Person, place, and past influence eye movements during visual search

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Abstract

What is the role of an individual's past experience in guiding gaze in familiar environments? Contemporary models of search guidance suggest high level scene context is a strong predictor of where observers search in realistic scenes. Specific associations also develop between particular places and object locations. Together, scene context and place-specific associations bias attention to informative spatial locations. At the level of eye fixations, it is not known whether a person's specific search experience influences attentional selection. Eye movements are notoriously variable: people often foveate different places when searching for the same target in the same scene. Do individual differences in fixation locations influence how a scene is subsequently examined? We introduce a method, comparative map analysis, for analyzing spatial patterns in eye movement data. Using this method, we quantified the consistency of fixated locations within the same observer and between observers during search of real world scenes. Results indicated a remarkable consistency in the locations fixated by the same observer across multiple searches of a given scene. This observer-specific guidance was shown to be distinct from general scene context information or familiarity with the scene. Accordingly, this is considered evidence for a uniquely informative role of an individual's search experience on attentional guidance in a familiar scene.

Keywords: visual search; eye movements; scene perception; learning; attentional guidance; fixation similarity

Introduction

An important feature of ecological visual search is that there are few truly novel, unfamiliar places in which a person is likely to search. Many tasks involve examining the same place repeatedly, such as the various times spent searching for a specific utensil in one's own kitchen. Locating the target in question benefits from both category based information (e.g. utensils are on countertops) and place specific information (e.g. in this kitchen, utensils hang over the stove). For any observer, there will be many sources of information that guide which scene regions are inspected during search. What influence does a person's own search experience (i.e. fixation locations) have in guiding where they are likely to look in familiar scenes?

A growing body of evidence suggests that observers use high level information, such as learned target features and global scene context, to guide their gaze when searching for an object in real world environments (Ehinger, Hidalgo-Sotelo, Torralba, & Oliva, 2009; Hwang, Higgins, Pomplun, 2009). At this level of *categorical* representation, knowledge of the basic-level scene category and target features directs gaze to expectation-based scene regions (Eckstein, Drescher & Shimozaki, 2006; Henderson, 2003; Torralba, Oliva, Castelhano, & Henderson, 2006). At the level of *scene exemplar* representations, spatial context can also be used to allocate attention preferentially to regions that have become associated with the target. In contextual cueing, for example, observers implicitly learn patterns in repeated displays that help them find a target faster in repeated configurations (Chun & Jiang, 1998). It is not well understood, however, whether a scene exemplar representation can systematically bias individual fixations.

How can "experience based" influences be distinguished from the myriad of sources that guide attention to relevant scene regions? One challenge is that attention is strongly guided by information that does *not* depend on specific experience. Figure 1 illustrates regularities in eye fixations across and within observers. In Figure 1A, fixations from 9 observers searching for a book are shown; the high fixation density along countertop surfaces illustrates how spatial layout and context guide where observers look. Systematic biases unrelated to the scene's content also influence gaze location. In Figure 1B, fixations sampled from random scenes have been projected onto the kitchen scene. Center bias in the fixation distribution is driven by oculomotor tendencies (Tatler, 2007; Tatler & Vincent, 2009) and photographer bias. A second challenge, of the opposing nature, lies in the significant variability in fixation locations across individuals. As a result, two independent observers may fixate different scene regions, even when looking for the same object in the same scene (Figure 1C). It is possible that individuals are biased by experience, but that the effects are masked by pooling over experienced observers. Given initial differences in search patterns, could systematic differences arise when an observer repeats her search of the scene? To reasonably estimate the influence of past experience, the search patterns of observers who have *never* viewed the scene must be contrasted with different observers who have *previously* searched the scene.

In this paper, eye movement data from a visual search study was analyzed using approach we have termed comparative map analysis. This analysis was used to evaluate how different sources of information contribute to attentional guidance during visual search of familiar scenes. In our experiment, observers' eyes were tracked while they looked for a book in pictures of real world scenes. On some trials, observers searched a scene that had been presented previously. Importantly, the target object and location remained unchanged in each presentation of the scene. The

main question was whether a person's past experience (as measured by fixated locations) biases attentional selection when searching a familiar scene. Using comparative map analysis, we show that visual attention is sensitive to the influence of a person's past experience of searching in familiar scenes.

