Cognitive State Measurement on Learning Materials by Utilizing Eye Tracker and Thermal Camera

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***Abstract*—We demonstrate how information derived from pervasive sensors can quantify cognitive states of learners while they are reading a textbook. Eye tracking is one of the most effective approaches to measuring reading behavior. For example, high fixation duration represents a reader's attention on a document. However, it is still a challenging task to predict the reason for the attention (i.e., is it because of his/her interest or trouble of understanding?). In this paper, we utilize additional sensing modality to solve the problem. On the dataset of 12 high school students' reading behaviors, we have found that the changing of pupil diameter and nose temperature are highly correlated with their cognitive states including their interests and efforts for reading/solving tasks on learning materials in Physics.**

I. Introduction

Documents have been playing an important role in learning and education. Still today, various school subjects are aligned with contents which are captured in textbooks. Although curiosity is an important factor for learning, every student has a different way of learning based on individual speed and preferences, textbooks have traditionally been found to be static and consistently dull for a variety of learners. Therefore, students sometimes avert their eyes from reading a textbook because it is boring. We believe that one of the solutions to this problem is to apply Human-Document Interaction in textbook reading, i.e., to develop a digital textbook which can make the materials for learning and instruction dynamic and anticipating on display. Especially in Physics, it is highly efficient to show phenomenon, experiments, representations and 3D models as dynamic contents using multi medias.

The idea of making texts *dynamic* has been originally proposed by Biedert et al. as Text2.0 [1]. They have created a framework to construct gaze-responsive realtime interactions to enhance the reading experience (e.g., displaying images, translations, footnote, and bookmarks). But even if the various interactions are actuated by each reader's reading behavior, the augmentations are same among all readers. The motivation of our study is to make texts not only dynamic but also *anticipating*. We measure the cognitive states of learners including their interests, workloads, and comprehensions, then augment the text by providing individualized information to enhance their learning abilities.

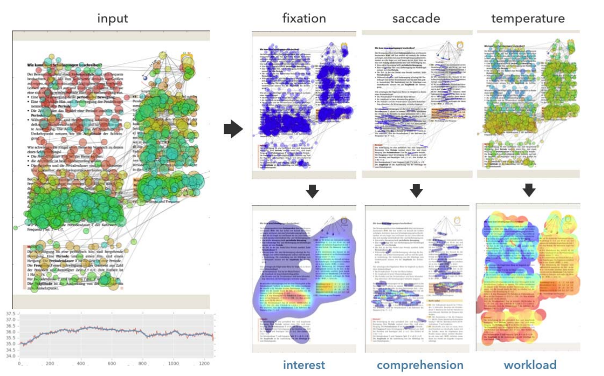

Fig. 1. The key idea of our work. Combining eye tracking and thermography to recognize cognitive states while learners are reading a document.

To develop such an anticipating textbook, it is necessary to investigate what kind of features can be used to recognize the learners' cognitive states. One of the most effective approach to investigate reading activity is to utilize eye tracking. There is extensive research on eye movements during reading in psychology and cognitive science [2]. High fixation duration, for example, represents a reader's attention on a document [3]. However, it is still a challenging task to recognize from eye movements alone, the reason for his/her attention, interest or difficulty in comprehension. In this paper, as shown in Figure 1, we utilize additional sensing modality to solve the problem. Based on the literature review (refer to Section II), we follow the idea of measuring the change of the nose temperature. We prepared a learning material about "Basic Phenomena in Acoustics and Pendulum" including teaching texts and related exercises, and asked high school students to read. The specific contributions of our work are two-folds:

- Demonstrating that the combination of commercial infrared thermal camera and facial landmark detection is accurate enough to measure students' nose temperatures.
- Investigating effective features measured by an eye tracker and an infrared thermal camera which are related to cognitive states collected as self-assessments.

