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Driving forces in free visual search: an ethology

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3 **Driving forces in free visual search: an ethology.**
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Visual search typically involves sequences of eye movements under the constraints of a specific scene and specific goals. Visual search has been used as an experimental paradigm to study the interplay of scene salience and top-down goals as well as various aspects of vision, attention and memory, usually by introducing a secondary task or by controlling and manipulating the search environment. An ethology is a study of an animal in its natural environment, and here we examine fixation patterns of the human animal searching a series of challenging illustrated scenes that are well-known in popular culture. The search was free of secondary tasks, probes and other distractions. Our goal is to describe saccadic behaviour, including patterns of fixation duration, saccade amplitude and angular direction. In particular, we employ both new and established techniques for identifying top down strategies, influences of bottom up image salience, and mid-level attentional effects of saccadic momentum and inhibition of return. The visual search dynamics we observe and quantify demonstrate that saccades are not independently generated, and incorporate distinct influences from strategy, salience, and attention. Sequential dependencies consistent with Inhibition of Return also emerge from our analyses.

Keywords: Visual Search; Ethology; Free Search; Inhibition of Return; Saccadic Momentum

Highlights:

- * We examine over 20,000 eye movements during free search
- * Saccade metrics reveal top-down and bottom-up search strategies
- * Mechanisms thought to influence saccade selection are assessed
- * Inhibition of return is observed in the direction, amplitude and timing of saccade

1. Introduction

Visual search entails a complex interplay between scene salience and search strategy. While we are capable of looking at any scene feature as often as we wish, it is usually in our best interest to be guided in our search by scene elements which closely resemble the object of our search, or to focus on locations which we believe will provide the most information. But search can also be influenced by bottom-up saliency, that is, it can be driven by attention-grabbing features in the search array, such as motion, sudden onsets, high luminance, or unique color or size (see Wolfe and Horowitz, 2004, for review). A further source of influence is mid-level mechanisms (Klein & MacInnes, 1999; MacInnes & Klein, 2003; Hooge Over, van Wezel, & Frens, 2005, 2005, Smith & Henderson, 2009, 2011a) that drive the saccadic system toward novel regions as suggested by models of human search performance (Itti & Koch, 2001) and neurophysiological investigations in Rhesus monkeys (Fecteau & Munoz, 2006). Two such mid-level effects that could drive the saccadic system toward novel locations are Inhibition of Return (IOR), which is a bias away from previous fixations, and Saccadic Momentum, which is a bias to repeat the most recent saccadic vector.

We move our eyes roughly three times every second to bring new parts of the environment to the central, high-resolution part of the retina. Patterns of these saccades can provide information on underlying visual processes and have been used to produce and test many models of saccadic behavior in visual search (Itti & Koch, 2001, Wolf, 2007, Foulsham & Kingstone, 2012). Saccade patterns are dependent on instructions (Yarbus, 1967), scene salience (Henderson, 2003), entropy of the search array (Gilchrist & Harvey, 2006) and the previous state of the oculomotor system (Zelinsky, 1996). Although the importance of a low-level salience map (e.g., Itti & Koch, 2000) for the control of overt orienting has been challenged (Einhäuser W. & König, 2003; Tatler, 2011; Tatler, Baddeley & Gilchrist, 2005) these challenges are aimed at narrow definitions of a salience map. Some have sought to

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3 overcome the challenges by redefining salience to include deviation or 'surprise' (Itti &
4 Baldi, 2006), a retinotopic priority map (Wischnewski, Belardinelli & Schneider, 2010), or
5 object-level salience (Einhauser, Spain & Perona, 2008). Search of complex scenes has
6 shown influences of both top-down and bottom-up factors (Huestegge & Radach, 2012). We
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11 define bottom-up contribution to search in broad terms as, simply, all the information that is
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14 in the image projected onto the retina. Viewed this way all orienting behavior in the real
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16 world will be influenced (albeit to different degrees) by both bottom-up and by top-down
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18 processes.
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21 Most studies that have reported on the patterns of eye movement in "free looking and
22 free search" have done so in situations that are not so "free." Although the *experimental*
23 results from these different paradigms have been fruitful and important, the *ethological* data
24 might have been compromised by the experimental manipulations. For example, one fruitful
25 paradigm has been to evaluate the aftermath of a search episode with responses to a
26 secondary, or probe task (e.g., Klein & MacInnes, 1999; MacInnes & Klein, 2003; Smith &
27 Henderson, 2011b). The "free" saccades made before probes in such a task might very well
28 be influenced by strategic adaptations to the possibility of the probes. The results from well
29 controlled studies that used highly regularized search arrays (e.g., Gilchrist & Harvey, 2006)
30 and gaze contingent display changes (e.g., Foulsham & Kingstone, 2012) both manipulations
31 that might permit the researcher to confidently link array features to saccadic behavior are
32 limited, from an ethological perspective, on grounds of oversimplification and ecological
33 invalidity.
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50 A number of studies have looked at the role of action in viewing by analyzing
51 saccades in tasks such as sports (Ballard & Hayhoe, 2009; Land & McLeod, 2000) or making
52 tea (Land, Mennie & Rusted, 1999). Many saccades tend to land in areas with no current
53 salient features, but where objects will be after an action, giving further support for the role
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3 of top-down influences over salience in these tasks. Here we present a descriptive analysis of
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5 human-generated saccades - an ethology for visual search in static scenes. Although the
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7 spatial scope of search was limited to a computer monitor, the search arrays were chosen to
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9 be extremely dense with the search target often intentionally camouflaged. This allowed us
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11 to analyze search over a much longer period of time rather than limiting search to its earliest
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13 stimulus driven stage (Parkhurst, Law & Niebur, 2002). In the current experiment, we
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15 measured the location of fixations and the direction, amplitude, and timing of saccades in free
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17 search. Because we were interested in natural search behavior, no probes interrupted search
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19 and observers were allowed up to 120 seconds of search per image. We analyzed our data
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21 with the intent of finding the relative contributions of image properties, top-down strategies
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23 and also midlevel orienting mechanisms. Although we stop short of producing a working
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25 model of visual search, we investigate and identify many factors that could be important in
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27 future models, and develop and test techniques that could be useful in future exploration of
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29 search patterns. We take two approaches to analyzing the data. In Section 3, we present
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31 descriptive analyses, and we look for similarities and repeating patterns across individuals
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33 and across images that would indicate top-down strategies or image-driven effects on search
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35 behaviour. In Section 4, we look at mid-level orienting effects, specifically inhibition of
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37 return (IOR) and saccadic momentum (SM), and use the search data to test specific
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39 hypotheses based on current models and theories of these effects.
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47 **2. Methods**

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49 Eight students of Aberdeen University were paid to participate in a simplified version
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51 of the Where's Wally© search task, a popular series of children's books in which a specified
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53 character, Wally, is hidden in a complicated illustration. The only task was to search for
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55 Wally and press the space bar when he was found. Thirteen scenes of varying complexity
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were displayed to observers until they found Wally or until 120 seconds had elapsed. Wally, or some portion of him, was present in all of the images, with his size ranging from 0.2 to 1.8 visual degrees. Images were presented at on a 19" Sony CRT monitor at a resolution of 1024x768 and a refresh rate of 100 hz. Eye position was monitored using an Eyelink 1000 desktop eye tracking system. With search times ranging from a few seconds to the full 120 seconds, we were able to record thousands of saccades in free search for each observer. From the eye movement data, we were able to extract a variety of dependent measures from trial saccades and fixations, namely: 1) the amplitude of each saccade, both on its own and relative to the distance between the start-point of the saccade and the one-back and the two-back fixations; 2) the angle (in degrees) of each saccade relative to the angle of

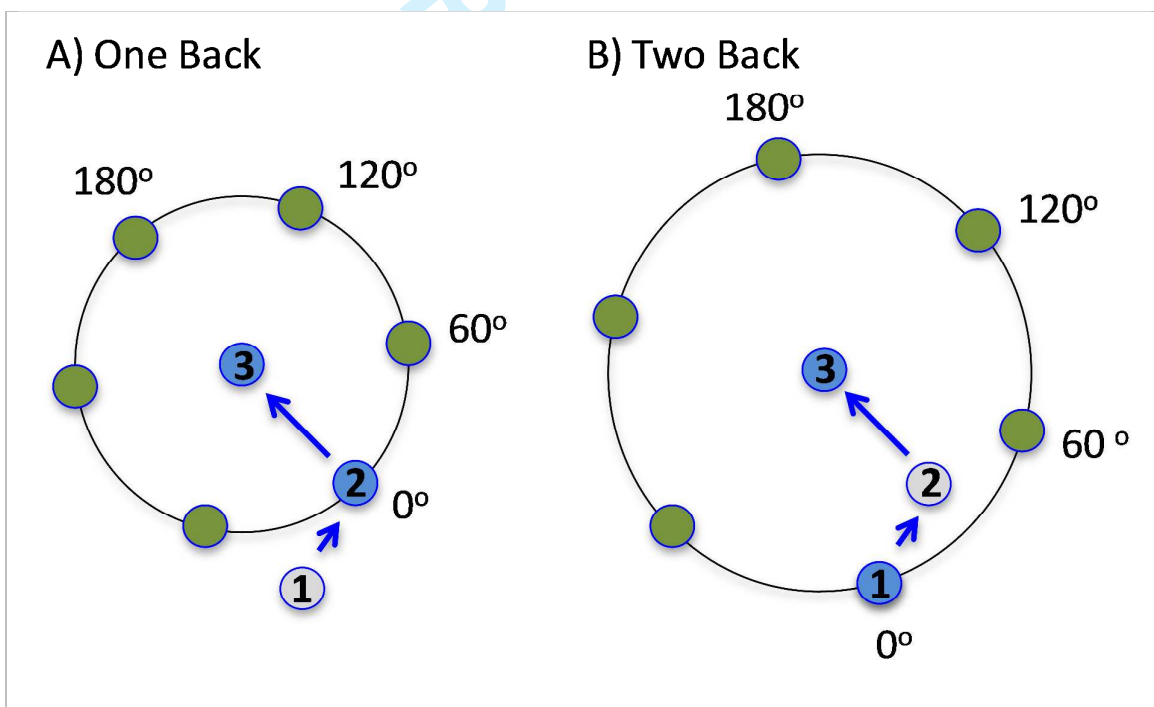


Figure 1. Illustration of how the relative angle of each saccade was coded. The circles represent locations of a sequence of fixations 1-2-3. A) Upon landing at '3', the previously-fixated location '2' would be coded as 0 degrees (A) left panel). Subsequent saccades would be coded relative to this location, such that a saccade along the same trajectory would be coded as a "forward" saccade (180 degrees, +/-5 degrees), and a saccade back to '2' would be 0 (+/-5 degrees), and would be considered a return saccade. The same coding scheme was applied to the "two-back" fixation location (B) right panel): upon landing at '3', location '1' would be coded as 0 degrees, and the angle of the subsequent saccade was calculated relative to this location.

