What Captures Gaze in Visual Design?
Insights from Cognitive Psychology

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Abstract

Visual information is vital for user behaviour and thus of utmost importance to design. Consequently, tracking and interpreting gaze data has been the target of increasing amounts of research in design science. This research is in part facilitated by new methods, such as eye-tracking, becoming more readily available. Visual attention is the principle mechanism that governs where we direct our gaze. Understanding the factors that influence how attention is directed is therefore necessary for understanding user intentions and gaze patterns.

In this paper, we provide an overview of the characteristics and factors that have been experimentally shown to capture attention, as well as those factors that modulate the capture and direction of attention. We do so by drawing on the large body of evidence provided by cognitive psychology, as we believe this research area could potentially provide a source of untapped potential for design research and practice.

Keywords: Attention, Design, Gaze, Eye-tracking, Visual Communication

1. Introduction

Visual information is of utmost importance when designing products or interfaces for both leisure and labour, as users judge the perceived value based on appearance of the products or interfaces (Crilly et al., 2004). Consequently, visual processing has increasingly been the target of research within design science, especially as novel methods for tracking the visual operations of users have become more readily available. In particular, the use of eye-tracking devices has shown increasing promise, as such devices allow for real-time insights into the direction of the gaze. Examples include a wide range of topics such as: Navigating a website (Goldberg et al., 2002; McCarthy et al., 2004), reading a diagram for use in work (Störrle et al., 2014; Lohmeyer et al., 2015; Maier et al., 2015) or monitoring how operators perform in realistic simulations of high-stakes situations in a chemical laboratory (Sharma et al., 2016). Through such investigations of the user's gaze, researchers and designers alike have found a powerful tool for shaping products and interfaces in ways that allow users to operate in accordance with both their own and the producer's intentions.

However, interpreting the reasons behind gaze movements is not always a straightforward task. Research, in particular from the field of cognitive psychology, has shown that the direction of our attention, and consequently our gaze, is not always under our control (Theeuwes et al., 1998). In this paper, we highlight characteristics that have been empirically investigated though rigorous cognitive experiments, and have been confirmed to *capture* attention. They are, in no particular order: Emotion (e.g. Öhman et al, 2001a; 2001b), contrast (usually colour, e.g. Treisman & Gelade, 1980; Nordfang, 2013), meaningfulness (e.g. Biggs et al., 2012), faces (e.g. faces Ro et al., 2001), onset of new stimuli (Jonidese, 1981; Theeuwes, 1990; Theeuwes et al., 1998) and task-relevance (Hodsoll et al., 2011). Furthermore, we discuss external factors that impact how well we are able to direct our attention in accordance with our goals and to ignore distractors (Lavie & Tsal, 1994; Lavie et al., 2004; Geng, 2014). Using psychological principles to form the basis of design science has led to many fruitful insights in the past: For example, the gestalt laws and SRK (skills, rules, knowledge) principle, which is based on psychological insights, has informed design decisions of displays for the nuclear and oil industries (Lau et al., 2008; Weyer et al., 2010; Braseth & Øritsland, 2013; Lau et al., 2008). Another example concept of functional fixedness (Duncker & Lees, 1945) has inspired a diverse and informative range of studies of what is now known as design fixation (Jansson & Smith, 1991; Purcell & Gero, 1996; Vasconecelos & Crilly, 2016). The present paper similarly aspires to inspire design research and practice: The papers selected in this overview seminal works in cognitive psychology have in common that they a) are extremely rigorous, and b) work under the assumption that, given the extreme rigour, their findings reflect basic psychological functions that reflect the way our brain is wired (and thus should be similar in all humans). In response to calls and movements for higher degrees of rigour in experimental design science (Papalambros, 2015; Cash et al., 2016), we hope that presenting these studies will inspire similar studies, as well as provide insights into how to interpret how gaze is captured.

These aims are accomplished in four parts. First, we establish some basic fundamental aspects of attention for use in further discussion. Second, we describe visual features that have been experimentally shown to capture attention. Third, we establish factors that mediate the extent of this attentional capture. Fourth and finally, we discuss potential implications of the presented insights for designers and design researchers alike.