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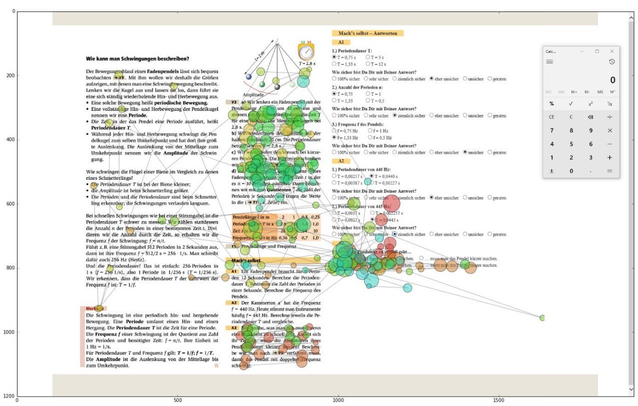

Fig. 2. Fixations on a display during solving a task. The colors represent the order (from red to blue) and the durations are visualized as radiuses.

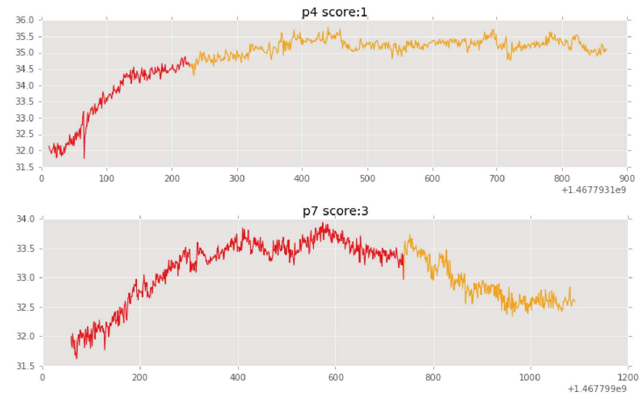

Fig. 3. Examples of changing of nose temperature of two participants (top: low workload, bottom: high workload) during they are reading the textbook (red) and solving the tasks (orange). The x-axis represents timestamps (sec.).

II. RELATED WORK

A. Cognitive state analyses in Physics education

Competent handling of multiple representations is supposed to be significant for learning and problem- solving in physics [4], [5]. A psychological model for understanding the cognitive processes while working with multiple representations is offered by the Cognitive Theory of Multimedia Learning (CTML; [6]) and the Cognitive Load Theory (CLT; [7]). Referred to as CTML, the generation of a mental model of the learning content requires an active part in information processing. The presentation format of the learning material is essential and can be structured into text/picture or classified according to dynamics and interactivity [8]. Students' learning is improved by presenting text/equations and pictures/graphs/videos instead of learning with text/equations alone. While using the pictorial and verbal/auditory channels simultaneously, sensory and representational differentiations are connected. As a result, cognitive load is reduced. So, greater capacity of working memory is available for forming mental representation models according to CTML and, therefore, learnability is increased.

Besides enhancing cognitive variables, our approach involves that students read textbooks actively through personalized feedback to learn in their way. So, they experience autonomy, which is said to foster motivation in general [9], [10] as well as curiosity, as special features of motivation, in particular [11], [12].

B. Eye tracking

Most of the studies mentioned above obtain students' insights from only answering sheets afterward and do not care about their learning process while reading texts and solving tasks. One of the interesting approaches to get realtime insights into cognitive behavior is to employ gaze data. Our vision is to enhance physics teaching and learning and develop possibilities for utilizing eye tracking. Rayner has investigated the relationship and has provided a good summary related to reading [13]. Bulling et al. have explored tracking eye movements in natural settings using Electrooculography glasses. They looked into reading, as well as other everyday activities and cognitive processes [14]. Features from eye movements can predict the volume of reading (counting the number of read words) [15], [16], a level of English skill [17], and difficult word for a reader [18]. As these authors employ general features from the eye (e.g. fixation duration, saccade length and velocity), their approach can be used on a Physics textbook as well.

