Information Processing and Management 49 (2013) 1075–1091

Contents lists available at SciVerse ScienceDirect

Information Processing and Management

journal homepage: www.elsevier.com/locate/infoproman

Inferring user knowledge level from eye movement patterns

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ARTICLE INFO

Article history:
Received 26 January 2012
Received in revised form 11 August 2012
Accepted 29 August 2012
Available online 17 November 2012

Keywords:
Knowledge detection
Cognitive effort
User study
Personalization
Information search behavior

ABSTRACT

The acquisition of information and the search interaction process is influenced strongly by a person's use of their knowledge of the domain and the task. In this paper we show that a user's level of domain knowledge can be inferred from their interactive search behaviors without considering the content of queries or documents. A technique is presented to model a user's information acquisition process during search using only measurements of eye movement patterns. In a user study ($n = 40$) of search in the domain of genomics, a representation of the participant's domain knowledge was constructed using self-ratings of knowledge of genomics-related terms ($n = 409$). Cognitive effort features associated with reading eye movement patterns were calculated for each reading instance during the search tasks. The results show correlations between the cognitive effort due to reading and an individual's level of domain knowledge. We construct exploratory regression models that suggest it is possible to build models that can make predictions of the user's level of knowledge based on real-time measurements of eye movement patterns during a task session.

1. Introduction

While users frequently seek information about something they do not already know (Belkin, 2000), an essential aspect of all information behavior is that one must use existing knowledge to make progress towards the task goal. Identifying relevant knowledge and using it to guide search in a problem space is a fundamental aspect of models of cognition (Anderson, 1990; Newell, 1990). Acquisition of new information is usually essential to the process of achieving the goal and it is typical for that information to be acquired by reading.

The only way to obtain information visually is by repeated gaze on a location. One must also allocate attention during this process and there is still much that is unknown about how the process and mechanism of attention works (Wright & Ward, 2008). In reading, it has been shown that one can distinguish between eye movements that are engaged in information acquisition and those that are not (Rayner & Fischer, 1996; Reichle, Reineberg, & Schooler, 2010). Research into reading eye movement patterns shows observations of eye fixations on words can be coupled with the process of acquiring the meanings of the words (Rayner, 1998). It is possible to not only understand what information the person has engaged with during search interactions, but also to learn important details of how it has been processed. Previous work shows this can be used to infer high level properties of the user's search situation, such as their current task type (Cole et al., 2010, 2011b) and their experience of the difficulty of the task (Cole, Gwizdka, Liu, & Belkin, 2011a).

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http://dx.doi.org/10.1016/j.ipm.2012.08.004

Analysis of eye measurements is particularly attractive for study and modeling of information search behavior because research shows they are connected directly with mental states. In particular, the acquisition of the meaning of a word or phrase is revealed by real time measurements of eye fixations (Rayner, 1998; Staub, White, Drieghe, Hollway, & Rayner, 2010). Analysis of eye movement patterns, unlike other observations of information search behavior, allows for unmediated measurement of user mental states that have an essential role in the search process.

Our research goals include understanding the value of predicting domain knowledge to improve information retrieval system performance. For broad practical application, one needs to learn not only how to detect domain knowledge but also how that can be accomplished in a domain independent manner. Implicit detection techniques are desirable and so we have studied the problem of inferring domain knowledge by concentrating on observable behaviors.

Cognitive modeling of a person's existing knowledge is challenging. Consistent with the research showing that the time to acquire word meaning depends on existing concept knowledge (c.f. Kieras, 1981; Foss, 1982), the cognitive effort due to reading experienced by a user during search may be expected to reflect, in part, their existing domain knowledge. This paper presents results of a user study showing correlations between individual cognitive effort features and a person's level of domain knowledge. It also constructs regression models based on the cognitive effort features to explore the possibility of predicting a user's level of domain knowledge based on real-time measurements of their eye movement patterns.

2. Related work

2.1. Implicit detection of domain knowledge during search

It is reasonable to think behaviors can be used to infer user knowledge levels without the need to consider the content of documents or queries. Domain knowledge or expertise has been shown to affect search behaviors. Users with low domain knowledge are found to have more non-productive queries (Allen, 1991), use less efficient concepts and make more query reformulation errors (Wildemuth, 2004), and resort to less effective search strategies (Hembrooke, Granka, Gay, & Liddy, 2005). Users with intermediate levels of knowledge about their task fail to select available documents of which they have the most knowledge as compared to users with high or low levels of domain knowledge (Cole, Zhang, Belkin, Liu, & Gwizdka, 2011c). High level information search behaviors, such as dwell time, selected document ranks, and query length, have been used to construct a domain knowledge model (Zhang, Cole, & Belkin, 2011).

2.2. Eye movements in search

In text-based interactive information retrieval (IIR), information acquisition is mediated by eye movement patterns in service of the reading process. Eye movements are known to be cognitively-controlled (Findlay & Gilchrist, 2003). They provide a low-level behavioral observation of interactive tasks (Karn & Hayhoe, 2000; Triesch, Ballard, Hayhoe, & Sullivan, 2003) and are well-suited to represent the textual information acquisition process during search tasks.

Eye tracking has received considerable attention as a new source of data for research into the information search process. Much of the work in information science using eye tracking data has concentrated on eye fixations, for example to indicate which items are considered in ranked search results pages (Pan et al., 2007; Brumby & Howes, 2008), or in identifying words useful for relevance feedback (Buscher, Dengel, & van Elst, 2008a, 2008b; Loboda, Brusilovsky, & Brunstein, 2011). Eye tracking has identified patterns of processing documents, for example an "F" shape reading pattern for a search engine result page (SERP) and other scanning patterns (Granka, Feusner, & Lorigo, 2006). Granka, Joachims, and Gay (2004) and Lorigo et al. (2008) studied the number of fixations, their duration and time on task in a user study of searches with the Yahoo! and Google search engines. Eye movements during different types of information retrieval activities have been investigated by looking at SERP interactions during informational and navigational tasks (Terai et al., 2008), different task types (Liu et al., 2010), information use (Cutrell & Guan, 2007), the effects of search page ranks on subsequent actions (Guan & Cutrell, 2007), and the usefulness of social navigation clues to users performing web searches (Loboda et al., 2011).

2.3. Eye movements and reading

Eye movement patterns are cognitively controlled and reading patterns have long been studied (Rayner, 1998). There are many results relating eye movements to semantic and cognitive processing states. Models of the reading process have been developed that explain observed fixation duration and word skipping behaviors.

The E-Z Reader model is a cognitively-controlled, serial-attention model of reading eye movements (Reichle, Rayner, & Pollatsek, 2004). It takes word identification, visual processing, attention, and control of the oculomotor system as joint determinants of eye movement in the reading process. The saccade (i.e., very fast movement of eyes during which eyes do not acquire any visual information) to the next word is programmed while the text in the current fixation is being cognitively processed.

There are several stages of text processing during fixations. In the E-Z Reader model it is supposed that the controller of eye-movement is triggered by completion of an early word identification stage, called the familiarity check, and the shift in attention to the next word selected takes place only after full lexical access is achieved. The mean minimum time to acquire