称号及び氏名	博士（工学）　Charles Lima Sanches
学位授与の日付	平成 31 年 3 月 31 日
論　文　名	「Reading behavior analysis via non-professional eye trackers to enhance knowledge acquisition」 （知識獲得増進のための一般向けアイトラッカによる読書行動解析）
論文審査委員	主査　黄瀬　浩一 副査　戸出　英樹 副査　本多　克宏

論文要旨

Reading is defined as “the cognitive process of decoding symbols to construct or derive meaning.” It is an activity we perform every day to gain knowledge or entertain ourselves. Therefore, the way we read and the content we read can tell a lot about ourselves. Extracting information by analyzing the way people are reading has been tackled by many researchers. Nowadays, the reading behavior can be tracked by various sensors to provide information such as the reader's understanding, emotion, interests, attention, but also the document type, difficulty, language, etc. To extract such information, it is possible to analyze the reader's heartbeat, body posture, head temperature, etc. The eyes are the main organs we use to acquire the information while reading. The way we move our eyes is directly related to our reading behavior. Therefore, a fundamental method to analyze the reading behavior has been to record the reader's eye movements.

From an oculomotor point of view, reading is a succession of eye movements divided into short stops on parts of the words called fixations and jumps between fixations called saccades. The characteristics of fixations and saccades, such as their duration or their number (for the fixations), their length or their direction (for the saccades), depend on the reader and the document being read. The detailed analysis

of the eye movements has become possible thanks to the development of eye trackers which can accurately record the eye movements. However, these devices are expensive (more than 10 000 dollars for the most accurate ones) and require special experimental conditions to get the maximal accuracy: it is common in eye tracking studies to ask the participants to use a chin rest or even a bite bar, in order to limit the head movements while reading. Such conditions limit the usability of the findings to a laboratory setting, where everything is controlled and expensive devices can be used. However, it is incompatible with most contexts in which the eye tracking studies results could be used.

In the context of education, for example, the students' reading behavior is an important indicator of their learning process. Knowing how a student reads a text can give information about his language skills, his understanding, his self-confidence, etc. Such information could be used by the teacher to adapt his teaching strategies. It would also be a step forward to an automated teaching system: the system can estimate the student's profile from the eye movements and can propose some adapted learning material. Moreover, a ubiquitous automated system could put the student in a learning situation anywhere, at any time: each time the student reads, the content of his reading and the way it has been read is recorded and analyzed to propose adapted learning materials.

However, using eye-tracking technology for enhancing education is a challenging task. First, to get a genuine reading behavior, it is essential to let the student free from any constraints. Such "in the wild" conditions involve unexpected head movements or luminosity changes which are difficult for the eye tracker to handle. Second, a student can usually not afford a professional device costing more than 10k dollars.

During the recent past years, some alternatives have become available. Nowadays there are non-professional devices costing around 100 dollars. Those devices have been designed for a non-professional audience and are easy to use. Moreover, with the progress in head-tracking, these eye trackers are quite robust to head movements, so they are the perfect candidates for a reading behavior analysis via eye tracking in the context of education. However these devices suffer from a significant flaw: their accuracy is much lower than the professional ones, making the analysis harder and the results achieved in the previous eye tracking studies impossible to reproduce.

This dissertation is an attempt to see how we can analyze one's reading behavior with non-professional eye trackers. There are two approaches to answer this research question:

- Improving the precision of the eye tracker, in order to be closer to the performance of professional eye trackers.
- Developing new algorithms which can be used with inaccurate eye trackers.

In the dissertation, I will explore the two approaches. As for the detailed content, the dissertation is organized as follows:

In **Chapter 1**, I introduce the background and the motivations of the research. Then, I describe the outline of the dissertation and detail the contributions of each chapter.

In **Chapter 2**, I present some basic notions about the eye gaze and the eye tracking technology. Then, I detail some fundamental studies about eye tracking in the context of reading. After introducing some of the publicly available databases which can be used to analyze the reader's eye gaze, I also detail the devices and the eye gaze processing which are used in the dissertation.

In **Chapter 3**, I focus on the eye tracking error correction. I answer the question of whether it is possible to automatically improve the accuracy of non-professional eye trackers in a reading context. I focus on the vertical error correction, which is the major error detected during a reading session with such devices. The goal of the proposed method is to align the gazes of the reader with the text. The main contribution of this chapter is to propose a vertical error correction method which is robust to rereading and skipping contrary to all other algorithms of the state of the art.