Our study is especially close to research by Mozaffari et al. [19] and Ishimaru et al. [20]. They have recorded eye movements of high school students during they are reading and solving Physics tasks to investigate specific gaze patterns for predicting expertise of students. Compared to their research, the position of our study is to investigate not only the performances of students but cognitive states including interest and workload by sensing devices.

C. Medical and physiological sensing

The obvious approach to measure cognitive states is to measure our brain. Electroencephalography (EEG) [21] and near-infrared spectroscopy (NIRS) [22] can be candidates, and perform well to recognize activities and cognitive states. But they are too bulky to be worn regularly by considering the application scenario that real school students use the system.

On the other hand, autonomic nervous system (ANS) including the sympathetic nervous system and the parasympathetic nervous system is a measurable component of emotional response [23]. The nose temperature drops when a person feels high workload [24] and high engagement on reading [25]. The diameter of the pupil also reflects the workload. The relation has been investigated in the tasks of memory [26] and driving a car [27]. Compared to sensing brain activation, these signals have an advantage that they can be measured remotely without wearing devices.

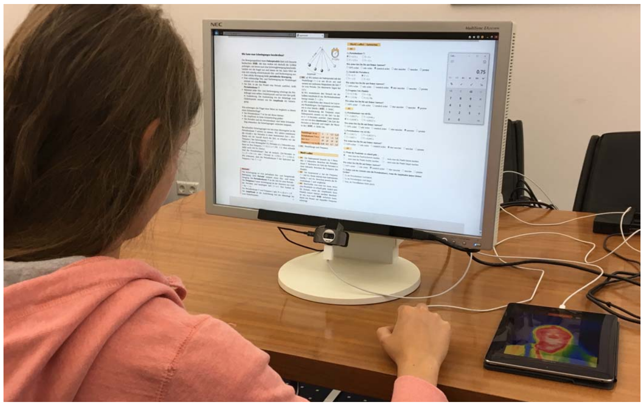

Fig. 4. An experimental setup using an eye tracker and a thermal camera.

TABLE I
THIRTEEN SURVEYS

id	type	scope	survey
s1	interest	macro	I enjoy solving physics problems.
s2	interest	macro	I am concerned about homework with topics dealing with physics.
s3	interest	micro	I like the content of the textbook.
s4	interest	micro	I am interested in learning more about the subject of the textbook as well as lectures and homework.
s5	interest	micro	I would like to know more on the topic of textbook in school.
s6	confidence	macro	I am good at physics more than other subjects.
s7	confidence	micro	The textbook text was easy to understand.
s8	confidence	micro	I knew what I had to answer during solving the tasks.
s9	workload	micro	I had to make an effort to solve the questions.
s10	workload	micro	It was difficult to find the right information to solve the questions in the text.
s11	workload	micro	I needed more assistance while reading the textbook.
s12	workload	micro	The textbook made me curious to know more about vibration and acoustics.
s13	expertise	macro	My physics record is about....

III. Approach

Based on the literature review, we select the combination of eye tracking and thermal image analysis to measure cognitive states because they can be sense without bothering readers and do not interfere with each other. This section describes the pre-processing and feature calculations of the sensing.

A. *Eye tracking*

We utilize a remote eye tracker which can attached to a display to track eye movements. Eye gaze data is composed of two metrics - fixations and saccades. A fixation occurs when the gaze falls on something of interest to the screen area and usually lasts for about 100 - 150 ms. The rapid movement of the eye between fixations is called a saccade. As preprocessing, we filter raw eye movements to fixations and saccades on the basis of the approach proposed by Buscher et al [28]. Figure 2 shows one of the examples of the filtering.

The average of left and right pupil diameters at any time instant is used as the pupil diameter feature for this work. The duration of each fixation during each question is aggregated to get the fixation duration feature. The length of a saccade is derived from the known values of fixation duration of the eye at a particular 2-dimensional coordinate on the screen, at a given timestamp. Similar to the fixation duration feature, the summation of the saccade length corresponding to each participant for each question is used to obtain the feature value. The mean and standard deviation of fixation durations and saccade lengths are calculated as features.

