Peripheral Popout: The Influence of Visual Angle and Stimulus Intensity on Popout Effects

Carl Gutwin[1], **Andy Cockburn**[2], **and Ashley Coveney**[1]

[1]Department of Computer Science
University of Saskatchewan
Saskatoon, Canada
gutwin@cs.usask.ca

[2]Computer Science and Software Engineering
University of Canterbury
Christchurch, New Zealand
andy@cosc.canterbury.ac.nz

ABSTRACT

By exploiting visual popout effects, interface designers can rapidly draw a user's attention to salient information objects in a display. A variety of different visual stimuli can be used to achieve popout effects, including color, shape, size, motion, luminance, and flashing. However, there is a lack of understanding about how accurately different intensities of these effects support popout, particularly as targets move further from the center of the visual field. We therefore conducted a study to examine the accuracy of popout target identification using different visual variables, each at five different levels of intensity, and at a wide range of angles from the display center. Results show that motion is a strong popout stimulus, even at low intensities and wide angles. Identification accuracy decreases rapidly across visual angle with other popout stimuli, particularly with shape and color. The findings have relevance to a wide variety of applications, particularly as multi-display desktop environments increase in size and visual extent.

Author Keywords

Information visualization; popout; peripheral vision.

ACM Classification Keywords

H.5.m. Information interfaces and presentation (e.g., HCI).

INTRODUCTION

Popout is a phenomenon in visual perception in which an object is immediately distinguishable from a field of distractor objects because of its unique visual properties [16,21,35]. For example, a red circle in a field of blue circles "pops out" and is immediately noticeable (Figure 1). Popout occurs because of the ability of the human visual system to process visual features in an entire scene without conscious attention [21,35]. This broad parallel processing ability means that popout occurs very quickly (within 200-250ms [16]), and is independent of the number of distractors – a red circle pops out whether there are 10 or 100 blue circles.

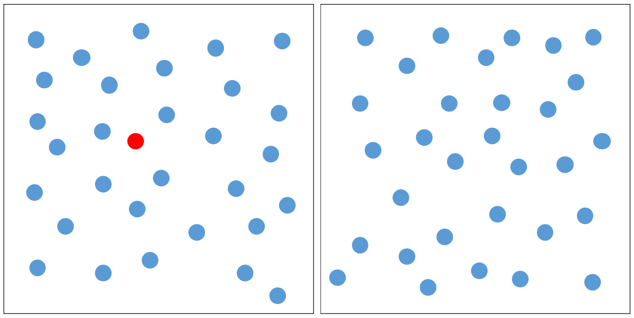

Figure 1. Popout of a red circle in a field of blue circles. Left: target present. Right: target not present. From Healey [16].

Popout can be very useful in the design of visual information presentations, because the effect can be used to draw the user's attention to important items in the display. Since the user's visual focus is limited to a small region of a screen, popout can provide visual notification from other areas, without requiring that the user continuously scan the display. As Raj and Rosenholtz state, "an alert that 'pops out' will draw our attention, and can easily be noticed even if we are not looking right at it" [32, p. 89].

The fact that popout draws attention "even if we are not looking right at it" is a critical part of its value for information presentation – but the degree to which popout works if a target is located further into peripheral vision is not well studied (despite a great many studies on different aspects of popout in general). Understanding how the distance from visual focus affects popout is important, because display environments are becoming larger and larger – with triple-monitor setups, curved widescreen panels, and large-format displays now common. In these settings, objects could appear far from the user's focus, and it is not clear whether popout will continue to draw the user's attention when it appears at a large visual angle from the focus point.

In addition, it is likely that the different visual variables that have been shown to pop out (e.g., Healey [16] discusses hue, luminance, shape, motion, flashing, orientation, and size) could be affected differently by increasing angle, because of the characteristics of the peripheral visual field. The distribution and density of cone, rod, and ganglion cells in the retina means that peripheral vision has lower acuity and is less able to see color, but has good sensitivity to luminance, contrast, and motion [1,5,37,39].

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To determine whether popout works in peripheral vision, we carried out a laboratory study that tested people's ability to see popout targets that were represented using six visual variables and five levels of difference between the target and the distractors (termed 'intensity'). The visual variables (hue, luminance, size, shape, motion, and flashing) have all been shown in previous research to exhibit popout effects [9,18,19,21,27,36]. The study used a three-monitor setup that allowed targets to be shown up to 62° from center in either direction. Participants were shown a field of distractor objects (and possibly a popout target) for 240ms, and were asked to indicate whether there was a target present. Our study considered two main questions: whether increasing horizontal angle reduces people's sensitivity to popout; and how the six different visual variables differ across their five levels of intensity. We also looked at other issues such as differences between the left and right visual fields, and whether the monitor bezel reduces performance.

The study provides several novel findings about people's ability to perceive popout effects in the periphery:

- For visual variables *hue*, *shape*, and *size*, there were strong negative effects of increasing angle (e.g., at level 3 of hue and shape, accuracy fell from 90% at ±6° to less than 20% at ±26°).
- At wider angles for lower levels of several variables, accuracy was near zero; this suggests that attempts to use subtle effects to attract attention are likely to be unnoticed for users with large displays.
- For *motion*, *luminance*, and *flashing*, increasing angle had less of an effect (e.g., accuracy above 70% even at 62° and level 3 of the variable); however, there were still substantial effects at the lowest levels of intensity.
- A preliminary follow-up study suggested that the effects of individual variables may be additive (i.e., it may be possible to combine variables to achieve larger pop-out).

Our study provides new understanding of how popout works across the large display settings that are now common, and shows that some approaches to achieving popout are unlikely to work in many scenarios. Our work provides valuable baseline information for designers who wish to use popout in large-scale information presentations.

RELATED WORK

Peripheral vision

The human visual field covers approximately 135° vertically and 210° horizontally (Figure 2), and is often divided into regions based on evidence about visual performance [14,40].

- *Central* vision is the region at the user's visual focus, and is characterized by high acuity and good color discrimination, due to the presence and density of cone cells in the fovea. The central region covers 5° of visual angle (2.5° on each side of center).
- *Paracentral* vision is the region immediately outside the foveal central region, and covers 8° of the visual field (4° on each side of center). Paracentral vision has a higher acuity than peripheral vision, although it does not have the cone-cell density of the central region.
- *Near-peripheral* vision is the region between 8° and 30°, based on evidence of a of a drop in acuity and color perception at 30° [14]. The near-peripheral region has a higher density of rod cells than other areas of the retina, with rod density declining rapidly towards the central region, and more graduadually away from it.
- *Mid-peripheral* vision covers the region from 30° to 60° from center, and defines the approximate limit of upwards peripheral vision.
- *Far-peripheral* vision covers the region from 60° to the boundary of the visual field (approximately 105° from center horizontally, and 70° downwards).