2. Attention: Conceptual Fundamentals from Psychology

Given the complexity and richness of the stimuli in our surroundings – be it the pages of a website or the dashboards of a control room – a key prerequisite for interacting with products and interfaces

is our ability to discriminate between relevant and irrelevant items, and to focus on the former while ignoring the latter. The processes and mechanisms that allow these selective operations are collectively referred to as attention, or selective attention (e.g. Deutsch & Deutsch, 1963). Furthermore, attention serves as a principle precursor for the movement of our gaze (Hoffman & Subramaniam, 1995; Kowler et al., 1995; Theeuwes et al., 1998), and we therefore largely frame our discussion around attention research.
Despite our frequent use and sense of intuitive understanding of the concept and despite decades of research on the topic (Posner & Petersen, 1990; Bundesen & Habekost, 2008), attention has so far remained elusive in experimental psychology and it is a highly debated and researched topic in all variations of cognitive psychology – even to this date. However, two fundamental properties of attention have been established that are important for this paper: One relating to the limited capacity of attention, and another relating to how stimuli are selected when several are present. Each is considered in the following as they provide a basis for understanding the subsequent sections of this paper.

2.1. Attention has Limited Capacity

Given that attention is primarily intended as a function that selects some information while ignoring others, it follows naturally that the capacity of the attentional system be substantially limited in comparison to the vast number of stimuli in our surroundings. In humans, the process of focusing is generally extremely successful, and we are consequently only able to hold 3-4 objects in our visual attention at any given time (Sperling, 1960). However, this capacity may be increased by "chunking" objects together to form objects with larger amounts of information (Miller, 1956) such as when remembering an 8 single-digit number as 4 two-digit numbers. Nevertheless, the principal fundamental feature of the attention system is that it has limited capacity.

2.2. Attention is Directed and Captured by Competing Stimuli

The prevailing view on the way stimuli are selected for one of the limited slots of attentional capacity is that of Biased Competition (Desimone & Duncan, 1995). In this theoretical framework, when viewing a scene, our attention system assigns relevance scores to stimuli depending on their characteristics. Following this, stimuli with higher relevance scores are more likely (but not guaranteed) to win the competition and be selected by attention and thereby allowed further processing. The process has sometimes been envisioned as a stochastic race (for details on this model, see Bundesen (1990) and Bundesen & Habekost (2008)). The Biased Competition framework furthermore serves as a powerful metaphor for understanding gaze direction; gaze-direction should be seen as inherently random, but skewed towards certain characteristics depending on the circumstances. In this light, the purpose of this paper is to summarise those characteristics that have been experimentally proven to consistently bias the competition towards certain gaze directions.

3. Characteristics that Capture Attention

Having defined some fundamentals of how attention works, we now turn to those characteristics that have been shown experimentally to capture attention. Possible confounding factors are listed and discussed where relevant. The characteristics are: Contrast, emotion and meaning, faces, onset of new stimuli and task-relevance. Outlining these characteristics serve as insights to consider when interpreting gaze direction. Factors that mediate the characteristics' attentional capture are discussed in section four of the paper.

3.1. Contrast

As possibly the earliest characteristic that was identified to capture attention, the effect of contrast is observed when one object deviates substantially from its surroundings in colour or shape. While other physical features, such as gestalt laws (Moore & Fitz, 1993), aesthetics (Crilly et al., 2004) or concrete layout features (e.g. number of line crossings in diagrams, Maier et al., 2014) have proven relevant for design decisions, contrast, in particular between colours, has been especially important for, and well investigated by, experimental psychologists. For example: When searching for a target letter amongst a display of letters, a coloured singleton presented alongside letters of a different colour will become immediately available for attention. This finding was a fundamental part of one of the earliest theories of attention (The Feature Integration Theory, Treisman & Gelade, 1980). This finding has been reproduced in numerous designs, and, importantly, has been reproduced in a context where colour is not a target-relevant criterion (Forster & Lavie, 2008b; Nordfang et al., 2013, see the importance of separating the feature effect from task-relevance below). Objects that differ from their surroundings in colour contrast thus represent one of the most robust and important examples of attentional capture in experimental psychology.

3.2. Emotion and Meaning

Stimuli that carry emotional value –be it positive (e.g. happiness) or negative (e.g. anger, threat) – have been extensively studied and shown to capture attention. Early studies focused on phylogenetic threat, showing that a threatening singleton (spider, snake) is found more rapidly amongst neutral distractors (mushrooms, flowers) than vice versa (Öhman, 2001a). Other studies have expanded on this research by showing that ontogenetic threats (i.e. a gun or knife: Brosch & Sharma, 2005; Blanchette, 2006), angry faces (Hansen & Hansen, 1988; Öhman et al., 2001b; Calvo et al, 2006), but also positive stimuli such as faces (Nummenmaa et al., 2006) or pictures of emotional scenes (Calvo & Lang, 2004) capture attention.

However, recent studies have questioned whether these effects are due to emotion specifically, or whether the effects were caused by task-relevance (see below) or simply that emotion was often the only meaningful category. A study by Biggs et al., (2012) found that meaningfulness in itself is indeed enough to capture attention, but some evidence has suggested that emotion may capture attention because of their valence and not just their meaning (Öhman, 2001a). However, this debate is largely unresolved and researchers are therefore advised to carefully consider the relative importance of emotion and meaning in their studies.