B. *Nose temperature tracking*

We utilize *FLIR One for iOS*, a commercial thermal camera which can be attached to a smartphone or a mobile tablet to measure face temperatures. We develop the sensor logging application of the device by ourselves and record the changing of temperatures as a video. Positions of the face and the nose on each frame are detected by utilizing the method proposed by Baltrusaitis et al. [29]

The temperature data consists of the nose temperature of each participant at a given time during the experiment as shown in Figure 3. From an initial analysis, we have found that generally, the temperature increases when the students read the textbook and decreases when they start solving exercises. From this data, the slope and the standard deviation of the participant's temperature during the process of solving each question are calculated. Finding out the slope and standard deviation serves to measure the ascend/descend and the fluctuations in temperature.

IV. Experiment

We have recorded students' reading behaviors and investigated effective features to recognize cognitive states. In the following, we present the experimental setup, the analysis results, and findings from this experiment.

A. *Experimental setup*

Figure 4 shows an overview of the experimental setup. The SMI 60 Hz remote eye tracker was set up alongside a normal computer desktop to record the eye gaze data and FLIR One for iOS was set to capture the thermal energy from the face. The eye tracker uses a reflection of infrared light to measure eye gaze. We made sure that there is no significant affect in thermal images before starting the experiment. We asked fourteen sixth-grade students (11 or 12 years old) to participate in the experiment. They read a Physics textbook on a screen and solved eight exercises related to the content. As shown in Figure 4, the content textbook was displayed on the left page on the screen, and exercises were displayed on the right page. Participants are allowed to use a calculator while solving the exercises. Eye movements on the calculator were excluded in the analysis. Note that 7 participants read the text first and other 7 participants read questions first. But we treat them as the same condition because there are no significant differences in their performances calculated by the score of the exercises.

To collect ground truth of cognitive states, we asked participants to answer surveys on a paper form after the recording. We prepared the surveys as shown in Table I from the viewpoint of Physics education research. They can be categorized with two indexes: the type and the scope. We asked

TABLE II
PEARSON CORRELATION AND p-VALUES FEATURES AND THIRTEEN SURVEYS.