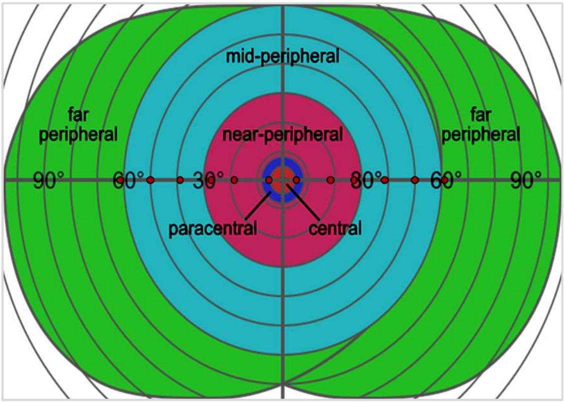


Figure 2. Regions in the human visual field (redrawn from [40]). Red dots indicate target locations in study.

Perception of stimuli in peripheral vision

Many studies have considered people's abilities to detect different types of stimuli in the peripheral visual field, although these have not considered the specific phenomenon of popout. Some tests have been consolidated into standard diagnostic procedures in optometry – for example, *perimetry* is the measurement and mapping of light sensitivity in the visual field, and involves testing a patient's ability to detect static or moving lights of different intensity at different locations in peripheral vision.

Researchers have also looked at other stimuli in addition to light intensity. Color is commonly considered: studies using constant-size stimuli show a decrease in hue discrimination in peripheral vision (e.g., [26]), but other studies that adjust the size of the stimulus proportional to the density of cones have shown that people can successfully differentiate hues [1]. Letter recognition has also been tested – early studies showed that response times significantly increased beyond 3° from the center of vision [10]. Response to motion also differs across the visual field. Studies have shown that for slowly-moving targets, response time and error in estimation of speed both increased with increasing angle from central vision; however, for fast-moving targets, response time and accuracy were unaffected [37].

Popout as a perceptual phenomenon

The observation that some visual features can be detected very rapidly has been made by numerous researchers in vision, perception, and visual attention. The processing of these visual features was initially called "pre-attentive" because detection of these stimuli appears to occur before focused attention can take place (i.e., less than the 200-250ms it takes to change visual focus [16]). Early studies coined the term *popout* because objects with unique visual properties seem to "pop out of the display" [35], regardless of the number of distractor objects – that is, visual search time is constant, not linear in the number of distractors.

Researchers have found that several different features (or *visual variables*) can pop out – in a review of the area, Healey [16] identifies sixteen different features (orientation, length, closure, size, curvature, density, number, hue, luminance, intersection, terminators, 3D depth, flicker, motion direction and velocity, and lighting direction) that have all been shown in prior studies to create popout effects. In addition, numerous studies have considered variations on the basic question – such as whether popout occurs when the target is composed of a combination of visual features (conjunction search), or whether popout occurs in situations where there are multiple kinds of distractors. Studies of popout use two main methods to test perception: either participants are asked to visually search a scene until they find a target object (here completion time is the dependent measure), or participants are shown a field of objects for 100-250ms, and are asked to state whether the field contained the target (here, accuracy is the dependent measure).

Several theories have been proposed to explain popout (for details, see Healey's review [16]). For example, Triesman's Feature Integration Theory [35] suggests that the human visual system maintains a set of feature maps for different visual attributes (such as color or shape). These maps are encoded and accessed in parallel, leading to the fast response time and the independence from the number of distractors. Another theory suggests that our early visual system is able to identify textural features called "textons," which are blobs with visual properties such as hue and shape, plus line terminations and crossings [21]. A third theory ("guided search") suggests that we process visual scenes using both bottom-up maps (similar to Triesman's) and top-down maps that encode user interest in specific properties (e.g., if a person is trying to find a blue item) [41].

An important aspect of several different theories is the recognition that the degree of popout is affected by the difference between the target object and the distractor objects for a specific visual variable. For example, "a long vertical line can be detected immediately among a group of short vertical lines, but a medium-length line may take longer to see" ([16], p. 1173). Duncan and Humphreys [7] identify two different types of similarity that can affect the perception of popout: first, as similarity between targets and non-targets increases, search efficiency decreases; and second, as the similarity between different non-target objects decreases (i.e., the distractors have a wider range of visual features), search efficiency also decreases.

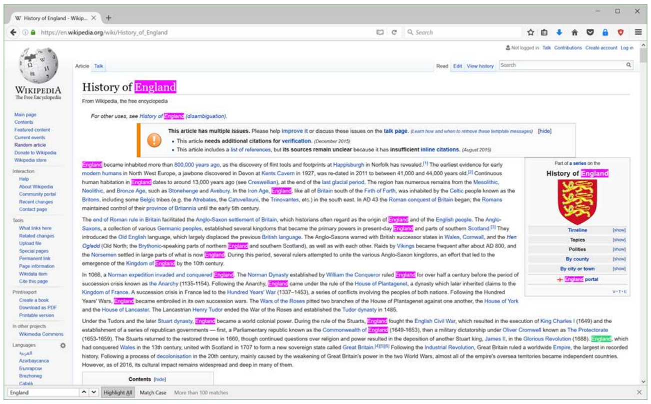
There have been only a few studies of how perception of popout varies with distance from visual focus, and these have considered only small angular distances. Experiments by Carrasco and colleagues looked at popout in a conjunction search (using line orientation and hue), where a field of up to 36 objects was shown on a single monitor for either 62ms or 104ms [4]. They compared accuracy when the popout targets appeared at angles of 0.7° – 3.5° from the fixation point, and found that accuracy decreased significantly as angular distance increased. A later study (using line orientation as the visual variable and an 84ms presentation, again on a single monitor) tested angles of 4°, 8°, and 12° from center, and showed a similar degradation of accuracy [27].

Popout in information visualization

The popout effect is well known in the field of information visualization, and several guides to designing visualizations discuss how the effect can be used [25,39]. The attention-drawing capability of popout is frequently mentioned in these guides: for example, Munzner states "An example of preattentive processing is the visual popout effect that occurs when a single yellow object is instantly distinguishable from a sea of grey objects, or a single large object catches one's eye. Exploiting pre-cognitive processing is desirable in a visualization system so that cognitive resources can be freed up for other tasks" ([28], p. 5). Similarly, Ware's textbook on information visualization suggests that popout is a useful technique for attracting the user's attention (for example, in visual monitoring tasks): "In displaying information, it is often useful to be able to show something 'at a glance.' If you want people to be able to instantaneously identify some mark on a map as being of type A, it should be differentiated from all other marks in a pre-attentive way" ([39], p. 165).

