contrast convex stimuli were the same as the flat and convex stimuli in Experiment 1.

**Procedure.** Participants completed vision testing, the visual search task, and the depth rating task during a single 30-minute session. Vision testing always came first, and the order of visual search and depth rating tasks was counterbalanced.

**Visual search task.** The visual search task followed the same procedure as Experiment 1 with the exceptions that conditions were added for the new stimuli and each trial type was repeated ten times, instead of fifteen. With two target types (convex, flat), three contrasts (low, medium, high), three display sizes (1, 6, 12), target presence (present, absent), and ten repetitions, there were a total of \((2 \times 3 \times 3 \times 2 \times 10)\) 360 trials.
**Depth rating task.** The depth rating task followed the same procedure as Experiment 1 with the exceptions that the new stimuli were used and each stimulus was presented three times, instead of one, for a total of (4 x 3) 12 trials. Trials were blocked by occurrence, and stimuli were presented in random order within blocks.

**Results and Discussion**

**Visual search.** Mean response times for correct trials in each display condition are shown in Figure 8, and the corresponding slopes (computed via method of least squares) are shown in Table 3. Significant departures of slope from zero are indicated by asterisks, as determined by a one sample t-test.

A three-way Repeated Measures ANOVA (α = .05) with Greenhouse-Geisser corrections was performed to examine the effects of target type (flat, convex), contrast (low, med, high), and target presence (present, absent) on the slope of reaction time over display size. There were significant main effects of target type, $F(1, 25) = 60.98$, $p < .001$, $\eta^2 = .32$, contrast, $F(1.36, 33.92) = 34.85$, $p < .001$, $\eta^2 = .15$, and target presence, $F(1, 25) = 34.12$, $p < .001$, $\eta^2 = .10$. There were also significant two-way interactions of target type by contrast, $F(2, 50) = 14.55$, $p < .001$, $\eta^2 = .04$ and target type by target presence, $F(1, 25) = 40.10$, $p < .001$, $\eta^2 = .10$. 


Figure 8. Experiment 2 response time graphs. Mean response times are shown for correct responses in the six target-distractor conditions: search for a low contrast convex target among flat distractors (top left), medium contrast convex target among flat distractors (top middle), high contrast convex target among flat distractors (top right), flat target among low contrast convex distractors (bottom left), flat target among medium contrast convex targets (bottom middle), and flat target among high contrast convex distractors (bottom right). Target present and target absent conditions are plotted separately.
Table 3. Experiment 2 response time slopes.

<table>
<thead>
<tr>
<th>Target-distractor</th>
<th>Target present</th>
<th>Target absent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-flat</td>
<td>8 *</td>
<td>8 *</td>
</tr>
<tr>
<td>Medium-flat</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>High-flat</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Flat-low</td>
<td>26 *</td>
<td>48 *</td>
</tr>
<tr>
<td>Flat-medium</td>
<td>11 *</td>
<td>30 *</td>
</tr>
<tr>
<td>Flat-high</td>
<td>7 *</td>
<td>25 *</td>
</tr>
</tbody>
</table>

Note. * = p < .05 (significantly different from zero)

With respect to the target type by contrast interaction, planned contrasts with Bonferroni corrections revealed that when searching for convex target among flat distractors, differences in search slopes were significant between low and medium contrast targets (p < .001) and low and high contrast targets (p < .001), but differences between medium and high contrast targets were non-significant (p = 1.00). This is visualized along the top row of Figure 8. When searching for a flat target among convex distractors, differences in search slopes were significant between low and medium contrast distractors (p = .02) and low and high contrast distractors (p < .001), but differences were non-significant between medium and high contrast distractors (p = 1.00). This is visualized along the bottom row of Figure 8.

With respect to the target type by target presence interaction, planned contrasts with Bonferroni corrections revealed that the difference in search slopes between convex target present and convex target absent searches was non-significant (p = 1.00), as visualized along the top row of Figure 8. On the contrary, search slopes were significantly different between flat target present searches and flat target absent searches (p < .001), as visualized along the
bottom row of Figure 8. All crosses of target presence between flat and convex targets were significant (all \( p < .001 \)).