both the preceding fixation (one-back) and the fixation that preceded the preceding fixation (two-back) (Figure 1); 3) saccadic latency, that is, the duration of the fixation that preceded the current saccade; 4) fixation coordinates in absolute screen pixels. These variables were explored in isolation, in combination, and as a temporal sequence. Other computational analysis techniques will be discussed as they are introduced.

3. Results and Discussion

Over 20,000 saccades were collected from 8 subjects searching 13 scenes from Where's Wally©.

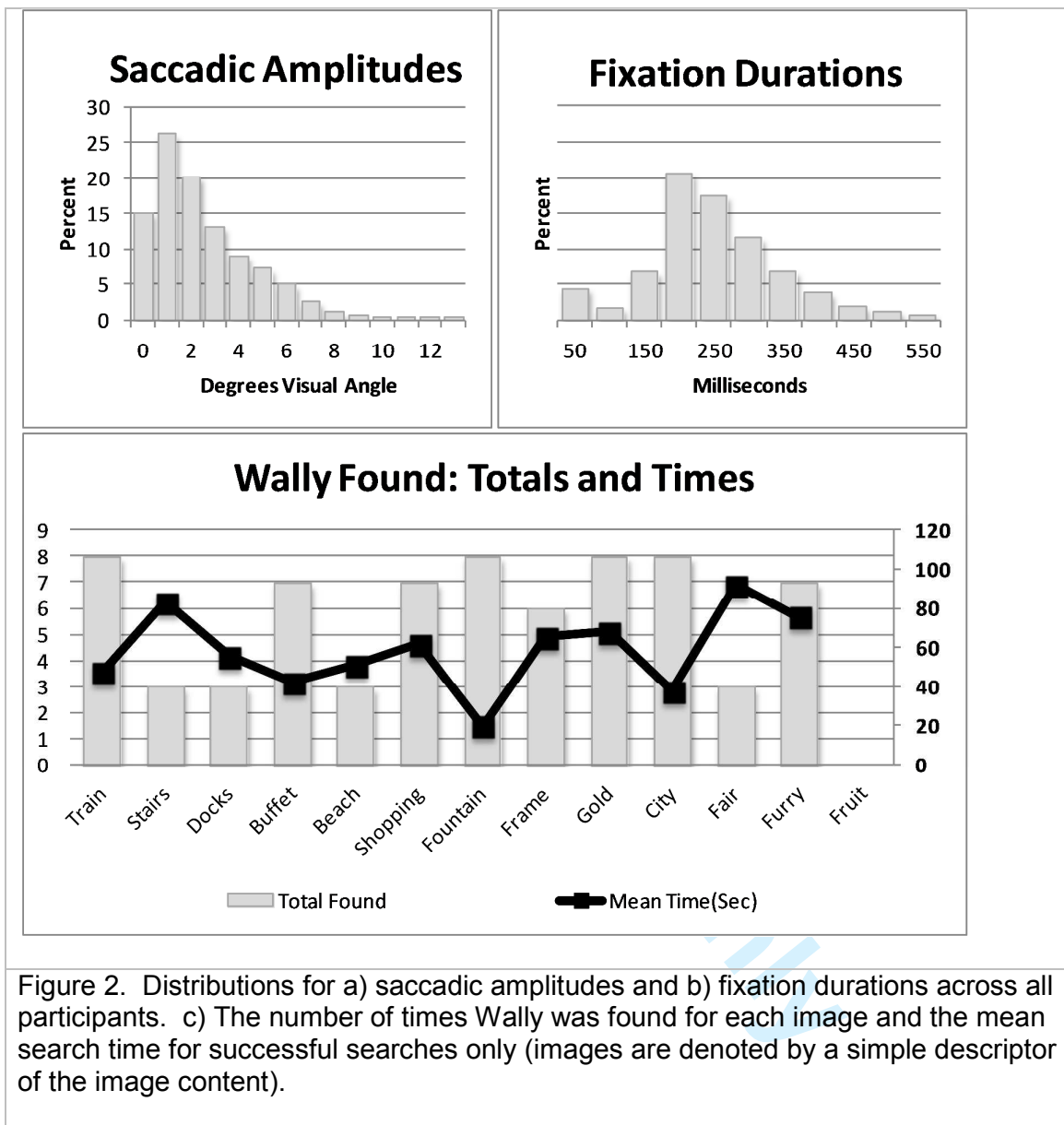
3.1 Descriptive statistics

Typical saccadic amplitude was skewed toward shorter distances (mean 3.97, median 2.68 visual degrees) and mean fixation duration was 277.15 milliseconds (Figure 2a and 2b). These general saccadic tendencies are similar to data from Klein and MacInnes (1999) and Smith and Henderson (2011b). In both of these previous studies, unlike the current one, search was frequently interrupted with a probe to which participants were instructed to respond as quickly as possible. Search scenes ranged in difficulty in terms of the number of times Wally was found and the average time required to find him. Wally was not found by any subjects in the 'fruit' scene, but was consistently found in less than 20 seconds in the 'fountain' scene (Figure 2c).

3.2 Top-down (Search Strategy) and bottom-up (Saliency map)

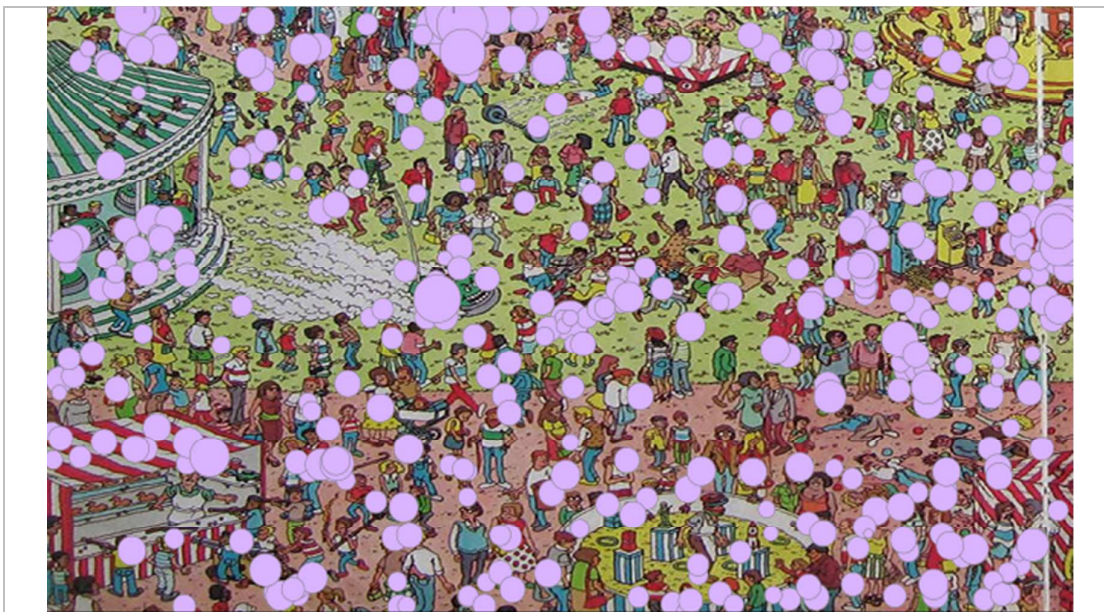
To explore the interplay of top-down strategy and image-based saliency we will begin with simple scanning strategies and then explore more subtle top-down influences. First, our observers do not seem to employ solely a simple strategy such as systematically 'reading' the scene from left to right and top to bottom. While typical reading studies (silent reading, English) show biases of 85% of saccades to the right and 15% to the left (Rayner, 1998),

search data do not show such an extreme bias (Figure 3b). Fixations for one observer (Figure 3a) illustrate a typical search with clusters of visits to salient locations. Binning the

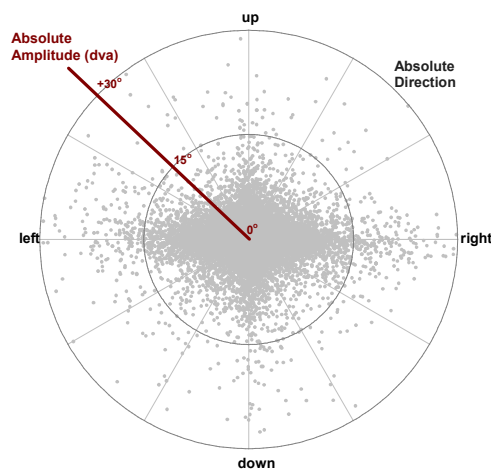


data into absolute angular distance and measuring saccadic tendency to the left and right (+/- 5 degrees) we see that observers do saccade to the left (7.7%) and right (7.0%) more than other directions (2.5% average in other equal size bins) (Left/Right vs. oblique $t(7=12.4), p<.001$). Rightward saccades are no more common than leftward ones, and 85% of saccades do not follow a simple left-right scanning pattern.