Several prototype and commercial systems have been built that use the idea of popout [18,19,24,34]. For example, the Popout Prism web browser [34] uses color highlighting and magnification to enhance the visibility of keywords specified by the user; and Gajos's Visual Popout interface highlighted recently-used items in pink [24]. In addition, several recent web and PDF viewers implement visual effects for text searches that can allow items to pop out. Figure 3 shows an example from the Firefox browser – in the figure, the user has searched for "England," and all text matches are highlighted in pink, which pops out from the mostly-black text. In addition, one match is considered to be the "current" match (and moves forward by pressing Control-G) – and this text is highlighted in green, with the intention that the large difference in color will be enough to draw the user's attention to the location of the text.

However, despite these implementations, and despite the field's statements that popout can be useful for drawing the user's attention (which implies that the effect is occurring outside of foveal vision), few guidelines discuss the issue of how perception of popout changes when the target is in the user's peripheral vision. Some texts, such as Ware's, state general principles indicating that sensitivity to color and small targets is reduced in the periphery, so other modes such as motion or auditory cues should be used instead [39] – but there are few details about exactly where and how people's sensitivity to different visual variables diminishes. Therefore, in the study described next, we set out to determine this information for a range of visual variables.



History of England

From Wikipedia, the free encyclopedia

For other uses, see History of England (disambiguation).

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- This article **needs additional citations for verification**. *(December 2015)*
- This article includes a list of references, but **its sources remain unclear** because it has **insufficient inline citations**. *(August 2015)*

England became inhabited more than 800,000 years ago, as the discovery of flint tools and footprints at Happisburgh in Norfolk has revealed.[1] The earliest evidence for early modern humans in North West Europe, a jawbone discovered in Devon at Kents Cavern in 1927, was re-dated in 2011 to between 41,000 and 44,000 years old.[2] Continuous human habitation in England dates to around 13,000 years ago (see Creswellian), at the end of the last glacial period. The region has numerous remains from the Mesolithic, Neolithic, and Bronze Age, such as Stonehenge and Avebury. In the Iron Age, England, like all of Britain south of the Firth of Forth, was inhabited by the Celtic people known as the Britons, including some Belgic tribes (e.g. the Atrebates, the Catuvellauni, the Trinovantes, etc.) in the south east. In AD 43 the Roman conquest of Britain began; the Romans maintained control of their province of Britannia until the early 5th century.

The end of Roman rule in Britain facilitated the Anglo-Saxon settlement of Britain, which historians often regard as the origin of England and of the English people. The Anglo-Saxons, a collection of various Germanic peoples, established several kingdoms that became the primary powers in present-day England and parts of southern Scotland.[3] They introduced the Old English language, which largely displaced the previous British language. The Anglo-Saxons warred with British successor states in Wales, Cornwall, and the *Hen Ogledd* (Old North; the Brythonic-speaking parts of northern England and southern Scotland), as well as with each other. Raids by Vikings became frequent after about AD 800, and the Norsemen settled in large parts of what is now England. During this period, several rulers attempted to unite the various Anglo-Saxon kingdoms, an effort that led to the emergence of the Kingdom of England by the 10th century.

In 1066, a Norman expedition invaded and conquered England. The Norman Dynasty established by William the Conqueror ruled England for over half a century before the period of succession crisis known as the Anarchy (1135-1154). Following the Anarchy, England came under the rule of the House of Plantagenet, a dynasty which later inherited claims to the Kingdom of France. A succession crisis in France led to the Hundred Years' War (1337–1453), a series of conflicts involving the peoples of both nations. Following the Hundred Years' Wars, England became embroiled in its own succession wars. The Wars of the Roses pitted two branches of the House of Plantagenet against one another, the House of York and the House of Lancaster. The Lancastrian Henry Tudor ended the War of the Roses and established the Tudor dynasty in 1485.

Under the Tudors and the later Stuart dynasty, England became a world colonial power. During the rule of the Stuarts, England fought the English Civil War, which resulted in the execution of King Charles I (1649) and the establishment of a series of republican governments — first, a Parliamentary republic known as the Commonwealth of England (1649-1653), then a military dictatorship under Oliver Cromwell known as The Protectorate (1653-1659). The Stuarts returned to the restored throne in 1660, though continued questions over religion and power resulted in the deposition of another Stuart king, James II, in the Glorious Revolution (1688). England, which had conquered Wales in the 13th century, united with Scotland in 1707 to form a new sovereign state called Great Britain.[4][5][6] Following the Industrial Revolution, Great Britain ruled a worldwide Empire, the largest in recorded history. Following a process of decolonisation in the 20th century, mainly caused by the weakening of Great Britain's power in the two World Wars, almost all of the empire's oversea territories became independent countries. However, as of 2016, its cultural impact remains widespread and deep in many of them.

Figure 3. Using color difference to show the next match.

STUDY METHODS

We carried out a laboratory study to determine the effects of visual angle and stimuli intensity on people's ability to perceive different types of popout effects. Participants were shown a visual field of objects for 240ms, after which it was hidden from view. In 60% of trials a single target object was present in the visual field (with some type and intensity of popout stimulus applied), and in 40% of trials no target was present (all objects were visually identical). Immediately following the presentation of the visual field, participants responded to a yes/no question asking whether they had seen the target or not. The presentation of targets was experimentally controlled to test six different types of popout, each at five different levels of intensity, and at different angles from the center of the display.

Visual variables and intensity levels

We chose six visual variables that have been shown in previous research to show popout effects, and that are either commonly used in information visualization (hue, shape, size) or likely to be visible in the periphery (luminance, flashing, motion). These variables (and the levels of each variable) are shown in Figure 4 (in the study described below, all objects were shown on a black background).

We created five versions of each visual variable to examine increasing levels of difference between the target and the distractors – we term these levels of difference as 'intensity'. For some of the visual variables, the range was constrained at both ends (e.g., there is a fixed range of hues between red and blue); for other variables, the range was constrained only at one end (e.g., size can range from the size of the distractors to an arbitrary upper end). The levels for each variable are shown in Figure 4 and Table 1.