In **Chapter 4**, I describe techniques to analyze the reading behavior in order to find information about the reader. I show how it is possible from the reader's eye gaze to detect the different types of understanding. The chapter is divided into two parts, corresponding to two different types of understanding: the subjective and the objective understanding. The objective understanding is a type of understanding usually measured by comprehension questions. The subjective understanding corresponds to the reader's perception of his own understanding. The contributions of this chapter are multiple. First, I show that it is possible to estimate the reader's subjective understanding of a text just by analyzing his eye gaze with a non-professional eye tracker. Then, I show that with a similar method, it is possible to quantify the reader's objective understanding.

In **Chapter 5**, I describe techniques to analyze the reading behavior in order to find information about the document which has been read. In the first part, I propose a technique to retrieve a text based on the readers' eye gaze. The contribution of this part is to present a text retrieval method based entirely on the eye gaze. In the second part, I show that the eye gaze is an indicator of the difficulty of a text. As an example, I asked Japanese language learners to read Japanese texts: by analyzing the reader's eye gaze pattern, one can retrieve the difficulty of the texts. The contribution of this part is to present a technique which combines two types of features (text and eye gaze) to get the difficulty of a text. In particular, I show that the combination of eye gaze and text features is more accurate than the text

features alone to estimate the difficulty of a text.

After having shown that it is possible to get information about both the reader and the document with non-professional eye trackers usable in everyday life, I introduce the first step toward a ubiquitous analyzer of the reading behavior in **Chapter 6**. I explain the concept of "Reading-Life log" where all the reading sessions of an individual are recorded and analyzed to propose adapted services. I introduce the first module of such a system, the "Wordometer", which is a way to count the number of read words by analyzing the eye gaze. The contributions of this chapter are multiple. First, I explain the concept of the Reading-Life log and detail the benefits of recording one's reading activity. Second, I present a way to count the number of read words based on the eye gaze. Third, I compare the performance of the proposed algorithm on different eye trackers. In particular, I show that non-professional, inexpensive devices perform as good or even better than professional, expensive ones.

Finally, in **Chapter 7**, I conclude the dissertation and propose some lines of thoughts to further improve and foster the reading behavior analysis with eye trackers.

審査結果の要旨

本論文は，人の学習・知識獲得を支援する目的のため，一般向けのアイトラッカを用いた読書行動の解析に関する研究についてまとめたものであり，以下の成果を得ている．

(1) 研究用途の高価なアイトラッカに比べて，一般向けの安価なアイトラッカは，計測誤差が大きくなる傾向にある．このため，その補正は，読書行動解析のために重要な機能となる．特に垂直方向の計測誤差が大きくなることに着目し，読み返しや読み飛ばしなどの多様な行動に対してもロバストな補正法を提案し,実験により有効性を確認した．

(2) 読書行動解析に基づいて，読者の情報を得る手法について提案した．具体的には，日本語文章を対象として，その客観的理解度と主観的理解度を推定する手法を提案した．ここで,客観的理解度とは,文章の内容をどれだけ理解しているかの度合い,また主観的理解度とは，読者自身がどの程度理解していると思っているかの度合いである．アイトラッカを用いた実験の結果，両理解度が推定できることを示した．

(3) 読書行動解析に基づいて，読まれる文書の情報を得る手法について提案した．具体的には，以下の２手法である．第一の手法は，アイトラッカから得られる視線データを用いた文書検索の手法である．第二の手法は，視線データを用いて文書の難易度を推定する手法である．各種文書を用いた実験の結果，両手法が有効であることを確認した．

(4) 読書行動解析を用いて実現できるサービスの一例として，reading-life log を取り上げ，その一機能として wordometer(万語計)を提案した．reading-life log とは，人の読みに関するライフログであり，wordometer とは人が読んだ語数を計量する手法（知の万歩計とも呼ぶべきもの）である．様々なアイトラッカを用いた実験の結果，提案手法が有効であることを実証した．

以上の研究成果は，人の学習・知識獲得を支援するための読書行動の解析に関する重要な知見を与えるとともに，本分野の学術的・産業的な発展に寄与するところが大である．また，申請者が自立して研究活動を行うに必要な能力と学識を有することを証したものである．