While there may not be an overriding simple scanning strategy, observers are likely employing some type of top-down influence in this task. Current models (Wolfe, 2007) take



A)



B)

Figure 3 A) Fixations for one trial, one participant. Purple dots are individual fixations with size reflecting the duration of the fixation. B) Polar plot of all saccadic angles (degrees) by amplitude (visual degrees) demonstrating no discernible bias for fewer and longer leftward saccades, as would be expected based on a reading strategy.

the stance that visual search is driven by a combination of top-down strategies and bottom-up salience. We believe that both of these factors can be modeled separately and that

their relative contributions can be measured even in a free search task. For example, our data include eight observers searching thirteen different images. To the extent that bottom-up control rooted in image properties matters there should be consistent differences between images across observers. Conversely, to the extent that top-down strategies residing in observers matter, there should be consistent differences between observers across images.

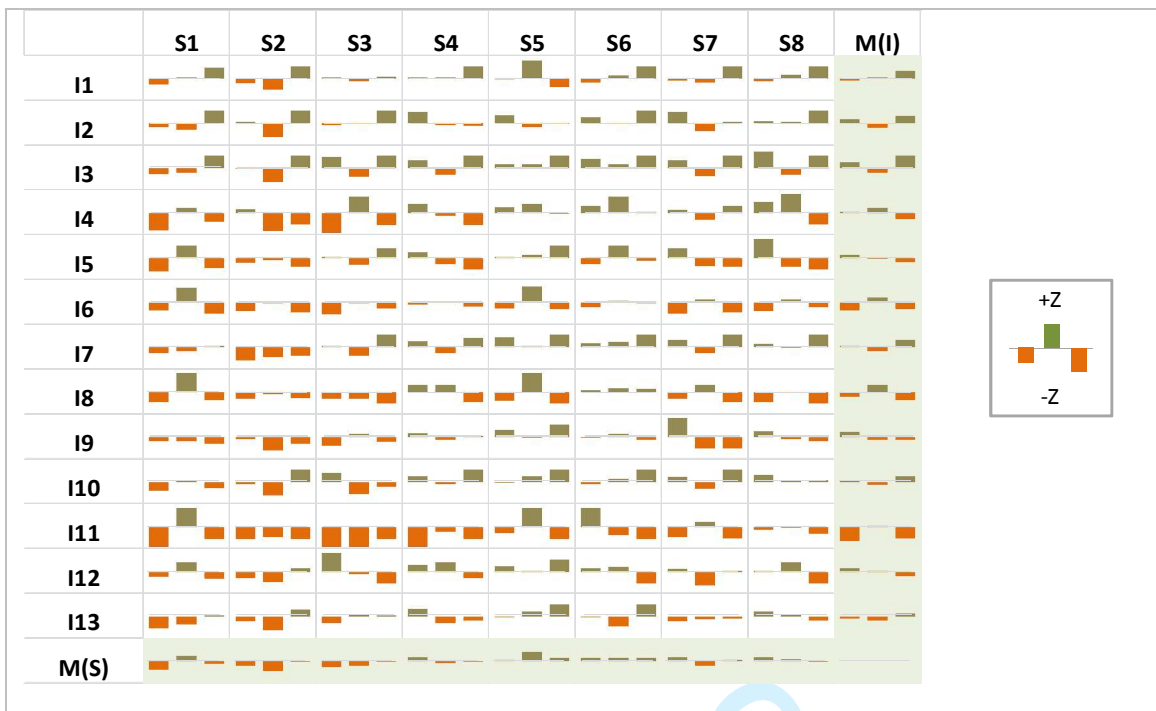


Figure 4: z-score histograms for all observer-image combination (individual cells) depicting mean fixation duration (first column in each cell), mean amplitude of individual saccades (second column) and total search time (third column). Zero/baseline is indicated with the horizontal hairline within each cell and reflects the global mean for each variable. Negative Z-scores are in orange beneath that line and positive z scores are in green above the line. Mean Z scores across each observer (bottom row) or across each image (last column) reflect how that image or subject differs from the mean in each variable. Consistent patterns across a single image, such as short fixation durations in Image 11, likely represent the influence of that image's salience, while patterns across subject, such as Observer 2's short amplitudes, are likely an individual's strategy.

Looking at Figure 4, we see fixation durations, amplitudes and search times for individual trials, but also the means for image (final column) and observer (final row). For example, Image 3 tends to have very long search times and Image 11 tends to have very short fixation durations. These are likely due to the particulars of the salience and feature maps of

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3 those images. Observers two and five however, tend to make saccades of very short and long
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5 amplitude respectively, and this is part of their search strategies since it is consistent across
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7 trial image. To further explore the relative contributions of salience and strategy, in what
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9 follows we introduce a number of new metrics of saccadic and fixational similarity, and
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11 analyze directly whether these similarities are predominant across image or observer.
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13 14 *3.3 Scanpath analysis*

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16 Two recent papers on scanpath analysis have tackled the problem of scanpath
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18 similarity using algorithms borrowed from genetics research used to compare sequences of
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20 genes. SCASIM (Von der Malsburg & Vasishth, 2011) and ScanMatch (Cristino, Mathot,
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22 Theeuwes & Gilchrist, 2010) use variants of the Needleman-Wunsch algorithm (Needleman,
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24 Saul & Wunsch, 1970) to calculate scanpath similarity by converting series of fixations into
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26 strings of discrete characters representing temporal features of the saccade or fixation
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28 sequence. These strings are then scored for similarity by the work it takes to convert one into
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30 the other through a series of deletions, insertions and the introduction of gaps. Our data
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32 differ from ScanMatch and SCASIM data, however, in that our trials include sequences of
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34 hundreds of saccades and that the Where's Wally[®] images do not lend themselves to easy
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36 'Region of Interest' division. We do use a number of ideas from these algorithms, but with a
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38 few important differences. First, we divide our fixation and saccade sequences into a number
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40 of smaller subsequences using a non-overlapping sliding window of random size between
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42 one and five eye movements. **Smaller ranges of subsequences were chosen as a first step to**
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44 **detect simpler patterns in saccadic data, and this range could be expanded to detect longer**
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46 **strings if any patterns of four or five saccades were detected. Non-overlapping windows**
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48 **were used to avoid sequence similarity confounds introduced with overlapping windows**
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50 **(Keogh & Lin, 2005).** Also, to convert our saccade and fixation information into discrete
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52 symbols, we use three separate coding schemes with each chosen to be sensitive to a number
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3 of strategies available in visual search. Since saccadic strategies could be relative to recent
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5 saccadic history or relative to the screen itself, we include codings for both absolute and
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7 relative saccadic angles.
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10 We first created a discretized variable to represent *absolute saccadic angle* (*AbsAng*),
11 using 18 bins of saccadic angle, each one 10°, as compared to an absolute rightward,
12 horizontal saccade. We also created a discretized variable to represent presaccadic latency by
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14 converting its duration to its \log_{10} and binning between 1.5 and 3.0 in 0.1 increments. Each
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16 saccade in a sequence could then be represented by a dyad of two alphabetical characters
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18 denoting its absolute angle and latency.
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23 The other two sequence codings are *relative saccadic angle (one-back)* (*RelAng1*) and
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25 *relative saccadic angle (two-back)* (*RelAng2*). These follow the same coding rules as
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27 absolute angle, except that saccadic angles are not calculated as compared to an absolute
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29 rightward direction, but instead as compared to a vector going back to a previous fixation.
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31 *RelAng1* codes the angular distance to the one-back location, while *RelAng2* codes to the
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33 two-back location (Figure 1). The log of the fixation duration completes the dyad in both
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35 variables.
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39 These different coding schemes may be sensitive to different influences on saccade
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41 sequences, given that absolute angle of saccades will represent sequences in absolute (or
42
43 scene-based) coordinates, while the relative angle will be sensitive to patterns based on the
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45 previous state of the oculomotor system. This is not to say that all *AbsAng* patterns will
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47 represent strategic planning. Frequent long strings in a rightward direction would clearly
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49 represent a reading bias, but if the most common sequences are short, a more likely
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51 interpretation would be a tendency or preference for edges or corners of the display. We will
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53 further discuss interpretation of common subsequences below.
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3 Finally, we suggest that these scan path sequences will be influenced by both scene
4 salience and observer strategy, but as with our descriptive analysis, we propose that
5 similarities in scanpaths common to a given subject will be more strategy-driven while
6 scanpath similarities within images will be influenced by scene features. We also propose
7 that patterns across an absolute scale (the entire image search) will be strategic, while local,
8 relative patterns will be influenced more by local features or attentional state.
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10
11 To carry out the scanpath analysis, substrings were extracted from each trial using a
12 non-overlapping sliding window, and the Needleman Wunsch (NW) algorithm (Needleman
13 & Wunsch, 1970) was used to generate a distance score representing the amount of work
14 required to convert one subsequence into the other. Valid string manipulations for NW
15 included gap insertion and the transformation of one character into the other. The **cost (T)** of
16 these transformations was set at 1.0 for gap insertion and a relative transition cost of 1.0
17 minus the inverse of the distance between alphabetical characters representing the discretized
18 angle and latency of the saccade.
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$$T = 1 - 1/(\text{abs}(\text{old} - \text{new}))$$

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34 This inverse distance allowed for the fact that our spatial, angular and temporal codes
35 represented a scale with closer categories taking less work to transform. Angle B is more
36 similar to C than it is to G.
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43 The score from comparing any pair of sequences **(A and B)** was the final number of
44 characters that matched in value and location, minus the cost of the transformations needed to
45 reach that match. This score was then divided by the number of characters in the sequence to
46 normalize for sequence length. This produced a range of similarity scores ranging from -1
47 (for no similarity) to +1 (for a perfect match). So
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$$NW = \left(\sum_{i=0}^n S(A_i, B_i) - \sum T \right) / n$$

where n is the length of the resulting string, $S()$ is the similarity value of each character in the subsequence, and T is the cost of each transform.

