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Gaze-based predictive user interfaces: Visualizing user intentions in the presence of uncertainty

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A B S T R A C T

Human eyes exhibit different characteristic patterns during different virtual interaction tasks such as moving a window, scrolling a piece of text, or maximizing an image. Human-computer studies literature contains examples of intelligent systems that can predict user's task-related intentions and goals based on eye gaze behavior. However, these systems are generally evaluated in terms of prediction accuracy, and on previously collected offline interaction data. Little attention has been paid to creating real-time interactive systems using eye gaze and evaluating them in online use. We have five main contributions that address this gap from a variety of aspects. First, we present the first line of work that uses real-time feedback generated by a gaze-based probabilistic task prediction model to build an adaptive real-time visualization system. Our system is able to dynamically provide adaptive interventions that are informed by real-time user behavior data. Second, we propose two novel adaptive visualization approaches that take into account the presence of uncertainty in the outputs of prediction models. Third, we offer a personalization method to suggest which approach will be more suitable for each user in terms of system performance (measured in terms of prediction accuracy). Personalization boosts system performance and provides users with the more optimal visualization approach (measured in terms of usability and perceived task load). Fourth, by means of a thorough usability study, we quantify the effects of the proposed visualization approaches and prediction errors on natural user behavior and the performance of the underlying prediction systems. Finally, this paper also demonstrates that our previously-published gaze-based task prediction system, which was assessed as successful in an offline test scenario, can also be successfully utilized in realistic online usage scenarios.

1. Introduction

For several years, great effort has been devoted to developing gaze-based prediction models that capture human behavior patterns naturally accompanying virtual interaction tasks such as reading an electronic document, or manipulating a virtual object (Fig. 1) (Bader et al., 2009; Bednarik et al., 2012; Campbell and Maglio, 2001; Çığ and Sezgin, 2015a; Courtemanche et al., 2011; Steichen et al., 2013).

However, existing models are generally evaluated in terms of prediction accuracy, and within offline scenarios that assume perfect knowledge about user's task-related intentions and goals. Such scenarios are called wizard-based test scenarios. Note that, in this paper, "online usage" does not refer to real-life usage scenarios. Online/offline distinction is made not based on how realistic the user interface is but based on whether the predictions are fed back to the user during interaction. In an example offline wizard-based test scenario, the users are asked to either select an object, or to manipulate a previously selected object (Bader et al., 2009). Collected data with labels corresponding to user intentions are then used to compute the accuracy of the related intention prediction model. The output of the prediction model is in no way shown to the users. In other words, in the wizard-based test scenarios, the loop between the user and the prediction system is open, i.e. the user is fed hardwired and perfect visual feedback via the user interface irrespective of predictions made by the prediction system (Fig. 2a). Existing studies do not take into account how these models would perform in the absence of wizards. They also do not examine how/if the prediction errors affect the quality of interaction. In this paper, we eliminate the wizard assumption and close the loop between the user and the prediction system. We achieve this by feeding highly accurate but imperfect predictions (since we do not have prediction systems that can perform with 100% accuracy yet) made by the prediction system to the user via appropriate visualizations of the user interface (Fig. 2b). By means of a thorough usability study, we seek answers to the following research questions: (1) How should a user interface adapt its behavior accord-