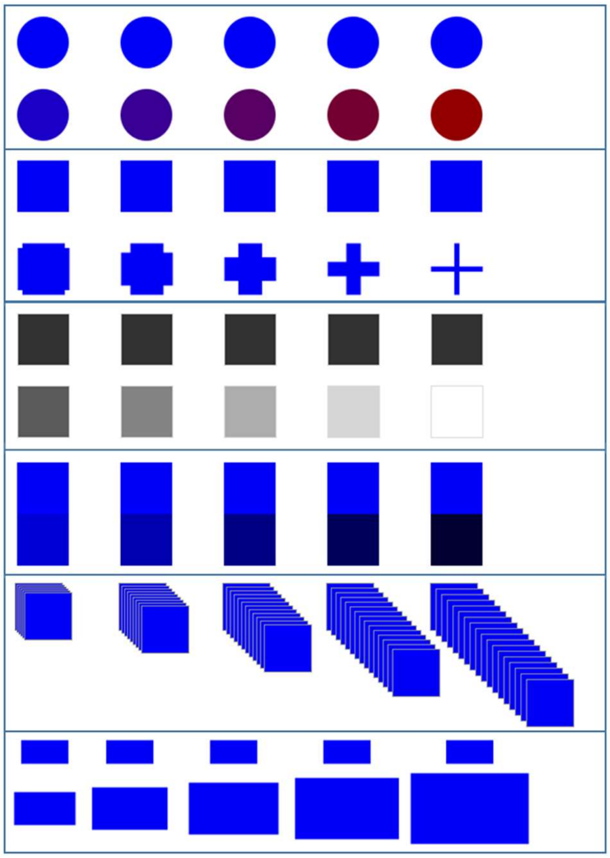

Figure 4. Visual variables and intensity levels. Rows 1-3: Color, Shape, Luminance (distractors upper, targets lower). Row 4: Flashing (upper and lower indicate alternating frames). Row 5: Motion (all frames shown). Row 6: Size (distractors upper, targets lower).

	D	1	2	3	4	5
Color (RGB)	R: 0 G: 0 B: 250	R: 29 G: 0 B: 200	R: 58 G: 0 B: 150	R: 88 G: 0 B: 100	R: 117 G: 0 B: 50	R: 146 G: 0 B: 0
Shape (line width)	50	41	32	23	14	5
Luminance (grey value)	50	91	132	173	214	255
Flashing ("off" color)	B: 250	B: 214	B: 173	B: 132	B: 91	B: 50
Motion (move/frame)	0px	1px	2px	3px	4px	5px
Size (width x height) = Area	25x50 =1250	32x65 =2080	40x80 =3200	47x95 =4465	55x110 =6050	62x125 =7750

Table 1. Values for intensity levels of the visual variables (D = value for distractor; 1-5 = target value for that level)

Color. Distractors and targets were circles of 50 px diameter. Target hues were equally spaced in RGB from isoluminant values of 'red' and 'blue' (using the luminance calculation in [38]). Maintaining equal luminance meant that the red end of the scale was RGB(146,0,0), and the blue distractors were RGB(0,0,250). Although RGB is not a perceptually-uniform color space, our approach still provides levels that are perceptually distinct (see Figure 4) and that increase towards a maximum isoluminant hue difference.

Shape. Distractors were 50px blue squares. Targets were an identical color, but their shape deviated from the square by an amount of intrusion at each corner (becoming a cross). The degree of intrusion varied across levels in increments of 9 pixels, from 9 px at level 1 to 45 px at level 5.

Luminance. Distractors were 50px gray squares with color RGB(50,50,50). Target brightness was chosen from five equally-spaced points (increments of 41) on a greyscale ranging from the color of the distractors (50) to white (255).

Flashing. Distractors were 50px static blue squares. Flashing targets abruptly changed hue every 60ms during the 240ms presentation of the object field. For the largest intensity (level 5), the target changed from blue to black (the color of the background); other levels changed between blue and an equally-spaced color in the range from blue to black.

Motion. Distractors were 50px static blue squares. Targets were animated using 17 frames during the 240ms presentation of the object field. Figure 4 shows the distance moved per frame for each level (from 1px at level 1 to 5px per frame at level 5); the movement direction was diagonal, with the displacement applied equally to *x* and *y* axes.

Size (Area). Distractors were 50×25px blue rectangles. Target dimensions on each axis were multiplied by 1 + (0.3 × *level*) to generate a larger rectangle. At level 5, the target dimensions were therefore 2.5× those of the distractor (i.e., 125×62 pixels; 7750 pixels total vs 1250 pixels total).

Visual angles to target locations

We chose six horizontal target locations (duplicated for left and right), organized into two groups according to the regions of the visual field (Figure 2). Three locations cover the near peripheral region (±6°, ±18°, and ±26°), and three cover the mid-peripheral region (±38°, ±50°, and ±62°). Angles were measured from the center vertical line. We placed targets at ±8° from the center horizonal (upper and lower locations were collapsed for analysis).

Participants and apparatus

Twenty-two participants were recruited from the local university community (14 male, 8 female, mean age 27.7 years). Participants were all experienced with mouse-and-windows desktop computers (more than 10 hrs/wk).

The study used a three-monitor setup with three Dell 25-inch HD LCD panels (Figure 5) to provide a visual workspace of 5760x1080 pixels with a physical size of 65x13 inches. Monitors used identical settings for brightness, contrast, gamma, and white balance. The monitors were arranged in a curve such that the user was 70cm from the center of all three monitors. All three monitors were driven from a single NVidia graphics card and a Windows10 PC. We built a custom experimental system for the study that presented all trials (in full-screen mode) and recorded performance data. All questionnaire data was recorded on web-based forms.

Study procedure

Participants completed informed consent forms and demographic questionnaires. They were then assigned to a random order of presentation of the visual variables (hue, shape, luminance, flashing, motion, and size). Participants carried out a series of trials for each intensity level of the first visual variable, in order from most intense to least intense. This ordering was chosen because prior sensitization to visual stimuli can improve detection, and we wanted this factor to be consistent (and to ensure that low-visibility stimuli were not missed simply because they were presented first). Once all of the levels were complete for a visual variable, participants proceeded to the next visual variable.

For each intensity level, there were two blocks, with each block containing 24 target locations: 12 horizontal angles (6 in each direction), and 2 vertical locations for each angle. At the start of each intensity level, the system showed the specific target that would be used for that level; this target had exactly the same appearance for all 48 trials of a level.

Each trial asked the participant to state whether they saw a target object (with particular visual properties specific to the condition) after a 240ms presentation of a field of objects. The 240ms time period was chosen to be within the 200-250ms period for pre-attentive processing [13], and to allow our motion and flashing effects time to be seen. Participants started each trial by focusing on a fixation cross at the center of the middle monitor. After a random interval of 1-2 seconds (to avoid anticipatory action), a field of objects was presented for 240ms (Figure 5). The field contained 104 distractors, distributed quasi-randomly across the three monitors (avoiding overlaps), and possibly one target object. In 60 percent of trials, a popout target was present, and in 40 percent, no target was present. The 60/40 split was chosen through iterative testing to maximize the number of positive trials without participants realizing that there were more of one type (which could have led to effective guessing); as discussed below, the split was successful in preventing a substantial false positive rate.