Because our trials lasted upwards to 120 seconds and many contained hundreds of saccades, the similarity score for any two full trials would be meaningless. We therefore sampled substrings of lengths one to five from each trial and looked at the mean NW similarity score for these trials. Sub patterns also allowed us to look for shorter repeating patterns within each trial. Selection used a non-overlapping sliding window of random length for reasons discussed in Keogh & Lin (2005).

3.3.1. Results for scanpath similarity

Similarity scores for our 8 observers were analyzed using paired t-tests and adjusted for multiple comparisons with Holm-Bonferroni (Holm, 1979). First we compared differences between our three coding schemes (AbsAng, RelAng1, RelAng2) to determine the relative strength of substring patterns (NW score) within each. There were significant

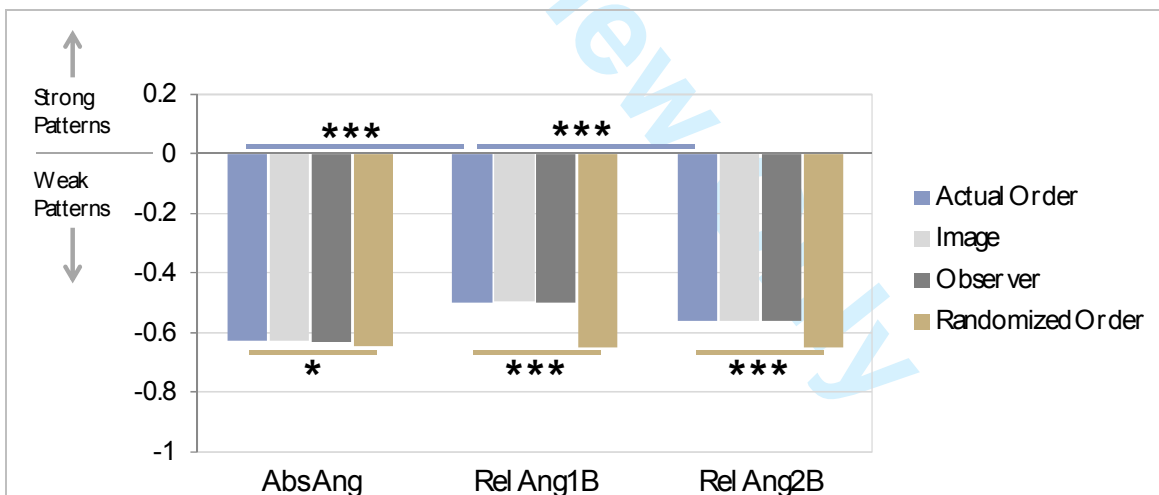


Figure 5: Mean Needleman-Wunsch similarity scores grouped by image, by observer, for the full data in actual order and the full data for randomized order. All scores are strongly negative, rejecting simple scanning strategies, but original angular data has more pattern similarity than random order. Relative patterns are stronger than absolute coordinate patterns. There is no difference in pattern strength when grouped by image or observer suggesting these patterns are equal combination observer (strategy) and image (saliency).

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3 NW score differences between all coding schemes with AbsAng less than RelAng2 ($t(7) =$
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5 24, $p < .001$), and RelAng2 less than RelAng1 ($t(7) = 25$, $p < .001$) (Figure 5). In general,
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7 relative patterns were stronger than those measured in absolute coordinates or angles. The
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9 mean NW values are also consistently negative suggesting that, overall, there was relatively
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11 little similarity of substrings within each search and the saccades were not likely generated by
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13 any single, simple repeating pattern. A second analysis compared NW scores when trials
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15 were grouped by image against trials grouped by observer. We propose that string
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17 similarities within a single image would be primarily caused by scene features, while
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19 similarity within subject would be more indicative of top down strategy. Substring t-tests
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21 were conducted for all of our coding schemes and the mean similarity score calculated for
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23 each. We grouped these means by image and by observer to determine which of these factors
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25 contributed more to any patterns observed with NW, but we did not find any differences for
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27 any of our string codings (AbsAng, $t(7) = .80$; RelAng1, $t(7) = .73$; RelAng2, $t(7) = .48$)
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29 (Figure 5). Again, NW scores are negative, suggesting few or weak similarities among
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31 substrings, while the lack of effect when comparing image against observer groupings
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33 suggests that neither is a stronger influence in determining what similarities do exist in
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35 saccadic subsequences. Relative and absolute patterns in these search data are equally
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37 influenced by scene features and top-down strategies.
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43 We wanted to ensure that our null result when comparing similarity of strings for
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45 observer and image groupings was due to weak but equal contribution of strategy and
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47 salience, so we performed two tests to ensure our measure would detect changes in patterns.
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49 First, we compared the results of the three codings in their original order to sequences
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51 resulting from a random walk of saccade locations (Figure 5). T-tests for each coding
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53 scheme were conducted comparing the NW score of each original ordering against its
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55 temporally randomized equivalent. These comparisons result in significantly more patterns
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(less negative) for all three angular measures (AbsAng, $t(7) = 2.75$, $p < .05$; RelAng1, $t(7) = 771$, $p < .001$; RelAng2, $t(7) = 283$, $p < .001$), suggesting that there are patterns in our data as measured by these coding schemes, and NW is sensitive to those patterns.

For further evidence that our NW score is sensitive to differences in search patterns, we turned to Gilchrist and Harvey (2006), who manipulated the entropy of search arrays to explore the effect on systemic search patterns that they attributed to cognitive strategy. In their results, they showed that regular search arrays tended to produce a stronger horizontal saccade bias than arrays which were less regular. Although we did not choose our images with this manipulation in mind, our stimulus set included one image with more regular features than the others. In most Wally[®] images, the character and object distractors are

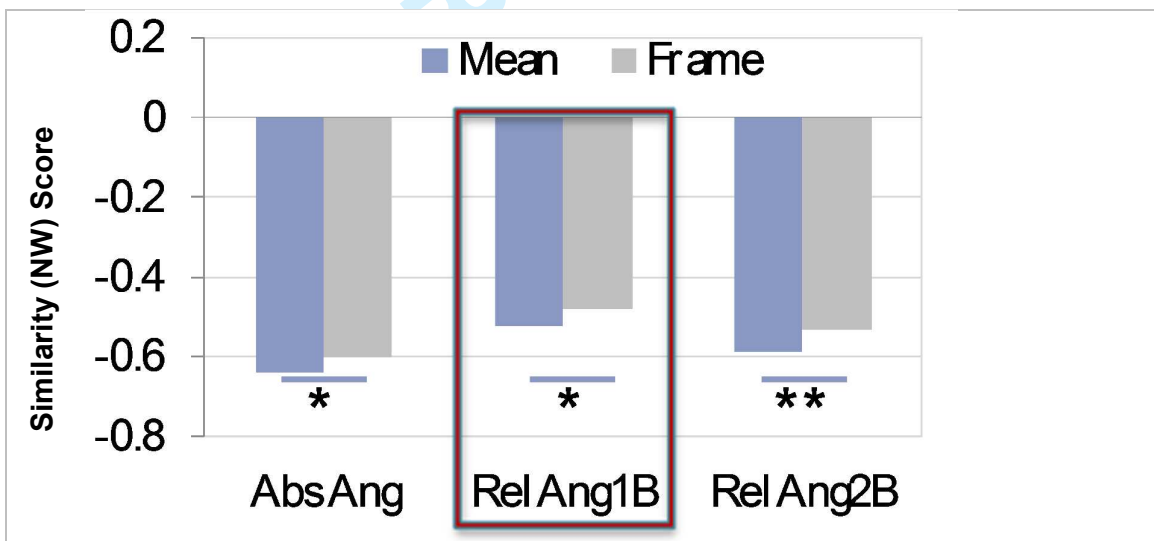


Figure 6: Comparison of NW score of 'Wally Frames' and the mean of the other images. AbsAng is a close replication of the search array manipulation and results in Gilchrist and Harvey (2006)

spread out equally throughout the scene, but for one image in our set, the distracter characters were displayed as framed portraits with empty space between the frames (The Great Portrait Exhibition in *Where's Wally: The Great Picture Hunt*, 2006). If our NW similarity measure is sensitive to systemic patterns, we should be able to replicate Gilchrist and Harvey's results with the picture frame image (Figure 6). We compared the mean NW similarity scores for our

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3 typical images to the mean of the frame image. We find the typical Wally image to contain
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5 less similar subsequence patterns than the Wally frame image for all of our angular sequence
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7 codings (AbsAng, $t(7) = 3.02$, $p < .05$; RelAng1, $t(7) = 3.15$, $P < .05$; RelAng2, $t(7) = 4.36$, p
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9 $< .01$). While the mean difference is small in each case (maximum .05 NW score), it is
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11 consistently in the expected direction of the 'frame' image producing more similar strings,
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13 and the Absolute Saccadic Angle coding (AbsAng) replicates the coding used in Gilchrist and
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15 Harvey(2006).
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20 21 3.4 Common Substrings