In summary, search for convex targets among flat distractors was efficient and robust to contrast and target presence effects – replicating and extending the findings of Experiment 1. Search slopes for low contrast targets were, on average, slightly steeper than medium and high contrast targets but still very efficient. These results supported the hypothesis that search for medium and high contrast convex targets among flat distractors would be efficient but contradicted the hypothesis that low contrast targets would be found inefficiently due to efficient search in the low-flat condition. Although the latter result was unexpected, high findability for all convex target contrasts was positive from an application standpoint.

In regard to flat target search, results supported the hypotheses that search would be inefficient among low contrast distractors and follow a mixed pattern (i.e. efficient when target present and inefficient when target absent) among medium and high contrast distractors. This indicated that medium and high contrast gradients resulted in similar visual search performance, but low contrast gradients reduced findability, relative to higher contrast gradients.

**Depth ratings.** Mean depth ratings for each stimulus are shown in Figure 9. The impact of stimulus type on depth ratings was analyzed with a one-way repeated measures ANOVA. Overall, stimulus type had a significant impact on depth ratings \( F(1.62, 40.43) = 18.48, p < .001, \eta^2 = .24 \). Planned contrasts with Bonferroni corrections revealed the flat
stimulus had significantly lower ratings than the low \((p = .02)\), medium \((p < .001)\), and high \((p < .011)\) contrast stimuli. The low contrast stimulus had significantly lower ratings than the medium \((p = .006)\) and high \((p < .001)\) contrast stimuli. However, the difference between medium and high contrast stimuli was non-significant \((p = .25)\).

![Figure 9](image)

Figure 9. Experiment 2 depth rating graph. Mean depth ratings are shown for each stimulus type.

As shown in Experiment 1, a user’s perception of three-dimensional shape may match a designer’s intentions (congruent) or may not (incongruent). To examine the impact of contrast on congruent convex shape perception, ratings of shaded stimuli were categorized as either convex (a positive depth rating) or not (a zero or negative depth rating), and McNemar’s chi-squared test for paired samples was conducted to examine whether perceived shape (convex or non-convex) varied between stimulus contrasts (low, medium, or high).
There was a significant difference in the proportion of shape perception between low and medium contrast stimuli, $\chi^2 (1) = 7.00, p = .008$, and between low and high contrast stimuli, $\chi^2 (1) = 6.40, p = .01$, such that low contrast stimuli were more frequently perceived as non-convex (incongruently). However, the difference between medium and high contrast stimuli was non-significant, $\chi^2 (1) = 0.33, p = .56$. Frequencies are shown in Table 4.

Table 4. Experiment 2 frequency of perceived convexity.

<table>
<thead>
<tr>
<th>Contrast</th>
<th>Perceived Shape</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Convex</td>
<td>Non-convex</td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>15</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>Medium</td>
<td>22</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>High</td>
<td>23</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

In summary, depth ratings were generally higher and more consistent when stimulus contrast was higher with the exception of the non-significant difference between medium and high contrast gradients. This result partially supported the hypothesis that all stimuli would differ significantly in depth. A non-significant difference between medium and high contrast stimuli, while unexpected, was positive from an application standpoint, because it suggested both types of stimuli could provide effective clickability signifiers. In addition, results strongly supported the hypothesis that incongruent perceptions would be more common among the low contrast stimulus than medium and high contrast stimuli and suggested low
contrast stimuli would be a poor choice for a designer trying to convey clickability signifiers, due to their inconsistent interpretation.

**General Discussion**

Results from Experiments 1 and 2 revealed that shaded objects had the benefit of high findability in almost-flat environments. Search was very efficient for all types of shaded targets among flat distractors, even when the target’s gradient contrast was low and the target was absent. From a theoretical perspective, these results indicated activation from a present shaded target was large enough to reliably attract attention early in the search process, allowing quick identification. Moreover, activation at flat distractor locations was low enough to not attract attention, allowing an absent target to be detected quickly. This agreed with similar findings documented in prior research that studied target objects with a unique feature and high salience, relative to other objects in the environment (Treisman, 1977, 1985; Treisman & Souther, 1985).