After the 240ms presentation, the visual field was hidden, and the participant was asked to state whether they saw the target – e.g., "Did you see a more-red circle among the blue circles?" They answered by pressing the '1' key for "yes" and the '0' key for "no." As soon as they had answered, the fixation cross appeared and the next trial started. Participants were asked to be as accurate as possible about whether they had seen the target, but were not asked to answer quickly.

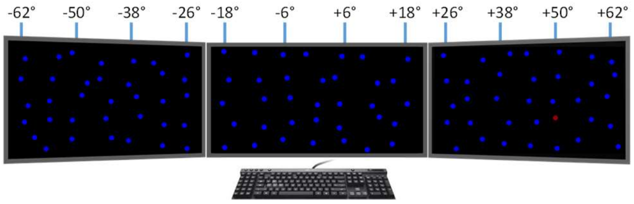

Figure 5. Object field presented to participant for one trial.

After each level, participants filled out a web-based effort questionnaire based on the NASA-TLX survey; they then returned to the study system and continued with the next level. With two blocks of 48 trials for each of 5 levels, each visual variable condition contained 240 trials; a single condition took approximately 20 minutes to complete.

Data analyses and design

Because each visual variable condition took approximately 20 minutes, not all participants were able to complete all six conditions. Therefore, we assigned later participants to balance the number of people per visual variable (11 people per condition). The fact that there is an incomplete mapping between participants and conditions, however, prevents the creation of a standard linear model for ANOVA. Therefore, our analysis uses a Hierarchical Mixed Model (HMM), which provides a similar model but allows for missing data from some participants [11]. The analysis was carried in R using the *nlme* library, using participant as a random factor.

The study therefore used a mixed between/within repeated-measures design, with three factors:

- *Variable*: the visual variable used to create the popout effect (hue, shape, luminance, flashing, motion, size)
- *Angle*: the horizontal visual angle from the center of the screen to the target (left: -6°, -18°, -26°, -38°, -50°, -62°; right: +6°, +18°, +26°, +38°, +50°, +62°)
- *Level*: the amount of difference in the visual variable between the target and the distractors (i.e, intensity); each condition used five levels as shown in Figure 4.

The dependent measure was accuracy (the proportion of responses in which participants correctly identified the presence of the target, using only the "target present" trials). For perception of effort, the dependent measures were the subject's responses to the TLX-style questionnaire.

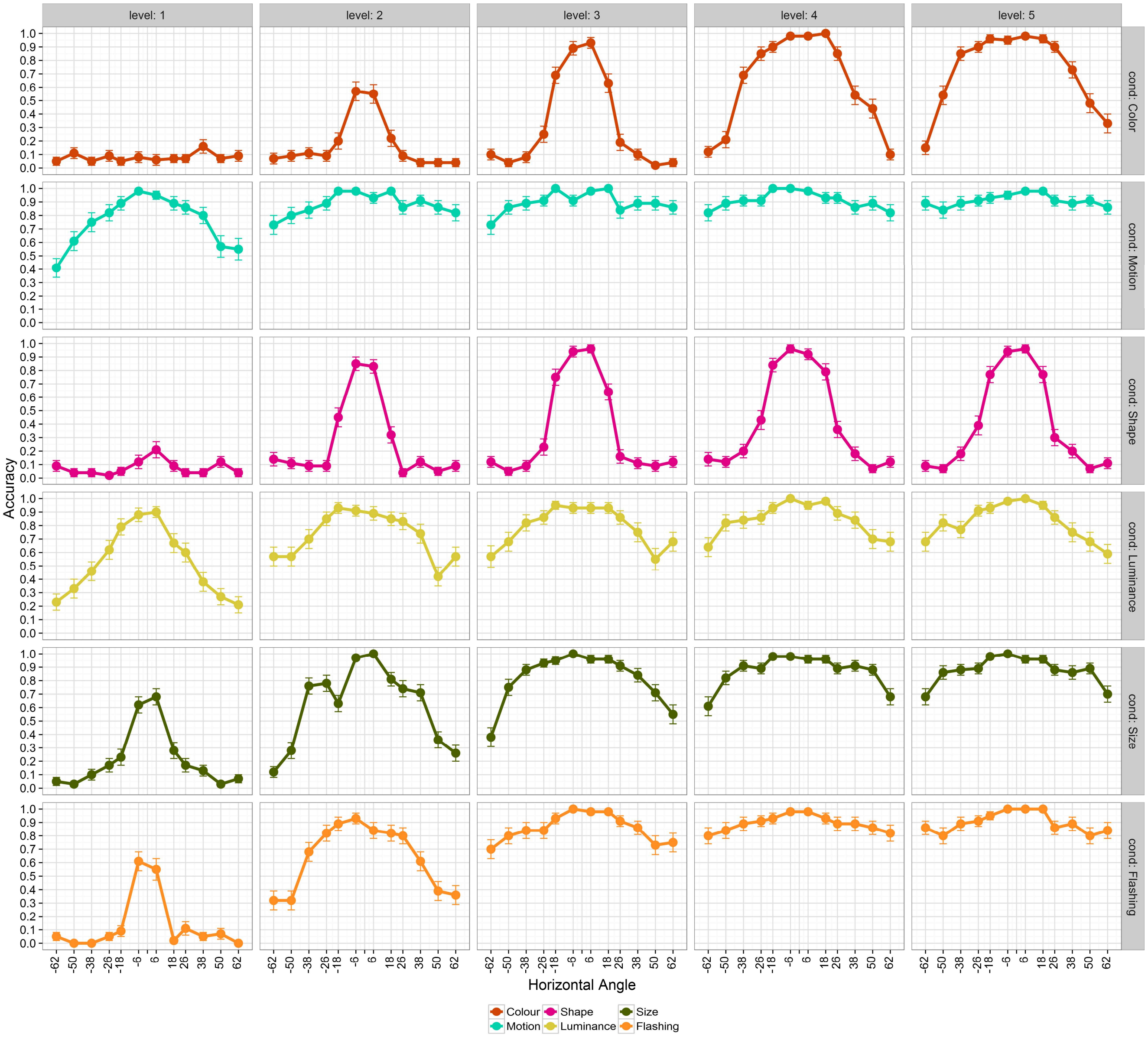

Figure 6. Accuracy ±s.e. by Variable (rows), Intensity Level (columns), and Angle (x-axis). Target-present trials only.