3.3. Faces

Identifying the facial expression of our fellow humans is vital to everyday life. This is reflected in a dedicated area for facial processing in the brain (the Fusiform Face Area; Kanwisher, 1997), but also in attentional capture. We previously highlighted studies that show that emotional faces capture attention. However, faces in general are processed more efficiently, are more easily detected and capture attention (Ro et al., 2001; Theeuwes & Van der Stigchel, 2006; Langton et al., 2008).

3.4. Onset of New Stimuli

The onset of new stimuli in the visual field has continuously been shown to capture attention and to direct the gaze (Theeuwes, 1991; Hillstrom & Yantis, 1994; Theeuwes et al., 1998; Cosman & Vescera, 2009). In fact, the appearance of new stimuli has such powerful attentional capture that some researchers have proposed that they are categorically "special" in how they are treated by the attention system (Theeuwes, 2010; Nordfang & Bundesen, 2010). Using this mechanism for attentional capture should consequently be done with care.

3.5. Task Relevance

Task relevance is an important factor in determining how likely an object is to capture attention. For instance, Nordfang et al., (2013) showed that objects with high task relevance were more likely to capture attention, and that task-relevance interacted additively with contrast such that targets of high contrast and relevance were even more likely to capture attention than stimuli that held only one of the characteristics. Similar findings have been shown for emotional stimuli (Hodsoll et al., 2011). Importantly, these studies have in common that they inform the participant about the target characteristics, which in turn leads to facilitated search for these task relevant objects. It may therefore be that objects that conform to the usual appearance of an object with a specific function are more readily detected due to their task-relevance (as opposed to any of the above factors) (Geng, 2014).

A possible complication with attentional capture due to task relevance lies in whether only low complexity stimuli such as letters and numbers may lead to this capture (Nordfang et al., 2013). However, recent evidence has shown that also high-complexity stimuli such as pictures can guide attention if they are task relevant (Alexander & Zelinsky, 2012).

3.6. Interactions between Characteristics

The relative importance or strength of the highlighted characteristics has so far not been well investigated. However, evidence exists for some examples of interactions: First, if several faces are present in the visual field, emotional faces will capture attention over neutral faces, and faces with negative emotion will capture attention over faces with positive emotion (Hansen & Hansen; Öhman et al., 2001b; Nummenmaa et al., 2006). Second, as noted above, if targets are task relevant and differ from its surroundings in colour contrast, the search for this target will be faster if the target has only one of the characteristics (Nordfang et al., 2013). This synergy is likely to be present between task relevance and other attention-capturing characteristics, but to our knowledge this has not been investigated experimentally. Similarly, it is possible that other synergistic relationships exist, as is the case with emotional faces, but, again, experimental evidence has thus far been lacking. As interfaces and products often comprise multiple and complex stimuli, determining these relationships could be vital for understanding the direction of gaze, and consequently provides an interesting target for research.

4. Factors that Facilitate and Inhibit Attentional Control

Having outlined characteristics that are highly likely to capture attention, we now focus on external factors that influence our ability to direct attention and ignore irrelevant stimuli. Importantly, the presented factors should be considered as interacting with the characteristics outlined in section 3 and eventually deciding direction of the gaze.

4.1. Cognitive Load

In their influential theory of attention, Lavie and Tsal (1994, see also Lavie et al., 2004) describe the relationship between likelihood that distractors affect behaviour and cognitive load. They propose two mechanisms: The first mechanism relates to the capacity constraint of attention and states that if the visual field contains few target objects, then the leftover capacity will be filled by distractors until the capacity is reached. This is in line with the outlined Biased Competition framework: If there is no competition, then everyone is a winner.

The second mechanism is that high mental load, such as from other tasks or the environment, will reduce our ability to suppress distractors because less mental capacity will be available for this suppression. The theory thereby establishes that high workload is associated with increased distractor interference due to lacking inhibition, while low workload may lead to distractor processing if the number of relevant objects is below the total capacity.

4.2. Alertness and Mental Fatigue

An important function of attention, which was most notably reviewed by Posner & Petersen (1990; Petersen & Posner, 2012), lies in preparing and sustaining alertness for high priority stimuli. This alertness, they noted, is reflected in faster response times, but sometimes comes at the cost of higher error rates because responses are made based on less information. For instance, relating to gaze direction, this could mean that users who are focused on finding a certain feature in an interface may direct their gaze rapidly to features that are congruent with their intentions, but that they may commit erroneous gaze directions if many similar objects are present in the visual field.