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23 Another common analysis for data mining and genetics is the discovery of common
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25 substrings or "motifs" (Chiu, Keogh & Lonardi, 2003). We looked for common sequences in
26
27 our dataset using a probability weight matrix applied to the dyads established above. Typical
28
29 sequences tended to be short, with most being only a single dyad, and none extending beyond
30
31 two dyads. These single common saccades generally reflected the broad tendency toward
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33 horizontal saccades reported above. These results suggest no clear motif search patterns exist
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35 in our data, either in absolute or in the relative angle of saccades, so the full analysis and
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37 results will not be reported in detail here.
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43 4. Mid-level orienting mechanisms

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45 Mid-level effects, rooted in an observer's prior orienting behavior, have been
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47 suggested to be a driving force in visual search. Both Inhibition of Return (IOR, Posner,
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49 Rafal, Choate, & Vaughan, 1985; Klein, & MacInnes, 1999) and Saccadic Momentum (SM,
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51 Smith & Henderson, 2009) have been proposed to play a role during search by biasing
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53 saccades: away from previously fixated locations or toward a continuation of the current
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55 vector, respectively.
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3 As opposed to top-down strategy which could be measured in lengthy, global
4 patterns, mid-level orienting effects are most likely to affect saccadic distribution as a
5 function of the current state of the oculomotor system. We therefore focus on short-term,
6 relative measures, specifically, in the only computationally explicit model of SM. Wang,
7 Satel, Trappenberg & Klein (2011) proposed that leftover activity in the superior colliculus
8 following a saccade leads to an increased probability of a repeated saccadic vector or
9 “saccades in the forward direction, particularly those with the same amplitude as the previous
10 saccade (p. 3)”. We will analyze our data with models such as this in mind, and in particular
11 the relative occurrences of saccadic amplitudes, fixation durations, and spatial locations at
12 recently visited (one and two-back) locations.
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24 4.1 Repetition of Amplitude

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27 Our null hypothesis for the distribution of amplitudes for individual saccades in a
28 given search is that they are chosen randomly from some distribution. Without making any
29 assumptions regarding the properties of the distribution of amplitudes for individual
30 saccades, we can still say something about the difference between two saccadic amplitudes
31 that are randomly sampled from that distribution. Notably, the distribution of differences will
32 have a mean and mode of zero and a normal distribution. Sequential saccades may not be
33 independent, however, and mid level orienting mechanisms could influence the selection of
34 saccades such that the difference in amplitudes within a saccade pair does not fit the
35 ‘expected’ distribution of differences based on random selection. In particular, SM predicts
36 that saccades tend in a forward direction (Smith, & Henderson, 2009), which, in the
37 computationally explicit model (Wang et al., 2011), produces a higher than expected
38 frequency of repeat vectors (amplitudes and direction) than expected by chance, resulting in a
39 mean amplitude difference of zero but an increase in the mode produced without SM (oblique
40 saccades). On the other hand, IOR would lead to a reduced probability of saccade pairs in a
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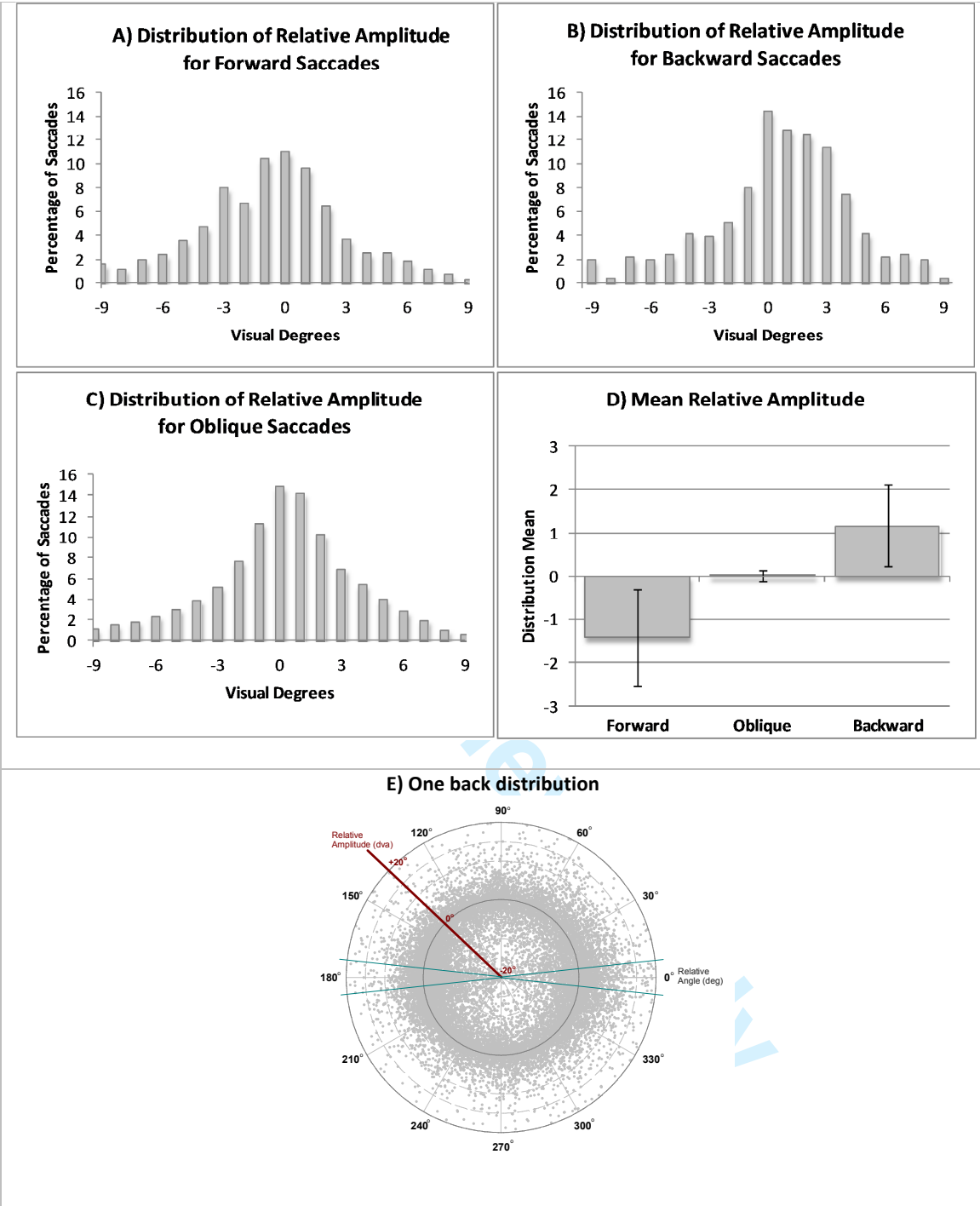


Figure 7. Distributions of saccade amplitude differences (current - previous) for forward (A), backward (B) and other (C) saccades as well as means for the distributions of differences (D). The polar plot (E) shows all saccades according to their relative angle and distance. Green lines represent pie slices used to designate forward and backward saccades in 7(A), 7(B), and 7(D).

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3 reverse direction having equal amplitudes, resulting in a deviation of the normal distribution.

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5 We also test this null hypothesis against oblique amplitude pairs (saccades that neither
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7 continued nor reversed), which should not be affected by either SM or IOR.
8

9
10 Smith and Henderson (2011) assessed relative amplitudes in their analysis of SM in
11 visual search, but they used a fairly coarse bin for relative saccadic amplitude. Their
12 difference measure subtracted the amplitude of the current saccade from that of the previous
13 saccade, and the fact that the distribution of differences tends to centre on plus or minus two
14 visual degrees in their results demonstrates a high likelihood of amplitude repetition.
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16 However, given that most saccades are likely to be less than four degrees in amplitude
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18 (MacInnes &
19 Klein, 2003; von Wartburg et al., 2007), and might be even smaller in complex scenes, this
20 binning could be masking subtly different patterns for refixations relative to saccades 180
21 degrees away. We divided our own data into 1.0° amplitude bins instead of 2° bins to gain a
22 more precise measure of repetition. For angular distance, we again used the angle between
23 the previous and current saccadic vector with repeat vectors being 180° +/- 5 and reverse
24 vectors being 0° +/-5 (see figure 1) and oblique containing all other saccadic angles. As can
25 be visualized in Figure 7, had we used larger bins of +/- 2° magnitude differences, too high a
26 percentage of the overall saccadic distribution of differences would have been in the first two
27 bins (as a consequence of the fact that almost 70% of saccades in our experiment fall between
28 0 and 4 visual degrees in amplitude).
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47 Using this analysis, mean relative amplitudes for forward and backward saccades are
48 both significantly different from zero with forward saccades tending to undershoot the
49 previous amplitude (mean -1.415, $t(7) = 3.37$, $p < .02$) and backward saccades tending to
50 overshoot (mean +1.169, $t(7) = 3.35$, $p < .02$). These results dismiss the null hypothesis that
51 pairs of sequential saccades are randomly selected from some underlying distribution. The
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3 significant difference in relative amplitudes (mean does not equal 0.0) among successive
4 forward saccades also dismisses the prediction made by SM that equal amplitudes should be
5 more likely when direction is also repeated. The significant amplitude difference among
6 successive backward saccades, while not predicted by IOR, is consistent with IOR. The
7 significant differences that we did detect were not an artifact of the bin sizes for the
8 amplitude or angle, given that we applied the same analysis to oblique saccades, and found
9 that the mean relative amplitude was not significantly different from zero ($t(7) < 1$, Figure 7).
10 It is true that the mode of all three distributions (forward, backward, and oblique) is at or near
11 zero, and we see no differences in the proportion of saccades at the mode between forward,
12 backward and oblique saccades ($t(7) < 1$). We do not dispute that repeat amplitudes are
13 common for both forward and backward vector saccades (this is discussed in more detail in
14 the “return probability” section below), but our null hypothesis predicts a distribution where
15 both the mode and mean of the distributions fall at 0, and either of these scores measuring a
16 non-zero value is sufficient to dismiss the null. Some process is acting on selection of
17 successive backward and forward amplitudes to shift them away from the purely random
18 selection observed in successive oblique saccades (Figure 7c). We do not see the increase in
19 repeat frequency we would expect from the Wang (2011) SM account of forward amplitudes,
20 nor do we see the decrease in the probability of repeat amplitudes we would expect to see in
21 backward saccades from an IOR account.. The pattern reveals multiple processes that could
22 be acting on selection of saccade vectors. For example, perhaps observers’ previous
23 attentional state shifts the distribution of differences for backward and forward saccades
24 away from the Gaussian predicted by random sampling or SM, and other factors, such as the
25 salience of the previous fixation, generate a large number of refixations. This is also evident
26 in the polar plot (Figure 7E) which shows frequent repeat amplitudes for all angles (the 0°

amplitude ring), but a break from normal distribution for forward and backward saccades (green pie slices).