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1071-5819/

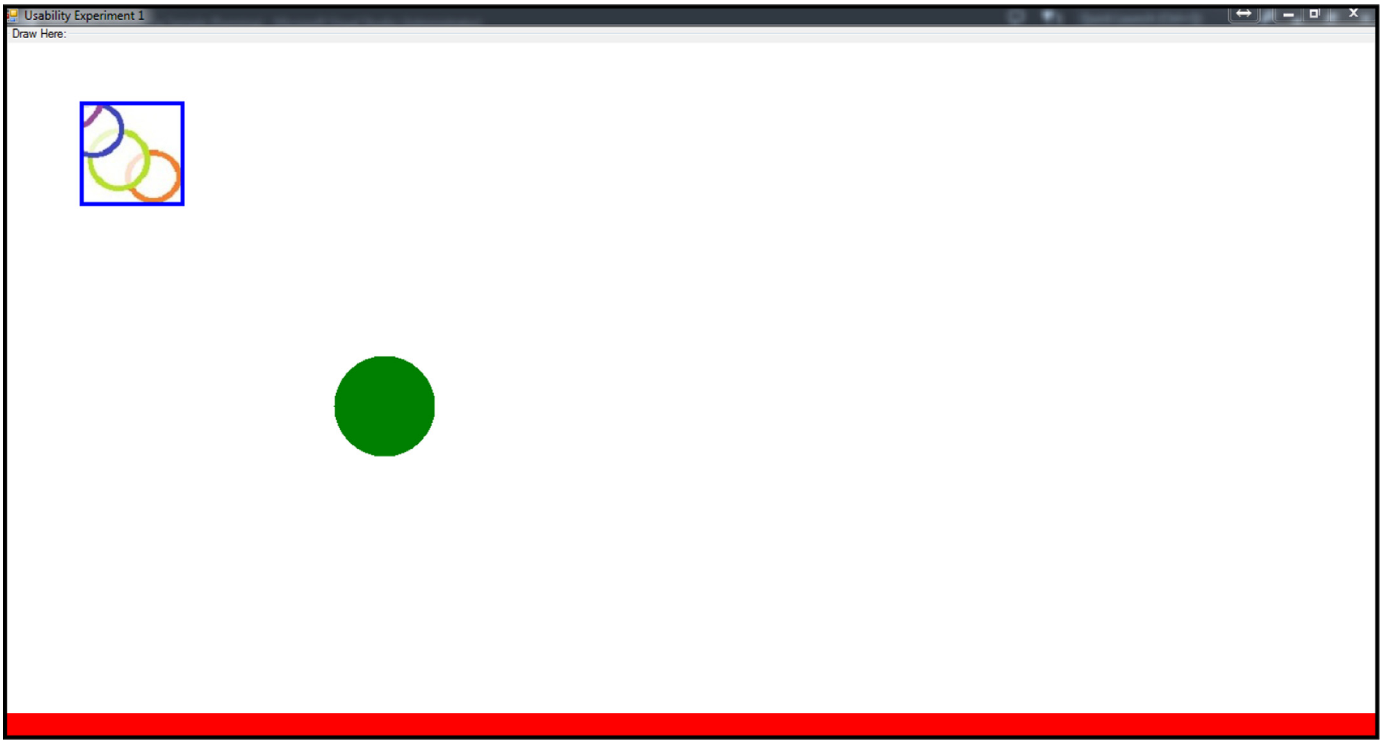

Fig. 1. Screen capture of one of our predictive user interfaces visualizing a virtual interaction task. User's task is to drag the blue square (located on the upper-left of the screen) onto the center of the green circle (located on the bottom-right of the screen). We use our gaze-based virtual task prediction model to predict user's task-related intentions and goals in real-time. Furthermore, we assist the user by automatically triggering various user interface adaptations that reflect these predictions. By adaptation, we mean the adaptation of the screen contents in terms of the visibility of visual feedback corresponding to possible tasks. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

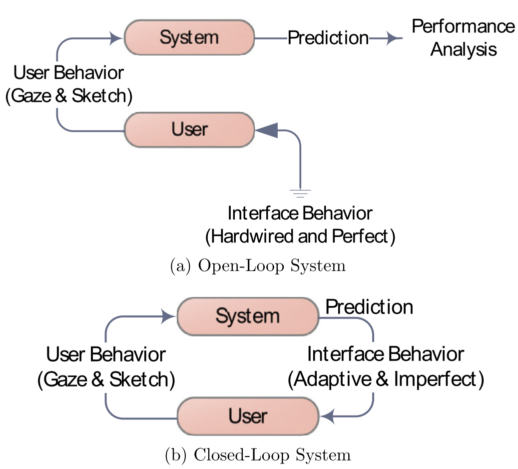

Fig. 2. Closing the loop between the user and the prediction system. The user behavior affects system prediction which in turn may affect user behavior.

ing to real-time predictions made by the underlying prediction system? (2) Will adaptations affect user behavior and inhibit performance of the prediction system (that assumes natural human behavior)? (3) Will prediction errors affect user behavior and inhibit performance of the prediction system? (4) Does users' compatibility with the prediction system have implications for the design of such interfaces?

Section 2 gives a summary of related work on gaze-based predictive interfaces. Section 3 provides details on our usability study, proposed adaptive visualization approaches, and proposed gaze-based predictive user interfaces. Section 4 describes the evaluation of our predictive user interfaces in terms of performance, usability, and perceived task load. Section 5 concludes with a discussion of our work and a summary of future directions.

2. Related work

Explicit interfaces (e.g. text terminals and graphical user interfaces) rely on direct commands from the user to the computerized system. In contrast, implicit interfaces sense and reason about user actions that are not primarily aimed to interact with a computerized system to automatically trigger appropriate reactions (Schmidt, 2000). In order to reason about user actions with innovative sensors like eye trackers, implicit interfaces model human behavior by extracting useful and usable patterns while users keep their normal habits and ways of interaction. The advantage of implicit interfaces is that the users do not need explicit commands, prior knowledge, or training to interact with the system. Shortcomings of the command-based explicit interaction model are especially highlighted in mobile computing systems where the ability to input commands is limited. In this paper, we show that well-designed intelligent user interfaces can assist the users by implicitly generating commands based on previously learned models of eye gaze behavior. Related work falls under two broad categories: gaze-based virtual task predictors and gaze-contingent user interfaces.

2.1. Gaze-based virtual task predictors

To the best of our knowledge, there is no line of work that uses online feedback from a gaze-based task prediction model to build a user interface that dynamically adapts itself to user's spontaneous task-related intentions and goals. The majority of the related work focuses solely on generating prediction models and evaluating them in terms of prediction accuracy. However, these systems pay little attention to how prediction models would perform in online usage scenarios. In this paper, we address the multi-faceted goal of building a real-time user interface