	interest					confidence			workload				expertise
feature	s1	s2	s3	s4	s5	s6	s7	s8	s9	s10	s11	s12	s13
nose slope reading	-0.0 (0.97)	0.3 (0.37)	0.4 (0.23)	0.0 (0.88)	0.0 (0.89)	0.2 (0.60)	-0.2 (0.49)	0.1 (0.75)	0.1 (0.73)	-0.5 (0.09)	-0.2 (0.50)	0.2 (0.53)	-0.2 (0.61)
nose slope solving	-0.3 (0.39)	0.3 (0.40)	-0.4 (0.25)	-0.0 (0.96)	0.2 (0.53)	**0.6 (0.04)**	0.1 (0.74)	0.4 (0.22)	**-0.7 (0.01)**	**-0.8 (0.00)**	-0.2 (0.48)	0.3 (0.41)	-0.4 (0.16)
nose std reading	0.0 (0.92)	0.3 (0.38)	0.4 (0.18)	0.1 (0.73)	0.1 (0.84)	0.0 (0.88)	-0.2 (0.55)	0.3 (0.40)	0.2 (0.51)	-0.4 (0.15)	-0.1 (0.76)	-0.1 (0.73)	0.1 (0.85)
nose std solving	**0.6 (0.04)**	-0.4 (0.22)	0.0 (0.90)	-0.1 (0.76)	-0.3 (0.42)	-0.2 (0.58)	-0.4 (0.19)	**-0.6 (0.03)**	0.1 (0.73)	0.3 (0.29)	0.2 (0.57)	0.1 (0.70)	0.1 (0.71)
pupil mean reading	**0.6 (0.03)**	**-0.6 (0.03)**	**0.7 (0.01)**	0.1 (0.72)	0.5 (0.14)	0.1 (0.80)	0.1 (0.88)	**-0.7 (0.01)**	0.3 (0.39)	0.5 (0.10)	0.5 (0.08)	-0.0 (1.00)	-0.2 (0.50)
pupil mean solving	**0.7 (0.01)**	-0.6 (0.06)	**0.7 (0.01)**	0.1 (0.80)	0.5 (0.12)	0.1 (0.76)	0.1 (0.77)	**-0.7 (0.02)**	0.3 (0.27)	0.5 (0.12)	0.5 (0.10)	-0.2 (0.63)	-0.1 (0.71)
pupil std reading	0.4 (0.16)	-0.4 (0.23)	**0.8 (0.00)**	0.4 (0.22)	0.5 (0.14)	-0.1 (0.67)	-0.0 (0.92)	-0.4 (0.20)	0.5 (0.07)	0.5 (0.09)	0.4 (0.25)	0.0 (0.99)	-0.1 (0.69)
pupil std solving	0.2 (0.57)	-0.4 (0.21)	**0.6 (0.03)**	0.6 (0.06)	0.4 (0.25)	-0.3 (0.40)	-0.0 (1.00)	-0.2 (0.47)	0.5 (0.13)	**0.6 (0.03)**	0.3 (0.40)	0.0 (0.91)	-0.2 (0.57)
fixation mean reading	-0.4 (0.25)	0.3 (0.36)	-0.4 (0.18)	-0.1 (0.87)	-0.1 (0.80)	0.0 (0.97)	0.3 (0.42)	0.5 (0.08)	-0.1 (0.85)	-0.1 (0.83)	-0.2 (0.58)	-0.5 (0.14)	0.3 (0.37)
fixation mean solving	-0.3 (0.29)	0.0 (0.91)	-0.4 (0.16)	0.0 (0.99)	-0.2 (0.51)	-0.2 (0.44)	0.5 (0.14)	0.4 (0.19)	0.1 (0.81)	0.3 (0.32)	-0.4 (0.24)	-0.3 (0.33)	0.2 (0.59)
fixation std reading	-0.3 (0.30)	0.2 (0.63)	-0.3 (0.40)	-0.1 (0.86)	-0.0 (0.89)	-0.0 (0.97)	0.2 (0.51)	0.4 (0.24)	-0.1 (0.73)	-0.1 (0.87)	0.1 (0.76)	-0.3 (0.31)	0.2 (0.63)
fixation std solving	-0.4 (0.26)	-0.1 (0.84)	-0.1 (0.83)	-0.1 (0.83)	-0.1 (0.68)	-0.2 (0.44)	0.5 (0.11)	0.1 (0.70)	0.2 (0.52)	0.4 (0.26)	-0.2 (0.53)	0.1 (0.84)	-0.1 (0.75)
saccade mean reading	0.1 (0.81)	**-0.6 (0.05)**	-0.1 (0.82)	0.2 (0.50)	-0.1 (0.75)	-0.0 (0.93)	**-0.6 (0.02)**	-0.5 (0.14)	-0.5 (0.12)	-0.0 (0.95)	0.6 (0.05)	**0.7 (0.02)**	-0.4 (0.23)
saccade mean solving	0.3 (0.28)	-0.3 (0.41)	0.4 (0.22)	-0.3 (0.41)	-0.3 (0.29)	-0.3 (0.42)	-0.5 (0.10)	**-0.6 (0.03)**	0.3 (0.43)	0.1 (0.74)	0.3 (0.41)	0.2 (0.50)	0.2 (0.60)
saccade std reading	0.0 (0.96)	-0.5 (0.10)	-0.1 (0.80)	0.3 (0.28)	-0.1 (0.68)	-0.1 (0.87)	**-0.7 (0.01)**	-0.3 (0.29)	-0.4 (0.26)	-0.0 (0.94)	0.5 (0.10)	**0.7 (0.01)**	-0.4 (0.24)
saccade std solving	0.3 (0.35)	-0.2 (0.61)	0.4 (0.18)	-0.0 (0.96)	-0.2 (0.49)	-0.2 (0.50)	-0.5 (0.11)	-0.5 (0.12)	0.3 (0.42)	0.1 (0.85)	0.1 (0.64)	0.4 (0.24)	-0.1 (0.87)