4.2 Forward Probability

That pairs of sequential saccades tend to repeat their current angular direction is not in dispute, and this pattern is observed in the present data as well as in previous studies (Klein & MacInnes, 1999; Smith & Henderson, 2011). Both SM and IOR have been proposed as a basis for this forward tendency, but most analyses have focused on the most recently fixated location. A forward tendency could be rooted in spatiotopic coordinates such as an inhibitory tag (Klein, 2000) or in vector coordinates as suggested by Wang et al. (2011),

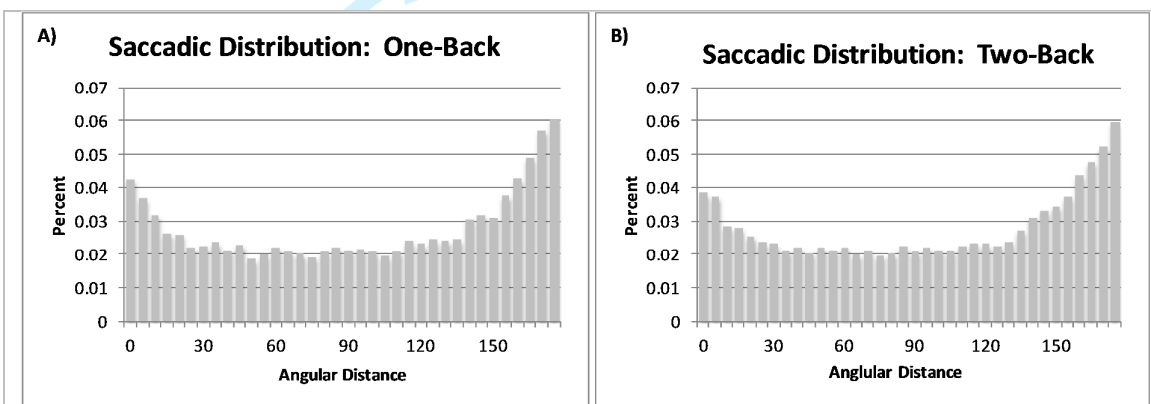


Figure 8. Distribution of all saccade angles relative to the A) one and B) two back locations, using bins of five visual degrees. Angular distances ranges from 0° (backward saccadic vector) to 180° (forward saccadic vector) (See figure 1 for calculation of angular distance).

and these theories are not easily distinguished at the one back location. A tendency to saccade forward (180° - away from previously-visited spatial locations) would cause a vector bias away from only the one-back location, and would predict a smaller bias away from the two-back location. IOR and SM would make different predictions in the expected reduction of the number of forward saccades from the one-back location relative to forward saccades from the two-back location. A vector-based explanation for the forward bias predicts a bias away from the two-back location only when two forward (180 degree) saccades were produced in a

row. A spatiotopic-based account such as IOR, on the other hand, predicts an increased probability of saccades being directed away from not only the immediately preceding fixation, but also the two-back fixation (Figure 1). Figure 8 shows the distribution of saccade angles relative to both the one-back and two-back locations and, although there is a decrease in forward saccades away from the two-back location relative to the one-back location of 0.2%, this reduction is not significant ($t(7) < 1.0$), suggesting an equal bias away from the two-back, and one-back locations, consistent with a spatiotopic attentional influence.

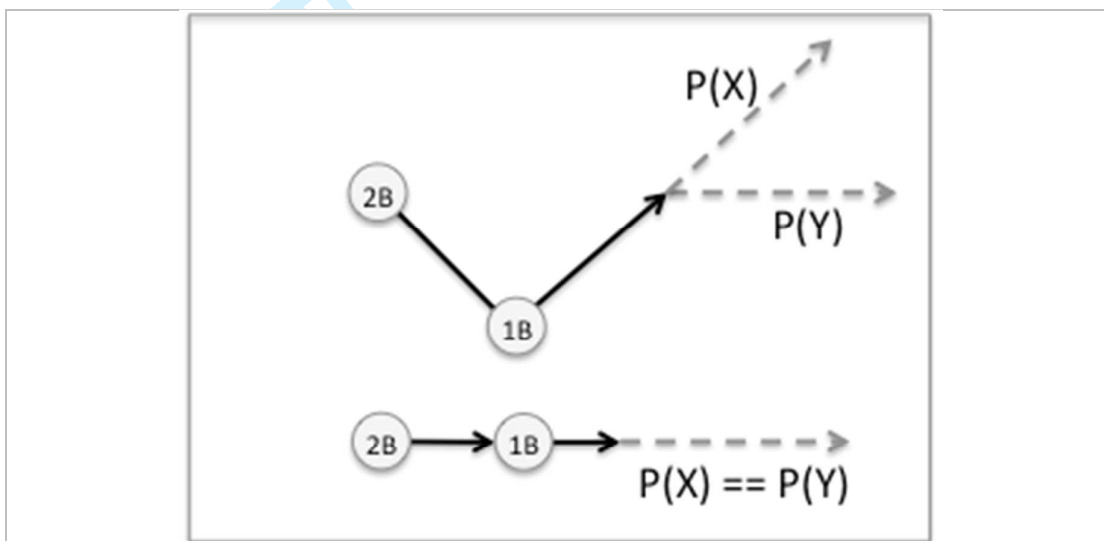


Figure 9: Under saccadic momentum, the probability of saccades away from the one back location, $P(X)$, should be greater than those away from the two back location, $P(Y)$. The only cases where saccades would be predicted to be directed away from the two-back location are those where the two previous saccades line up.

Some of these saccades away from the two-back location, however, are also saccades away from the one-back location when the two previous saccades line up with the current vector (See Figure 9 for illustration). We measured the probability that the two-back location was forward given that the one-back location was also forward to determine if these sequences could explain the lack of reduction in two-back saccades. Selecting only saccades directed forward relative to the two-back location, we found that 54% of these saccades were also directed forward relative to the one-back location (180 ± 5). The percentage of repeat

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3 saccades, however would have to be the probability that one back saccades fall in the 180°
4 bin divided by the probability that the two back fell in the 180° bin. Taking these numbers
5 from the 180° bin in Figure 8a and 8b we need $.058/.060 = 96.7\%$ saccades continuing
6 forward to entirely explain our observed lack of reduction of two-back forward saccades.
7 Since the percentage of forward saccades do not decrease from one to two back, we must
8 conclude that either 97% of saccades continue in the same direction (they do not) or that
9 something else is shifting saccadic direction away from the two back location. Thus, these
10 results are consistent with an IOR effect biasing saccadic direction away from spatial
11 inhibitory tags generated during previous inspections. It is also clear from Figure 8 that
12 backward saccades are as prominent for one-back as for two-back locations, which is also a
13 problem for IOR to explain. This issue is addressed in the next section.

24 25 26 27 *4.3 Backward Probability*

28
29 The proposal that IOR is a facilitator of visual search leads to the prediction that the
30 likelihood of a saccade returning to previously fixated locations will be reduced (Klein,
31 1988). But reduced from what? While the incidence of return saccades has consistently been
32 shown to be less than forward saccades, it is also higher than for neutral, oblique angles
33 relative to previous locations (Klein & MacInnes, 1999; Smith & Henderson, 2011; present
34 data). However, the location that was just fixated is likely to be relatively more salient and/or
35 task-relevant than any otherwise equivalent location, simply because the observer has already
36 fixated that location at least once. This makes its salience unique among other equidistant
37 locations. Comparing the frequency and metrics of forward saccades to a baseline (such as
38 90-degree saccades) is therefore justified (because neither has been previously fixated), but
39 comparing refixations to a similar baseline would be confounded by previous fixation status.
40 To determine whether refixations are more or less likely than baseline, that baseline must be
41 equivalent to the previously fixated target in saliency, task-relevance, and distance from
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current fixation. Smith and Henderson (2011) control for saliency and task-relevance by comparing the probability of returning to a location within one or two fixations to the probability of those locations repeating when the sequence of fixations is randomly shuffled. The idea was to generate a proportion of refixations that would be expected if IOR did not influence the sequence in which salient locations were fixated. The rate of refixations in the actual sequence was higher than the shuffled baseline, which they took as evidence that IOR was not discouraging refixations. This shuffled baseline does not, however, control for the distance of the previous fixation from the current one. Sequences of fixations are spatially clustered, and when shuffled this clustering would be eliminated. The shuffling method used by Smith and Henderson (2011b; also Hooge et al. 2005) therefore introduces a new problem, which is that the distance between consecutive fixations when their order has been randomly shuffled will be larger than in the original sequence of fixations (Figure 10). Because locations closer to the fovea will be more attractive than more distant locations, refixations would be expected to have a higher base rate than other locations in a natural sequence of saccades.