Based on this “feature search” pattern, wherein both target present and target absent searches were efficient, three conclusions were drawn about guidance provided by the stimuli. First, shaded objects had a visual feature (depth) that influenced guidance. The individual contributions of depth to top-down and bottom-up activation of shaded targets were not separable in this experimental design, but their combination was sufficient for discrimination during guidance in target present conditions. Second, flat objects were not salient and produced negligible bottom-up activation. This was supported by efficient search
in target absent conditions. Third, low contrast shaded objects yielded slightly less guidance than higher contrast gradients, as evidenced by slightly steeper search slopes. This could have been due to increased similarity with distractors (top-down), a decrease in salience (bottom-up), or both.

Results from Experiments 1 and 2 also revealed that shaded objects had three notable consequences for flat object findability in almost-flat environments. First, all flat target absent searches were inefficient, regardless of distractor shading type and contrast. This indicated all shaded objects had a noteworthy salience yielding enough bottom-up activation to attract attention, even when shaded objects were not the target. Similar salience problems have been documented in prior research with a variety of other visual features (Treisman, 1977, 1985; Treisman & Souther, 1985).

Second, flat target present search was inefficient when distractors had concave shading. This indicated concave objects were very salient and yielded enough bottom-up activation to distract guidance from the combined top-down and bottom-up activation of a present flat target. Comparing flat target present searches between high contrast concave distractors (inefficient) and high contrast convex distractors (efficient) revealed that convex distractors were less salient and distracting than concave distractors. This could be explained by the “familiarity effect” which claims distractor salience is lower when distractor features are more familiar to the viewer (Shen & Reingold, 2001; Wang, Cavanagh, & Green, 1994; Yamani & McCarley, 2011). Specific to shading, Ramachandran (1988a) noted that convex
shading is ubiquitous in the real world and much more common than concave shading, which would likely make convex gradients more familiar and less salient to bottom-up guidance processes.

A third consequence of shading emerged from flat target present search among low contrast convex gradients, which was inefficient. Comparing flat target present searches between low contrast distractors (inefficient) and medium and high contrast distractors (efficient) revealed that top-down discrimination was less effective when similarity between the target and distractors was higher. Bottom-up processes were ruled out, because the paragraphs above established flat objects had negligible salience and bottom-up activation. This explanation agreed with prior literature which reported search efficiency decreased as target-distractor similarity increased (Duncan & Humphreys, 1989). Fortunately, medium and high contrast convex distractors avoided negative consequences in the target present condition, because top-down activation from the flat target was large enough to outmatch bottom-up activation from the salient distractors.

Finally, depth ratings in Experiments 1 and 2 revealed some types of shading had the benefit of conveying consistent clickability signifiers, while other types of shading had the consequence of conveying inconsistent clickability signifiers. Medium and high contrast convex gradients consistently conveyed a sense of depth and a raised three-dimensional shape, which was effective for reliably signifying clickability. Concave and low contrast
convex gradients, on the other hand, were interpreted inconsistently and often opposite the intended direction of depth, which resulted in mixed clickability signifiers.

In conclusion, these findings indicated medium and high contrast convex shading gradients have design utility for improving findability and perceived clickability in almost-flat environments. The moderate salience of medium and high contrast convex objects balanced well with the low salience of flat objects in visual search, and the raised appearance of medium and high contrast convex objects mimicked appearance of a physical button waiting to be pressed. In addition, these findings indicated that, when possible, medium and high contrast convex gradients should be used instead of concave and low contrast convex gradients to prevent distraction during search and misinterpretation of clickability signifiers.

However, this study’s limitations must be taken into account when applying these findings. First, ecological validity was limited because this study intentionally used simple displays. Tight experimental control was necessary for assessing the guidance provided by shaded objects, but in practice, guidance would also be influenced by many other features that typically appear in software interfaces. Future research could investigate competing guidance and facilitation effects in an ecological almost-flat environment. Second, the search aspect of this study focused on findability (how easily users can locate objects they know exist) and only indirectly addressed discoverability (how easily users can encounter content of which they were previously unaware), which is also an important quality in software interfaces. For example, many on-screen alerts are not expected by users but should be
encountered and attended to. Future research could investigate the degree to which shading gradients are capable of bottom-up attentional capture and increasing the likelihood of a user encountering unexpected content.
References