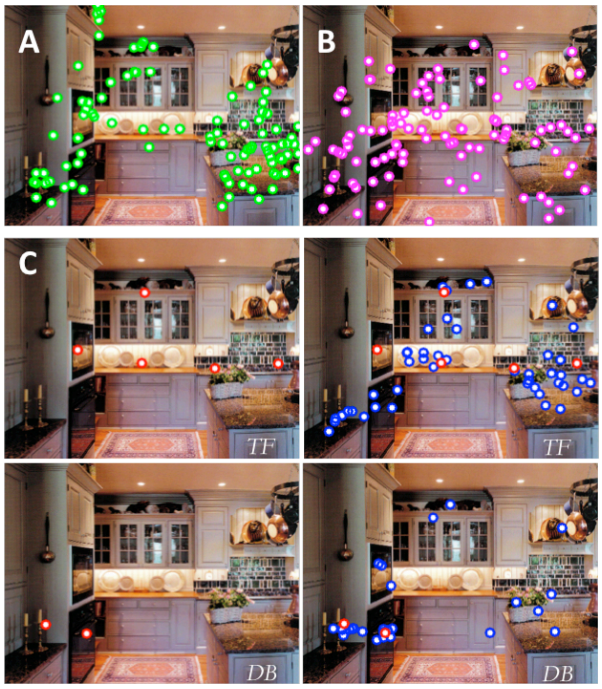

Figure 1: Regularities in eye movements while searching for books. (A) Fixations from 9 observers searching for a book in this kitchen (green dots). Context and spatial layout constraints guide search (e.g. high density along countertop surfaces in the foreground and background. (B) Fixations sampled from random scenes and projected onto this scene (pink dots). Oculomotor and photographer bias contribute to a roughly central fixation distribution with sparse fixations in the image periphery. (C) Fixations from 2 observers who repeatedly searched this kitchen. Each row shows fixations from: the observer's first search (Left, red dots), and the next 7 search trials (Right, blue dots). Individual differences in fixation patterns are evident, before and after learning.

Comparative Map Analysis

The approach we describe here as comparative map analysis is used to evaluate how well different distributions of fixations predict where observers will look in a scene. Critically, each fixation distribution is sampled from a different, strategically chosen, population of fixations. The resulting distributions are evaluated in regards to how well they distinguish between fixated and unfixated locations. In the present paper, this analysis was used to determine whether an observer's experience plays a significant role in attentional selection during search.

Logic of the approach. Given the challenges outlined in the introduction, how can we isolate the bias resulting from an individual's experience searching a *specific* scene? The solution lies in strategically identifying fixation populations relevant to the question of interest. One population, for example, includes the locations fixated by novel searchers in a given scene. A second population includes the locations fixated by a *single observer* when the same scene was repeatedly searched. While the first population represents the influence of (general) scene context on search, the second population reflects the specific influence of the observer's own examination of the scene. Fixation maps were created for each population and used to predict fixation locations from a separate trial. If the two populations are equally informative, then there will be no significant difference in the accuracy between the predictions. The logic is analogous to established methods for determining whether fixated and control locations can be discriminated (e.g. Parkhurst & Niebur, 2003; Tatler, Baddeley, and Gilchrist, 2005). In those studies, the two distributions represent measurements of a dependent variable (e.g. visual feature content) at fixated versus unfixated locations. If the dependent variable successfully discriminates between these locations, then it is considered to inform fixation selection. Control distributions, it should be noted, can be constructed in several ways. Recent studies of attentional guidance have constructed control distributions by randomly sampling fixations from other populations (e.g. Ehinger et al, 2009; Tatler et al, 2005; Tatler & Vincent, 2009). Comparative map analysis extends this rationale by defining several control populations that vary with respect to the degree of "person," "place," and "past" information represented.

Broadly, we consider three *scene dependent populations* representing scene regions empirically fixated by observers when searching that specific scene: (1) Fixations made by a single observer's repeated searches, (2) Fixations of other observers who searched the scene repeatedly; (3) Fixations of novel observers (i.e. searched the scene once). Importantly, these populations represent slightly different sources of information: self-consistency, scene familiarity and general scene context, respectively.