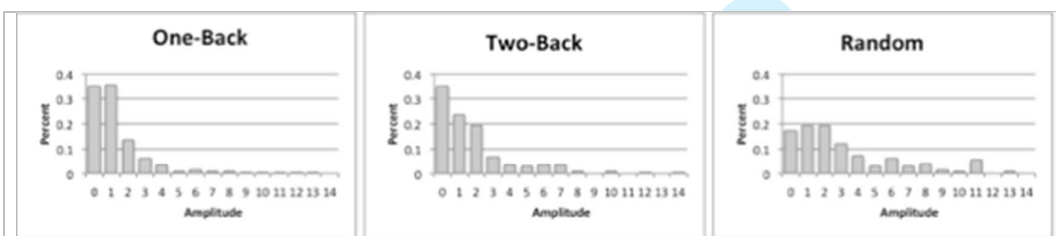


Figure 10. Percentage of saccades which revisit the one-back and two-back locations in the actual data, and when the fixation order is randomly shuffled. Amplitudes of refixations in the actual data **for both locations** are shorter than in the randomly shuffled data set.

To verify this, we conducted a similar comparison in the current study, defining a refixation as a saccade that fell within one visual degree of a previous fixation. The mean probabilities for all observers to return to the one-back, two-back and shuffled locations are illustrated in Figure 10. While refixations were significantly more likely for one-back ($t(7) =$

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3 11.4, $p < .001$) and two-back ($t(7) = 7.5$; $p < .001$) than the shuffled locations, the distance
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5 between the current location and these shuffled locations was also much higher than to one-
6
7 back return locations (one-back $t(7) = 3.6$, $p < .01$; two-back $t(7) = 2.2$, $p < .06$). Thus,
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9 observers may have returned to previously fixated locations because, despite any influence of
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11 IOR, they were still nearby or salient locations. Moreover, Bays and Husain(2012) conducted
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13 a Bayesian analysis of search saccades, and were able to control for scene salience and
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15 compare the observed likelihood of return fixations to the likelihood that would be predicted
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17 by a memory-less system. Relative to this salience-controlled baseline, return saccades were
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19 indeed less likely, giving further support to the IOR account.
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22 23 *4.4 Fixation Durations*

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25 While mid-level orienting effects can and do generate spatial patterns and
26
27 probabilities, top down influences can certainly override these tendencies. There would be
28
29 no benefit to an orienting system which influenced saccade selection if that system could not
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31 be overridden when needed. We would, however, expect to see repercussions of those
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33 choices in data such as the fixation durations prior to saccades. In particular, if effects like
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35 SM and IOR ease the oculomotor system forward or discourage it from returning,
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37 respectively, then we should see a temporal cost when return saccades are executed and
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39 advantages when vectors are repeated. These predictions for fixation durations (FDs) are not
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41 mutually exclusive, and indeed Smith and Henderson (2009) found evidence for both SM and
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43 IOR in natural viewing.
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47 The SM account suggests that when observers follow the tendency to continue
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49 forward, there should be an effect of reduced FD prior to that forward saccade. Alternatively,
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51 the IOR account predicts an increased FD when observers override that inhibition to re-fixate
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53 a previous location. As discussed in the introduction, observers can and do return to
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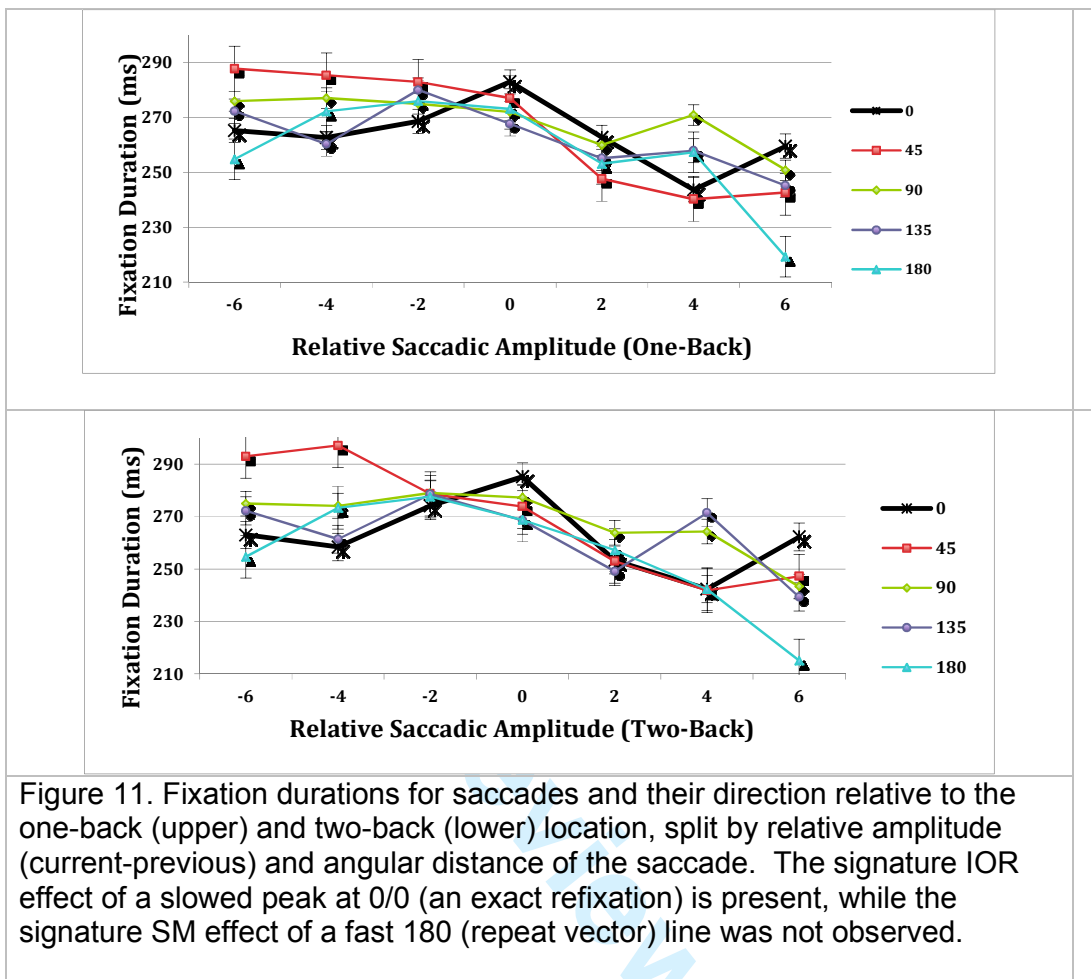


Figure 11. Fixation durations for saccades and their direction relative to the one-back (upper) and two-back (lower) location, split by relative amplitude (current-previous) and angular distance of the saccade. The signature IOR effect of a slowed peak at 0/0 (an exact refixation) is present, while the signature SM effect of a fast 180 (repeat vector) line was not observed.

previously fixated locations, especially with noisy or complex scenes, in which observers may choose to revisit a location to ensure nothing was missed. We analyzed the fixation durations of gaze locations prior to the current saccade. Since a true return saccade is one which matches the previous in amplitude yet reverses in **direction**, we binned our data by both relative amplitude and angular difference. To match the equivalent analysis from Smith and Henderson (2009, 2011), for relative amplitude we created seven bins, each of two degrees, **centered on relative amplitudes** from -6° to $+6^\circ$. For the angular difference we created five bins of 45° from 0° to 180° (0° , 45° , 90° , 135° and 180°). Saccades of less than one degree were excluded, as were relative amplitudes greater than **7° or less than -7°** , and fixations that fell within one degree of the screen edge which limited the potential angular bins. The remaining 8600 FDs were analyzed in $7(\text{relative amplitude}) \times 5(\text{angular$

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3 difference) within-subjects ANOVAs, separately for the one-back and two-back locations.
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5 We expected two patterns to emerge based on previous research: return saccades of equal
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7 amplitude (0° angular distance and 0 relative amplitude) should be slowed relative to other
8
9 combinations as predicted by IOR, and forward saccades (either the entire 180 line or the
10
11 180/0 bin) should be speeded compared to other directions as predicted by SM (Smith &
12
13 Henderson, 2009).
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17 There was a main effect of relative amplitude in both the one-back ($F(6,42) = 11.7, p$
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19 $< .001$) and two-back ($F(6,42) = 14.5, p < .001$) analysis, with longer fixation durations when
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21 short saccades follow long saccades (consistent with an observation made by Smith and
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23 Henderson [2011]). There was no effect of angular distance for one-back ($F(4,28) = 1.3$) but
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25 it was significant for two-back ($F(2,28) = 3.3, p < .03$) locations, though was not caused by
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27 differences in 180° or 0° . The absence of significance at one-back 180° is contrary to Smith
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29 and Henderson (2009, 2011) who found shorter fixation durations for forward saccades in
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31 search and free viewing. The interaction was significant in both analyses – one-back
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33 ($F(24,168)=1.7, p<.04$) and two-back ($F(24,168)=2.5, p<.001$).
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37 We tested for significance of the 0° peak by comparing the observed $0^\circ/0^\circ$ peak against
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39 those predicted by the regression line of the other **amplitudes**. Based on expected interactions
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41 between durations and **relative** amplitudes (Smith and Henderson, 2009, Tatler & Vincent,
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43 2008; Unema, Pannasch, Joos, & Velichovsky, 2005) we expect a linear decrease in Fixation
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45 durations from **relative** amplitudes of -6 to +6. **Separate** regressions for each observer's 0°
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47 angular distance line **was used** to determine their expected fixation duration **at the 0**
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49 **amplitude location and resulted in a predicted value of 251.8 ms (SD = 15.8) for one-back and**
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51 **249.4ms (SD = 19.2) for two-back**. These expected return fixation durations were then
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53 compared against the *measured* fixation durations (**one-back mean = 270.3; SD = 29.4; two-**
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55 **back mean = 268.4; SD = 33.6**). **Dependent-measures t-tests** against the actual subjects'
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3 means revealed that the 0 degree peak was significantly slower than predicted for one-back
4 location ($t(7) = 2.5; p < .05$). This difference was not significant in the two-back location
5 ($t(7) = 1.8, p < .11$).
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9 This analysis suggests that saccades that return to the previously fixated location
10 (reversing direction and repeating amplitude) are particularly slow. If IOR exists
11 independently of, or despite, bottom-up or top-down mechanisms that might generate a return
12 saccade, such saccades are likely to be delayed by IOR, as reflected in longer fixation
13 durations prior to these return saccades. This is exactly the pattern of results observed for
14 return saccades of repeat amplitudes in Smith and Henderson (2009, 2011) and in the current
15 study (Figure 11). It is interesting to note that the 0/0 peak does not produce the slowest FD
16 of all the locations measured; clearly there are other factors contributing to saccadic latency
17 in addition to IOR. Consistent with the IOR account, we do find a relative cost in FD for
18 saccades which return to previously fixated locations, but we do not find the signature SM
19 effect of shorter FD for forward saccades from one-back locations¹.
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36 5. Summary and Conclusion