RESULTS

Data check: performance on target-not-present trials

Participants could, in theory, have answered 'yes' or 'no' to all trials, regardless of the presence or absence of the actual stimuli. To test the veracity of each participant's responses, we calculated the mean accuracy for trials where the target was *not* present. Accuracy in these trials for all visual variables was above 90%, suggesting that participants were in fact answering honestly and to the best of their ability.

Main effects of Angle, Variable, and Level on accuracy

Overall, there was a substantial drop in perception accuracy as visual angle increased – from 86% at ±6° from center to less than 40% at ±62° (Figure 6). The Hierarchical Mixed Model (HMM, see Data Analyses section above) showed a strong effect of *Angle* on accuracy ($F_{11,17447}$=396.76, p<.0001). The effect of *Angle* was essentially symmetrical across left and right angular deviations, with the HMM showing no significant effects of *Side* ($F_{1,17803}$=0.07, p=0.80), and no interactions of *Side* × *Angle* ($F_{1,17803}$=1.77, p=0.18) or *Side* × *Variable* ($F_{1,17795}$=1.63, p=0.15).

The HMM showed strong effects on accuracy for both *Variable* ($F_{5,17447}$=908.90, p<.0001) and *Level* ($F_{4,17447}$= 1415.29, p<.0001). Averaged across all levels, accuracy means varied from 87% for Motion, 74% for Luminance, 69% for Flashing, 67% for Size, 38% for Color, down to 29% for Shape. Follow-up oneway analyses of the pairs in this sequence (Bonferroni corrected) showed differences between each contiguous pair (all p<0.0001) except for Flashing→Size (p=.036). A similar follow-up analysis of *Level* showed significant differences between pairs of intensity levels (p<0.0001) except for level 5 → 4 (p=.22). However, the main effects of *Variable* and *Level* must be considered in light of the interactions described below.

Interactions between Angle, Variable, and Level

The HMM showed significant two-way interactions between *Angle* and *Variable* ($F_{55,17447}$=16.84, p<.0001) and between *Angle* and *Level* ($F_{44,17447}$=5.68, p<.0001); there was also a three-way interaction ($F_{220,17447}$=8.07, p<.0001).

These interactions are illustrated in Figure 6. Accuracy with different visual variables responded differently to increasing angle. Accuracy with Motion was relatively constant and high across *Angle*, whereas accuracy with Shape or Color followed a bell-shaped curve across *Angle*. The different levels for each variable also performed differently across angle – e.g., accuracy with Color and Shape vary from a floor effect (near ~7% across angle) at level 1 to a rounded-hill shape at level 3 and above, with maximum accuracy over 90%; in contrast, Luminance varies from a peak shape at level 1 (with a maximum at 90%) to a near-flat ceiling effect at level 4 and higher. The interpretation of these interactions is considered further in the Discussion below.

Does the bezel reduce perception of popout?

We were interested in whether the visual discontinuity of the bezels in our three-monitor setup influenced people's ability to perceive popout. From inspection of the overall results by angle (Figure 7), there appears to be a slightly steeper decrease from ±18° to ±26° (which includes the monitor bezels) than would be suggested by the overall curve of the data. In addition, the 18-26° angular range is within the near-peripheral region of the visual field – so there are no obvious physical changes in the eye that might explain this steeper gradient (compared, for example, to the changes observed beyond 30°); the blind spot is located in the 12-15° region and should therefore not influence identification here.

This partial finding suggests that target proximity to display edges *may* adversely affect the accuracy of popout perception. If this is case, it might arise from the lack of uniformity in the visual field near the display edge (i.e., the display edge and bezel adds visual stimuli that are not present within the body of the display). However, the effect of the bezel is small (corresponding to the limited impact of bezels seen in other work, e.g., [41]), and further research is necessary to explore this issue.

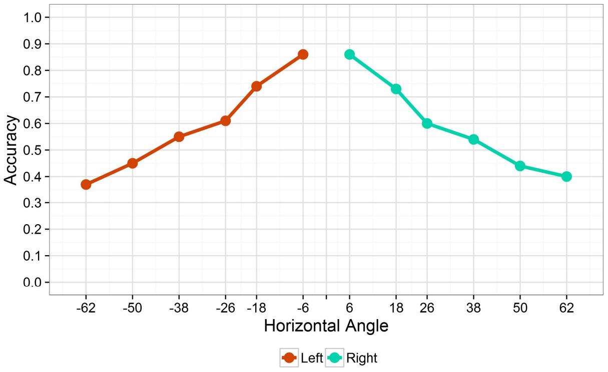

Figure 7. Overall accuracy (±std.err), by Angle.

Perception of Effort

After each intensity level, participants completed a NASA-TLX effort questionnaire. Mean results from this survey are shown in Figure 8 – although the mixed design of the study meant that we did not carry out statistical analyses of these data. However, Figure 8 shows that there were substantial overall differences in perceived effort, which approximately follow the performance results. For example, perceived effort for Motion and Luminance is consistently less than that for Color and Shape, which mirrors participant accuracy with these visual variables. In addition, for Luminance, Size, and Flashing, perceived effort scores increase as the visual intensity lessens (i.e., moving from right to left in the chart).

We also asked two additional questions for each level and condition: "How visible was the target?" and "How accurate were you in locating the target?" Results from these questions are shown in Figure 9.

The two main findings from these analyses are that Shape required relatively high effort, resulted in low levels of perceived success, visibility, and accuracy, and that these perceptions were relatively uniform across intensity level. Motion, in contrast, showed low levels of effort, and high levels of perceived success, visibility and accuracy. These positive results for motion were also relatively stable across intensity. Other variables showed a clear increase in perceived visibility and accuracy across intensity.