Control populations are crucial to assess the relative informativeness of other regularities (e.g. oculomotor biases) in predicting the same eye movements. These *scene independent populations* provide controls for different sources of information: (4) Fixations from the same observer on random scenes, (5) Fixations from different observers on random scenes. These populations reflect spatial biases in oculomotor behavior that manifest across the set of scenes (intra-observer and inter-observer biases respectively). Two simple model-based populations (as opposed to sampling from empirical fixations) serve as controls to evaluate the extent to which a central gaussian distribution (6) and uniform distribution (7) predicted observers' fixations. The uniform distribution serves as the true measure of chance, while the widely recognized central fixation bias in human eye movements (Tatler, 2007)

suggest that a central gaussian distribution may predict fixations above chance level.

Building fixation maps. Fixation maps were created for each of the above populations using the following procedure, shown schematically in Figure 2. First, we collected a list of the locations fixated by one observer in all repeated searches of a scene; trials in which the eye was lost or the observer failed to find the target object were not included. For each repeated search trial *R*, a self-consistency fixation map (1) was built by excluding fixations from one search trial and using the remaining *N* fixations to define a prediction map. Next, the other fixation maps were created by sampling *N* times from the appropriate population of empirical fixations (2-5) or statistical model (6-7). This process was iterated for R repeated search trials, and the resulting fixation maps were used to predict the excluded trial's fixations (probe fixations).

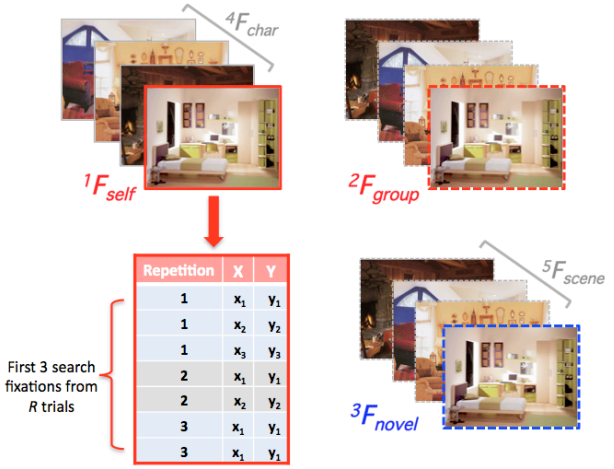

Figure 2: Schematic of comparative map analysis. This illustrates the source of fixation populations (1-5) and how they are sampled to create fixation maps that represent several influences on eye guidance. The following steps are performed iteratively for each of *R* trials: select one search trial (i.e. first 3 fixations of one trial) from F_{self} ; use the remaining *N* fixations to create a prediction map for intra-observer similarity. Fixation maps for populations (2-5) are created by sampling *N* times from the corresponding distributions. Red (familiar observers) and blue (novel) outlines represent scene dependent populations. Dashed outlines indicate non-self fixation populations.

In the present analysis, the first 3 *search* fixations in each search trial were used to build the fixation maps. Search fixations are defined as fixations made during active exploration of the scene, thus excluding fixations landing on the target and the initial central fixation. The maps were compared in terms of how well they predicted the first 3 search fixations of the excluded trial. Given past findings that the consistency of fixation locations across observers decreases over time (Mannan, Ruddock, Wooding, 1997; Yarbus, 1967), we used the first 3 search fixations because it represented a time window appropriate for capturing the highest consistency across novel and repeated conditions.

Evaluating fixation maps. We used the Receiver Operator Characteristic to evaluate how well fixated and unfixated locations could be discriminated. The ROC curve is a common signal detection technique that represents the proportion of real fixations falling within a fixation map (detection rate) in relation to the proportion of the image area selected (false alarm rate) (e.g. Ehinger et al, 2009; Renninger, Verghese, & Coughlan 2007; Tatler et al, 2005). The area under the curve or AUC area (Green & Swets, 1966) was used to compare differences in prediction maps.

Search Experiment

In this experiment, observers searched for a book in indoor scenes (e.g. kitchens, bedrooms) while their eye movements were recorded. The original goal of this study was to investigate how time influenced the retrieval and use of scene specific associations to guide search in realistic scenes. We examined this by introducing a variable stimulus onset asynchrony (SOA) between the scene onset (observers fixating centrally) and the initial search fixation on the scene. We predicted that there would be an interaction between scene familiarity and SOA, such that longer delays would predict shorter search times on familiar, but not novel, scenes. For the present analysis, the eye movements collected from this study were collapsed across the retrieval-time manipulation since this variable was tested using a within-subject design.