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38 Visual search is a complex interplay of scene salience, searcher strategy and mid-level
39 aftereffects of orienting. Fixations and saccades from search data unfettered by control
40 conditions or secondary tasks can provide insights from all three of these perspectives using
41 analyses across scene images, observers and patterns over time.
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47 Top-down strategy and attentional sets are pervasive in all search tasks, whether
48 controlled or free, and they interact with the underlying scene salience (Henderson, 2003).
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50 Traditional measures such as search completion times, fixation durations, spatial distributions
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55 ¹ Contrary to Smith and Henderson, 180 is no faster than other directions and for
56 180 there is no benefit for exact magnitude repeats as would have been predicted by
57 Wang et al. (2011) for the amplitude ranges we test here (Wang et al., 2011, Figure
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3 of saccades can be augmented with measures of temporal sequence similarity, such as the
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5 Needleman-Wunsch score. Through inspection of search data as a sequence of fixations,
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7 these measures can be applied to access patterns which are absolute in scene terms or relative
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9 to the current state of the oculomotor system. In addition to these more data-driven
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11 approaches, it is also possible to test specific hypotheses about the relative impact of effects
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13 such as IOR and SM in natural search data. While no single one of these measures alone is
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15 sufficient in itself to describe the complexities of search, each lends a lens through which we
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17 are able to observe the respective contributions of strategy, salience and attention in visual
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19 search.
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22 23 *5.1 Strategy and Salience*

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25 Patterns of search involving an observer's top down strategy can be simple, such as a
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27 left-right 'reading' strategy, or more complex and situational such as focusing attention on
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29 red-ish scene items that might match Wally's shirt. Simple global strategies were not seen in
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31 our data, as evidenced by relatively low string similarity for our observers and the very short
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33 length of common substrings. Consistent strategies would predict saccadic sequences that
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35 were more similar when grouped by observer than those grouped by a particular image, yet
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37 we found no evidence for this. Saccade sequence similarity across image and observer were
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39 not different, suggesting an equal contribution of each. Patterns as detected by analysis of
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41 sequence similarity suggest that, overall, repeated sequences are uncommon and short, with
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43 most lasting one or two saccades. Those that are present tend to be more frequent in local
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45 and relative coordinates than those measured in global or absolute coordinates, meaning they
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47 are more likely influenced by the then current state of the oculomotor system and image
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49 salience. Due to the complexity of the Where's Wally © search scenes, our sequence and
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51 strategy analyses did not consider scene, object, or feature-based strategies except insofar as
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53 they would be represented by saccadic selection and consistent across observers.
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3 Just as patterns for any given subject implicate strategic control, patterns for any
4 given image implicate a role for the salience and features of that image. As mentioned, a
5 comparison of saccade similarity by observer and image showed no differences suggesting
6 relatively equal contributions of each while searching in complex scenes. Comparing
7 specific images of differing regularity, however, replicates the controlled study by (Gilchrist
8 & Harvey, 2006) in that the image with more regular features showed more local patterns in
9 both absolute and relative angular coordinates.
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18 *5.2 Aftereffects of orienting behavior*

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20 We confirmed that saccades are not independent in visual search. Saccades are more
21 likely to move in a forward direction compared to the previous saccade. Our analysis of eye
22 movement behavior during natural search suggests that there is a bias away from recently
23 visited locations. This tendency towards novel locations can of course be overridden; in the
24 context of complex scenes, for example, refixations are common and necessary to discover
25 missed details. Here, we also find that refixations are a common occurrence during natural
26 search. However, in most cases when an oculomotor bias is overridden, and a saccade is
27 directed towards a recently-visited location, we observed the effects of the bias in fixation
28 durations.
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40 Although SM has been shown to contribute to saccade behavior in other studies, the
41 majority of the evidence here points toward IOR being the primary mechanism driving
42 saccades away from previously attended locations. We found a tendency for forward
43 saccades to diminish in amplitude, for return saccades to increase in amplitude, and for
44 saccades in other directions to be, on average, of similar amplitude. Although a reason for
45 diminishing amplitudes in consecutive forward saccades cannot be endorsed with our data
46 alone, it is inconsistent with saccadic momentum, which predicts that the amplitudes for
47 consecutive saccades executed in the same direction should be similar in size. It is similarly
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3 not clear why return saccades tend to increase in relative amplitude, but it is consistent with
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5 the possibility that these saccades are targeting not a previously-fixated location, but another
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7 object along the same trajectory. One explanation for these results could be strategic;
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9 Although saccades falling close to the screen's edge were excluded, a string of forward
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11 saccades will eventually run out of search space given the screen dimensions. In fact, for
12
13 every pairing of forward saccades in the relative amplitude analysis, the second forward
14
15 saccade must have less screen space in which to move forward than its penultimate.
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17 Corrective forward saccades that result from undershooting a saccade target could also
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19 explain this tendency in some portion of saccades. Either of these explanations, along with
20
21 scene saliency, would likely combine with any momentum in the SC to produce relative
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23 forward amplitudes which approach repeat amplitudes, but fall short. Just as IOR might
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25 compete with other mechanisms which influence backward saccades, saccadic momentum
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27 may combine with other mechanisms for forward repetitions. Considering that successive
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29 oblique saccades do average to zero, these inhibitory and forward mechanisms are unique to
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31 those directions.
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36 For an IOR account based on spatial inhibitory tags, there should be a tendency to
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38 saccade away from not only the immediately previous (one-back) location, but also the
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40 location before it (two-back), given that IOR has been measured for locations extending back
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42 four fixations previous to the current one (Dodd, Van der Stigchel & Hollingworth, 2009).
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44 Our results clearly show the existence of a bias away from the two-back as well as the one-
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46 back locations, consistent with IOR. However, forward saccades are an indirect measure of
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48 the effect of IOR, based on the idea that the forward direction opposite the previously fixated
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50 location would carry the least inhibition. The more difficult, but perhaps most important,
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52 question is whether IOR effectively biases saccades away from previously fixated locations;
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54 that is, whether previously fixated locations are less often visited than would be expected
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3 based on chance. Bays and Husain (2012) have completed just such an analysis and show a
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5 clear bias away from previously fixated location as compared to the predictions of a
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7 memoryless model.
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10 Finally we look at the expected effects of both IOR and SM on fixation durations
11 during search. Previous results (Smith and Henderson, 2009) have shown both a slowing of
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13 fixation durations for those saccades that repeat one-back locations as well as an overall
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15 speed advantage for saccades continuing in a repeat direction. While we do find the slowed
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17 duration of saccades returning, we find no speed advantage for forward saccades even in the
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19 one-back location where we would expect the greatest influence from SM. The key
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21 difference between our study and previous ones is that we explore saccadic patterns without a
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23 secondary probe detection task. If the secondary probe task is indeed the reason for the
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25 contradictory results, we are inclined to favor ours as the more valid approximation of natural
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27 search behavior. It is reasonable to suspect that fixation durations would be affected by the
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29 expectation of the sudden onset of a task-relevant probe. Indeed, the probe onsets are usually
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31 yoked to fixation behavior in learn-able ways, and observers may be inclined to learn these
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33 contingencies, and change their behavior to try and anticipate or accommodate them. Another
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35 possibly important factor is search time, which was much longer here than in previous
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37 studies. This could also contribute to differences in fixation durations, although one could
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39 argue that by looking over a longer timeframe we are extending conclusions that can be made
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41 based on our data, as opposed to limiting them by repeatedly calling off the search earlier
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43 than an observer naturally would.
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50 It is possible to observe mid-level effects, in the form of IOR, supporting its putative
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52 role as a foraging facilitator in visual search. Although we do not see evidence for SM in
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54 these data, we cannot rule out the existence of mechanisms that drive search forward in
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56 addition to biasing it away from returns. Questions remain, however, about how low-level
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3 and oculomotor mechanisms interact with scene salience, experiment instructions and
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5 observer strategy during search. For instance, free search and reading produce very different
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7 strategies and saccadic tendencies, yet both produce reliable IOR (Rayner, Juhasz, Ashby &
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9 Clifton, 2003), and yet IOR is not always found when observers are asked to memorize a
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11 scene (Dodd et al., 2009). This suggests there is much left to learn about the role of context
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13 and task in IOR.
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For Review Only

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