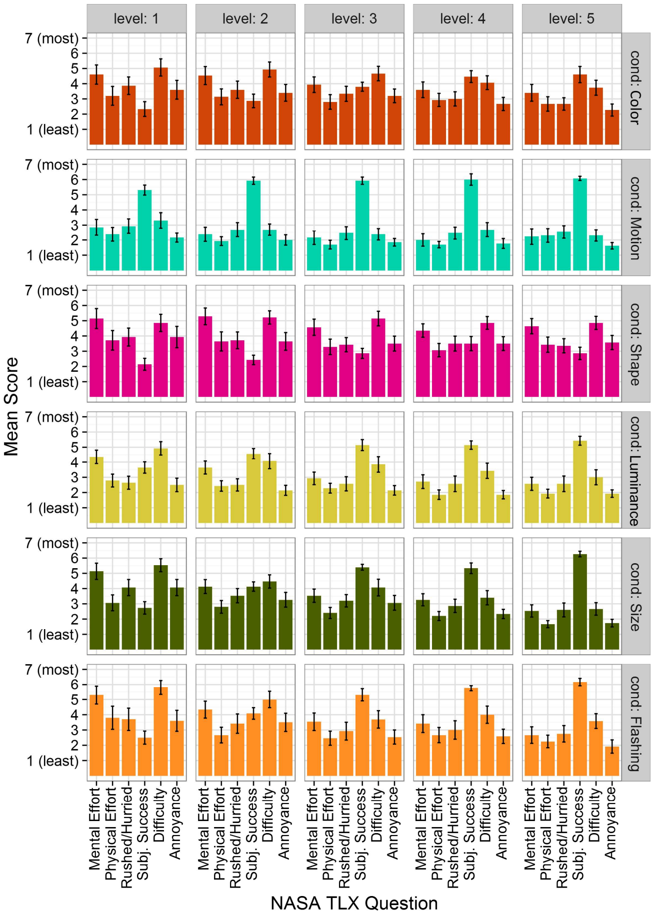

Figure 8. Mean responses (±s.e.) to NASA-TLX questions, by intensity and visual variable.

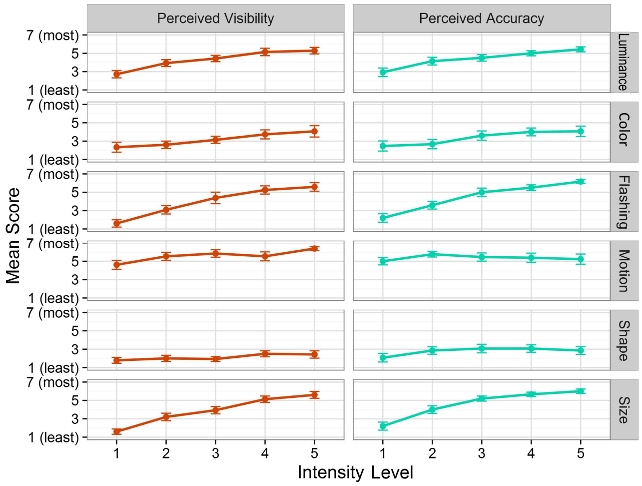

Figure 9. Mean responses (±s.e.) to questions about visibility and accuracy, by intensity level and visual variable.

FOLLOWUP STUDY: ADDITIVE EFFECTS

The study described above tested visual variables in isolation – however, several real-world interfaces enhance the presentation of a highlighted item using more than a single visual variable. For example, the Mac OS/X preview application highlights the next item in a search with an animation that uses both hue change and an increase in size (Figure 11). This raises questions of whether the effects described above are additive – that is, whether accuracy with an effect that uses two variables would be the sum of the performance for each variable on its own.

To provide some preliminary data on performance with combinations of popout cues, we carried out a small exploratory study as a follow-up, with four new participants. We asked participants to complete tasks similar to those described above, but in a set of conditions designed to allow examination of specific combined popout cues. First, we tested their accuracy with Color at level 3 and Motion at level 1 – and then tested the combination of Color and Motion. Second, we tested Luminance at level 2, Size at level 2, and then combined Luminance and Size.

Results are shown in Figure 10. For Color and Motion, the effect of combining the variables was not entirely clear. For targets presented on the right side of the display, there appeared to be a positive additive effect, with the 38, 50 and 62° combined data points much higher than Color or Motion alone. However, data on the left of the display did not show the same outcome, with the combined effects resulting in similar accuracy to Motion alone. The combination of Luminance and Size showed a clearer advantage both for left-side and right-side targets. Accuracy for angles ±(18° to 38°) ranged from 10%-70% with either Luminance or Size alone, but was above 90% with both variables. Again, in some cases the combination was better than the sum of the components.

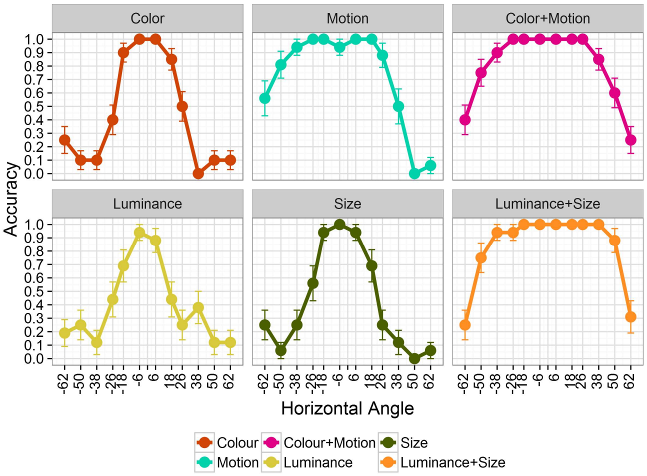

Figure 10. Additive effects. Top: Color level 3, Motion level 1, and Color+Motion. Bottom: Luminance level 2, Size level 2, and Luminance+Size.

This study is highly preliminary and involved only four people. Therefore, our limited results suggesting that combinations of effects can increase noticeability must be explored further with additional studies.

DISCUSSION

Summary of findings

The main findings are summarized in Figure 6. The key observation from the figure is that there are substantial differences between visual variables in how the accuracy of popout identification decreases as targets appear further from the center of vision – some variables support stronger peripheral popout than others.

At intensity level 3 and above, all of the visual variables allowed high accuracy at the center of the visual field (90% and higher, following a presentation that lasted only 240ms). However, accuracy dropped off steeply as the angle from center increased with Shape and Color, whereas accuracy remained comparatively high across angle with dynamic methods (Motion and Flashing). Motion was particularly accurate at wide angles, even when the movement was small. Subjective assessments of visibility and accuracy (Figure 9) mirrored the accuracy results, with high perceived accuracy and visibility for Motion, and low values for Shape.

Reasons for results

Perceptual factors

Properties of the human visual system help explain some of the results. For example, the distribution of cone cells, which detect color, is dense in the central visual field, but sparse beyond it, which explains why the accuracy of Color deteriorates abruptly beyond central target placement. The lower density of cones beyond the parafoveal region means that humans are much less sensitive to color in the periphery, so hue-based popout primarily occurs when a saccade brings the target into the parafovea (unless targets are large [1]).

Accuracy with Shape also dropped off rapidly with angle. It is possible that physical attributes of the eye contribute to this finding. For example, the differential distribution of certain types of ganglion cells across the retina [7] might make elemental visual features, such as edges or corners, less prominent at the periphery. Alternatively, it is also possible that shape interpretation is best achieved subsequent to inclusion of an object within the parafoveal region. The possibility of a saccade within the 240ms presentation in our experiment was low, but the bell-shaped curves for Shape accuracy may reflect the probability that a saccade from a central location includes the target within the presentation period. Further research on perceptual feature extraction is required to properly explain the cause of the Shape results.