Participants. Eighteen observers, ages 18-34, with normal acuity gave informed consent, passed an eyetracking calibration test, and were paid $15/hr for their participation.

Materials. Eye movements were collected using an ISCAN RK-464 video-based eyetracker with a sampling rate of 240 Hz. The stimuli were high resolution color photographs of indoor scenes presented on a 15" LCD monitor with a resolution of 1280 x 1024 px and refresh rate of 60 Hz. The original images were cropped and resized to be presented at a resolution of 1024 x 768 px, subtending 30 x 20 deg of visual angle. Presentation of the stimuli was controlled with Matlab and Psychophysics Toolbox (Brainard, 1997; Pelli, 1997). The target prevalence in the stimuli set was 100%: all scenes contained a target and, importantly, the target location never changed in a particular scene. To make the task challenging, book targets were small (from 1 to 2°) and spatially distributed across the image periphery.

Procedure. The experiment consisted of a learning phase followed by a probe phase. In the learning phase, observers learned associations between specific scenes and a book's location in each scene. In the probe phase, observers searched following a variable SOA (200, 400, 800, or 1600 ms) on a novel or familiar scene. In both phases, observers freely explored the scene with their eyes. Each phase was comprised of 4 search blocks: 24 repeated search trials and 8 novel search trials presented randomly in each block. Scenes were counterbalanced across observers with respect

to the novel or repeated conditions. The trial sequence, similar in learning and probe phases, is as follows. Observers fixated a central fixation cross for 500 ms to begin the trial (gaze contingent). First, a scene was presented with a fixation cross superimposed over the scene; observers fixated the central cross for the duration of this interval without saccading away otherwise the trial ended. In the test phase, this was followed by a variable SOA on a gray screen. Finally, the same scene was presented again and observers actively explored the scene to find the book. Observers had a maximum of 8 s to respond via key press (learning phase) or by fixating the target for 750 ms (probe phase). Feedback was given after each trial (reaction time displayed for 750 ms) to encourage observers to search speedily throughout the experiment. The entire experiment lasted approximately 50 min.

Eyetracker calibration was critical for the gaze contingent aspects of the procedure, as well as to ensure accurate dependent measures (fixation locations). For this reason, calibration was checked at 9 locations evenly distributed across the screen after each search block; fixation position had to be within 0.75° of visual angle for all points, the experiment halted and the observer was recalibrated.

Eye movement analysis. Fixations were identified on smoothed eye position data, averaging the raw data over a moving window of eight data points (33 ms). Beginning and end positions of saccades were detected using an algorithm implementing an acceleration criterion (Araujo, Kowler, & Pavel, 2001). Specifically, the velocity was calculated for two overlapping 17 ms intervals; the onset of the second interval was 4.17 ms after the first. The acceleration threshold was a velocity change of 6 deg/s between the two intervals. Saccade onset was defined as the time when acceleration exceeded threshold and the saccade terminated when acceleration dropped below threshold. Fixations were defined as the periods between saccades. Saccades within 50 ms of each other were considered continuous.

Comparative map analysis. Forty eight scenes were searched by equal numbers of participants in the novel and repeated conditions. Search trials in the learning and probe phases, excluding block 1, were combined to yield a maximum of 7 repeated trials for each observer. The following experiment conditions correspond to each population: (1) One observer's repeated searches of a familiar scene, (2) *Other* observers' repeated searches of the same familiar scene. (3) Different observers' *novel* search of the same scene. (4) Any scene searched by the same observer. (5) Any scene searched by other novel observers.

Results

The results of comparative map analysis are shown in Figure 3. Our main finding is the evidence of experience based influences on attentional selection, specifically during the first 3 search fixations in a scene. An identical pattern of results was found when using only the *first* search fixation. We first report the results from the populations based on scene dependent information (F_{self}, F_{group}, F_{novel}), followed by the scene independent control populations.