More recently, Boksem et al., (2005) found that mental fatigue results in symptoms that are similar to this state: As participants worked on a tiring visual attention task for 3 hours, performance decreased steadily due to increased reaction times and distractibility, as well as more false alarms and errors. This is corroborated by Geng (2014) who found that the proactively suppressing distracting information is mentally demanding - and next to impossible if very little is known about the target's characteristics. Therefore, she notes, we usually rely on reactive corrections of initial misfires of attention. In other words, we let ourselves get distracted and correct subsequently, because proactively suppressing distractors is mentally strenuous, which further underlines the importance of knowing where the gaze goes initially.

Table 1. Overview of Characteristics and Factors that Influence the Capture of Gaze

		Description	References from Cognitive Psychology
Characteristics	Contrast	Differences in physical features, such as colour or shape	Treisman & Gelade, 1980; Forster & Lavie, 2008b; Nordfang et al., 2013
	Emotion	Differences in emotional valence	Öhman et al., 2001a; 2001b; Brosch & Sharma, 2005; Blanchette, 2006: Hansen & Hansen, 1988; Calvo et al., 2006; Nummenmaa et al., 2006; Calvo & Lang, 2004
	Meaning	Being meaningful rather than meaningless	Biggs et al., 2012
	Faces	Pictures of human faces or stylistic drawings	Kanwisher, 1997; Ro et al., 2001; Theeuwes & Van der Stigchel, 2006; Langton et al., 2008
	Onset	Onset of new stimuli	Theeuwes, 1991; Hillstrom & Yantis, 1994; Theeuwes et al., 1998; Cosman & Vescera, 2009; Theeuwes, 2010
	Task-Relevance	Degree of congruence with the target of a task	Hodsoll et al., 2011; Nordfang et al., 2013; Geng, 2014
Factors	Mental Load	High mental load interferes with inhibitory mechanisms	Lavie & Tsal, 1994; Lavie et al., 2004
	Visual Load	More relevant targets allows for less processing of distractors	Lavie & Tsal, 1994; Lavie et al., 2004
	Alertness	Alertness allows for higher sensitivity to targets, but at the cost of more errors	Posner & Petersen, 1990; Petersen & Posner, 2012; Boksem et al., 2005; Gent, 2014

5. Implications and Guidelines for Design

This paper described characteristics and factors that influence the direction of attention and thereby the gaze. We presented evidence that contrast, emotion, meaningfulness, novelty, faces and task-relevance are characteristics that capture attention. Furthermore, we offered a number of theoretical and empirical insights that shows how mental- and visual load, alertness and fatigue are factors that influence our ability to control our attention and ignore distractors thus mediating the attentional capture of the characteristics.

Based on these findings, we propose that researchers and designers should interpret the direction of the gaze to products and interfaces with care whenever these factors are involved, as they may capture attention regardless of their task relevance. Concluding this paper, we further expand how these insights may impact how researchers and designers should interpret gaze movements.

5.1. Implications for Research

For researchers, we offer that the highlighted characteristics and factors should be considered when studying the gaze in order to avoid misleading interpretations of participants' behaviour. This is especially important given that the highlighted characteristics and factors are present in almost all studies of gaze direction. Consequently, knowing whether a participant directed his/her gaze intentionally or due to attentional capture is of critical importance for interpreting results of gaze movements. In particular, task-relevance and meaningfulness were found to be important confounding factors for studies of attentional capture. Researchers should therefore carefully consider the role of these variables in their study designs.

Furthermore, we hope that future research may further improve our understanding of the exact mechanisms of user perception in design, as well as shaping the future of design. In particular, as noted above, additional research on the interplay between attention-capturing characteristics and factors is needed for truly understanding the direction of gaze.

5.2. Implications for Designers

For designers, we hope that the provided overview of characteristics and factors, as well as the research behind, can be translated directly into design practice. For instance, designers could use attentional capturing characteristics for those features that should be viewed immediately. Furthermore, designers should consider whether the conditions in which their products will be viewed will impose constraints on mental workload or fatigue, as goal directed behaviour is affected When, for example, mental load is higher, characteristics that capture attention may do so more effectively, and gaze will consequently be directed to objects with such characteristics more readily.

We envision several situations where these insights could have direct practical implications for design. For instance, planned future studies our research group will investigate how design solutions can alleviate the complexity of critical situations in control rooms, such as in those operated in a nuclear reactor or the cockpit of an airplane. One avenue of this research will be on how information processing of complex interfaces could be aided by applying the attention capturing mechanisms for highlighting the most important areas. Similar application areas should be found in all aspects of design where visual information processing is required. We therefore hope that researchers and designers alike will join us in mapping the mechanisms and design applications of insights in the visual attention system.

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