Finally, prior research on visual perception strongly suggests that the high accuracy findings for Motion, Luminance, and Flashing (across broad angles) stem from the selective firing of ganglion cells in response to input from rods and cones (see [5] for a review).

Experimental factors

We designed the experiment with the intention that the intensity levels of each visual variable would provide roughly equivalent increments in the distinction between distractor and target. Although we described our manipulations in a replicable manner, it is possible that our findings are influenced by the exact manipulations tested. One important issue is that there were different ranges of intensities possible with each visual variable – as described above, levels of Color are limited by the distance between the colors of the distractors and the target, whereas other variables have a larger possible range (e.g., Luminance, Motion, and Size). It is difficult to equalize the perceptibility of different intensities for different visual variables, so to some degree the variables must be treated as independent.

Other factors could be considered as well. It is possible (though we believe unlikely) that our findings for Shape would be different if a different form for Shape targets was used. For example, the different levels of Shape might instead transition between a square (distractor) and a perfect circle (level 5) with intermediate levels of rounded corners. Similarly, it is possible that results for Luminance or Color would differ if a white, rather than black, background was used. Further experimental work is required to cross-validate and generalize these findings. In addition, considering our results using computational models of visual attention (e.g., [21]) may provide additional predictive and explanatory power about the mechanisms that led to different results for different stimuli.

Implications for designers

Interface designers often need to address tradeoffs between the desirability of drawing the user's attention to a salient data item and the risks of distracting the user from their current tasks [2]. While findings from this research improve our basic understanding of visual characteristics that draw the user's attention to objects placed at different locations across the visual field, we have not addressed issues of unintended distraction caused by popout effects (and we note that motion and flashing are often criticized as being distracting in many information presentations). We intend to examine the correspondence between noticeability and distraction for different visual variables in upcoming work.

A first and unsurprising implication of the results is that popout effects are more reliable if the target object is placed near to the center of the visual field. This was evident for all levels of our popout stimuli except level 1 of Color, which had low accuracy even with central placement. We assume that the stimulus chosen for level 1 Color was close to the just-noticeable-difference level for color discrimination from the distractor. While some interaction contexts may prohibit or discourage placing a popout target near the center of the display, others will permit it (e.g., "find" functionality in a browser might scroll the view to present the target near the center of the display). If the visual field does not allow scrolling, another possibility involves tracking the user's visual focus in order to calculate an ideal popout effect for the specific location of the target. It is likely that eye trackers will become common in some display environments, and camera-based gaze tracking is becoming feasible [19]. Eye tracking can also be used to compare the approach of peripheral popout to that of Bailey and colleagues, who used subtle modulations of the peripheral visual field to draw the user's visual attention [2].

A second design implication is that motion effects are highly accurate even at wide angles and at subtle levels. At level 1, our tested motion effects involved movements of only a few pixels on the screen (~1mm of movement), yet they enabled better accuracy than higher levels with other visual variables. Subjective responses including workload measures and perceived accuracy were also better for motion effects than other visual variables. Motion, then, is a powerful popout cue at high angles and at low movements. Yet some commercial examples of Motion popout cues are highly exaggerated, and possibly unnecessarily so; for example, the icon bounce effect in the Mac OS/X Dock involves animated vertical movements of ~80 pixels, but our results indicate a subtler effect would be sufficient to make users aware of the alert.

Our results can be applicable in a number of contexts. First, previous work has shown that alerts are often difficult to see in multi-display environments (e.g., [12]), which is a substantial problem for control rooms or systems for emergency response. Designers can use the findings from our study to help ground the design of multi-display systems on empirical evidence. Second, our study provides a better understanding of different methods for visual feedback. For example, feedback during "Find" tasks in different PDF viewers provides an interesting contrast between commercial approaches to the design of popout effects. Figure 11 (top) shows "Find" results in Apple's Preview application (v8.1), which over 400ms scrolls the next occurrence into view, highlights it with a yellow background, and then briefly zooms the text. This effect – combining flashing, luminance, hue, and motion – appears to be much more effective than that used in the Chrome PDF viewer (Figure 11 bottom), which scrolls the next item into view and highlights it with a low luminance blue-grey highlight. When not in the visual focus, the lack of movement or other strong stimuli may be insufficient to induce a desired popout effect.

Figure 11. Commercially deployed highlighting techniques that are used to popout text targets in PDF viewers: Apple's Preview (top) and Chrome's PDF viewer (bottom).

Limitations and future work

This research has generated a set of empirical characterizations of the effectiveness of different pop-out visual variables at different levels of intensity and at different angles from the center of the visual field. However, there are abundant opportunities for extending these findings and for validating them with different stimuli, intensities and angles. For example, we plan to test accuracy when participants do not see the stimuli in the most-visible to least-visible pattern used in our study – it is possible that changing this order will reduce accuracy (because participants will not be sensitized to low-visibility stimuli). Another opportunity is the examination of other motion effects than the simple diagonal displacement used in our studies. Harrison and colleagues examined the broad opportunities for designers working with kinetic icons, presenting an initial 'kineticon vocabulary' [15]. It is likely that different styles and patterns of motion will induce different popout outcomes in humans. For example, studies might examine the different impact of motion frequency, shape (e.g., pulse versus jiggle), and abruptness (e.g., slow-in/slow-out versus instant velocity changes). Analogous manipulations of other visual variables and their combinations also needs further examination.

A third area for future work will build on our preliminary results regarding the potential additive effects of combined visual variables. For example, different combinations may allow the benefits of different variables to be exploited. Our results show that motion effects are highly accurate in prompting accurate popout, but continued motion after initial popout may impair overall performance (e.g., reading moving text will be harder than reading static text, and selecting a moving object could be frustrating). By combining motion with other variables (such as luminance, hue, or shape), users may be able to gain from an initial popout induced by a brief burst of motion, followed by static presentation that is temporally enduring but uses less distracting stimuli with other visual variables that remain effective because they lie within the center of view.

CONCLUSIONS

Visual popout effects allow users to rapidly identify one item among a field of many candidates. Interface designers can use a variety of popout visual stimuli to alert users to objects that need attention. The results presented in this paper demonstrate that different popout visual stimuli vary significantly in their effectiveness as target items are displayed further from the center of the visual field. While nearly all of the evaluated techniques allowed high levels of target identification accuracy when presented at high intensities near the display center, some also maintained high levels of accuracy at the periphery (such as Motion, Flashing, and Luminance) while others did not (Color and Shape). These findings are particularly relevant as the size and extent of display environments increase, and they contribute to a growing vocabulary for the application of visual stimuli in interface design.

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