Role of the person

The role of a person's own search experience was evaluated by using the locations of their own fixations (F_{self}) to predict empirical fixations from the same observer on a separate search of the same image. We found that this population provided the most accurate predictions (mean AUC=0.907) relative to the other scene dependent populations F_{group} ($t(94)=5.41$, $p < 0.001$) and F_{novel} ($t(94)=6.57$, $p < 0.001$), and was significantly higher than control populations. Interestingly, observer's own population of fixations resulted in the most consistently accurate predictions across the set of images, as evident in the boxplot of figure 3.

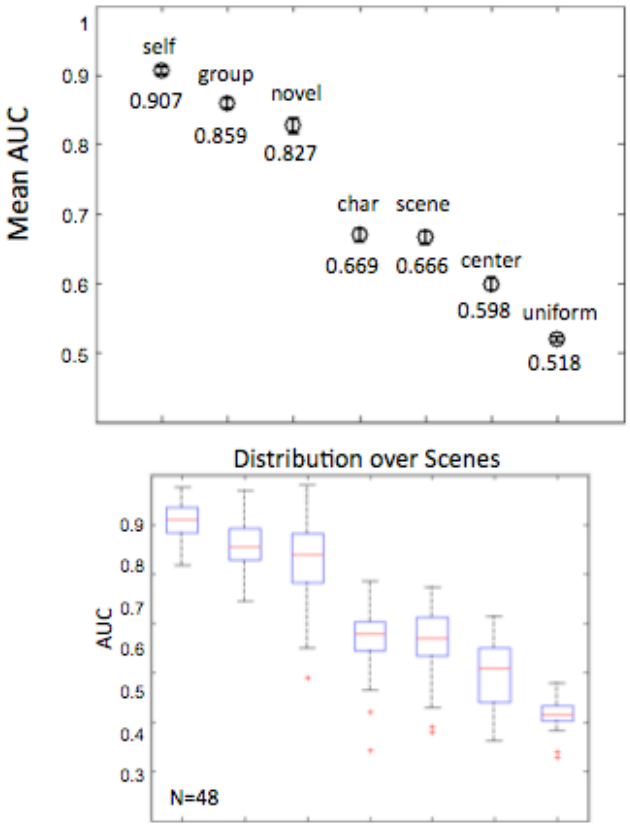

Figure 3: Results of comparative map analysis on eye movement data from the book search experiment. Distributions shown in the boxplot show the median (red line), upper and lower quartile values (box), and outliers.

Is this influence in fact due to a person's *specific* search experience? Perhaps the experience of the individual is not unique from the experience of the group. This is a reasonable hypothesis, given that all observers have the same opportunity to learn the association between the scene's identity and the location of a book. To examine this hypothesis, we compare F_{self} and F_{group}.

Role of the past

The role of past experience was evaluated using the fixation locations from other observers who searched the same scene repeatedly (F_{group}). Interestingly, there was no significant difference between the prediction accuracy of this group and a group of novel observers (mean AUCs of 0.859 and 0.827, respectively; $t(94)=1.97$). This suggests that sampling from many individuals with past experience is not significantly more informative than sampling from the population of novel observers.

Role of the place

The role of the place is perhaps the most intuitive source of information: it represents how scene context drives consistency in fixation locations across different novel observers. We found that F_{novel} provided a significant source of guidance relative to the random scene control F_{scene} ($t(94)=11.7$, $p < 0.001$). Our finding confirms previous reports of overall high inter-observer consistency in search tasks (Ehinger et al, 2009; Torralba et al, 2006).

Scene Independent Control Populations

Two control populations were based on empirical fixations sampled from different scenes: F_{char} (same observer as F_{self}) and F_{scene} (different observers). These populations predicted fixations well above chance with mean AUCs of 0.669 and 0.666 respectively and were not significantly different from one another ($t(94)=0.11$). The overlap in these distributions is not surprising given that these populations reflect systematic oculomotor tendencies and regularities in the stimuli set (e.g. photographer bias). The two model distributions, central gaussian and uniform, were used to compare with the other populations and confirm intuitions about the results of comparative map analysis. Indeed, the central gaussian model was a better predictor of fixations than the uniform distribution ($t(94)=2.7$, $p < 0.05$).

Discussion

We have shown that the past repeats itself: a person's experience, as indexed by fixated scene locations, influences how they search familiar scenes. Although the notion of idiosyncratic gaze patterns has been previously presented (Noton & Stark, 1971), to the best of our knowledge, this is the first time observer-specific experience has been shown to influence gaze patterns in a naturalistic search task. What is the nature of the information that underlies this self-consistency effect? Is it behaviorally relevant or an incidental consequence of scene exposure? Is the encoded information object-based or spatially-based? How does self-consistency interact with other well characterized forms of search guidance (e.g. saliency)?

In order to refine our understanding of why intra-observer consistency occurs, it would be helpful to examine patterns across observers and scenes. Are certain scenes searched more consistently than others? This question can be approached in two ways. From the perspective of general scene context constraints, scenes vary in the distribution of target-probable surfaces they contain. Looking for books in a library, for example, may present a significantly less constrained search than searching a bathroom. Still, the boxplot in figure 3 suggests the scenes are variable with respect to how consistently similar regions are selected by different viewers. From the perspective of person specific constraints, what is the relation between inter-observer and intra-observer consistency? One possibility is that scenes searched consistently by novel observers also promote self-consistency among a large proportion of familiar observers. Alternatively, high *variability* in intra-observer consistency (i.e. high F_{self} variance) may negatively correlate with inter-observer consistency. Identifying properties of the scene and task that promote self-consistency across searches remains an open question.

In the ecological psychology tradition (e.g. Gibson, 1979), our findings also raise questions about the behavioral significance of self-consistency. Are some observers more self-consistent than others? If so, what are the implications for the search task? One hypothesis is that *high* self-consistency may be associated with good search performance (e.g. fast overall reaction time). Indeed, a widely recognized feature of human memory relates to the benefit of reinstating the encoding context in retrieval (Jacoby & Craik, 1979; Tulving & Thomson, 1973). Furthermore, embodied cognition accounts suggest that a person's own movements may play a role in perceptual and cognitive performance (e.g. Knoblich & Flach, 2001). When imagining a previously viewed stimulus, for example, observers tend to make reenact patterns of eye movements from the initial viewing (Brandt & Stark, 1997; Laeng & Teodorescu, 2002; Spivey et al, 2001).

It is important to note the role of our task in driving similar patterns of viewing across observers. A number of recent studies have sought to predict where observers will look in naturalistic scenes. Many of these studies, however, deliberately employ free viewing (e.g. Bruce & Tsotsos, 2006; Itti & Koch, 2000) or a memory task (e.g. Foulsham & Underwood, 2008) so as to reduce the influence of having a common goal. Theories of visual search guidance (e.g. Wolfe, 1994) describe observers' deployment of attention as resulting from a combination of stimulus and goal driven factors. Seeing how the magnitude of self-similarity varies across tasks can serve as another approach to assessing the behavioral significance of intra-observer consistency. Recognition memory tasks, in particular, provide an opportunity to investigate the causal role of re-fixations in scene recognition. Holm & Mantyla (2007) used a remember/know paradigm to evaluate whether successful recognition was associated with similarity between an observer's fixations during study and test phases. Indeed, they found evidence that recollection ("remember" responses) were related to a high degree of study-test consistency. Recently, Underwood and colleagues (2009) investigated the roles of domain knowledge and visual saliency on fixation consistency in scene recognition. Their

findings again support the idea that observers look at scene locations that have been previously fixated and, interestingly, that the effect is stronger for individuals who were experts in the domain related to the picture.

Our experiment shows that observers have access to perceptual and memory based information that helps them locate the book in a familiar scene. What is the nature of this information? Two possibilities are that observers encoded the oculomotor movements to *spatial locations* (e.g. left side of the screen) or the *objects* (e.g. empty bookshelf) that were attended on the way to finding the target. One way to distinguish these possibilities would be compare the resulting search patterns when an observer initiates search from a familiar (e.g. center of the scene) or an unfamiliar location and comparing whether similar objects or locations were still fixated. Moreover, the speed of human eye movements (roughly 3-4 per second) suggests an automatic component to self-consistency that may not be available to conscious awareness. Although our experiment cannot speak to this issue directly, we found the same pattern of results shown in figure 3 using only observer's first fixation on the scene. This suggests that the information underlying self-consistency is rapidly available to bias eye movements.

Conclusion

Comparative map analysis, a novel approach for analyzing patterns in eye movement data, was used to evaluate the role of various sources of search guidance. We found evidence from a search study showing a uniquely informative role of an individual's experience on attentional guidance in a familiar scene

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