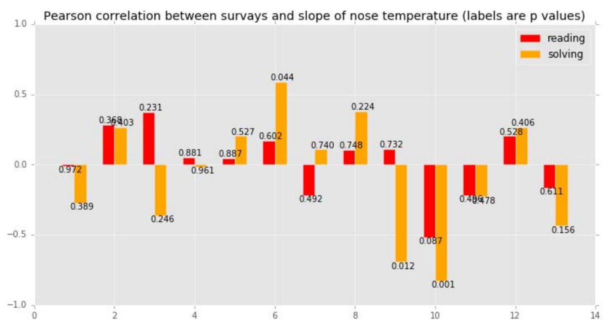

Fig. 5. Pearson correlation between surveys and slope of nose temperature.

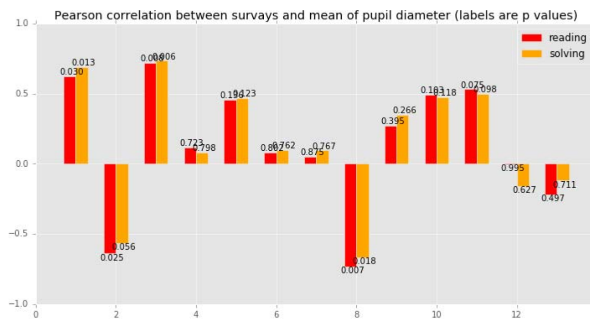

Fig. 6. Pearson correlation between surveys and mean of pupil diameter.

three types of subjective cognitive states (interest, confidence, workload) plus one objective measurement (expertise). Some of the surveys are general questions about Physics learning (macro) and the others are specific questions about the content (micro). The survey brought to light the interest these students had in learning and researching about physics. The ratings ranged from 1 to 6, 6 being "I agree completely and wholly" and 1 being "I do not agree with it at all". Note that there are two differences about the survey between the original form used in the experiment and reported in this paper. 1) The order of the surveys in the form during the experiment was s7, s3, s8, s6, s12, s11, s1, s10, s4, s2, s9, s5, and s13. In this paper, they are sorted by their semantic. 2) The surveys were written in German during the experiment. They are translated into English in the table for readers of this paper.

We reluctantly exclude two of 14 participants' data as outliers. Their reading and solving time were too fast than other participants, they seemed to select the answers randomly, and their score of exercises were zero. They could not be attentive enough or understand the purpose of the experiment.

B. Results

Table II represents the Pearson correlation and p-values (in brackets) between the features and surveys. High correlations with p-values less than 0.05 are highlighted as bold fonts. From these values, we have found three insights. First, surveys related to workload including s10 "It was difficult to find the right information to solve the questions in the textbook." and s9 "I had to make an effort to solve the questions." can be measured by a decrease of the nose temperature during solving exercises (p = 0.001 and p = 0.012). Second, increase of pupil diameter represents a student's interest including s3: "I like the content of the textbook." and s1 "I enjoy solving physics problems." (p = 0.008 and p = 0.030 during reading; p = 0.006 and 0.013 during solving). Third, students who read a textbook and exercises with small saccades felt high confidence in their understandings reflected in s7 "The textbook was easy to understand" and s8 "I knew what I had to answer during solving the tasks" (p = 0.025 and p = 0.035). Details of the relation between surveys and effective features, the slope of nose temperature and mean of pupil diameter are visualized in Figure 5 and 6 for clear visualizations.

C. Discussion

The temporal resolution of sensing is a remaining issue. Although the change in the nose temperature is an effective feature to understand a student's effort, it requires a long time to be observed (see Figure 3). In the application scenario, it can be used for the measurement on each learning unit or page. But it seems difficult to apply our measurements on small parts such as each paragraph, image, or sentence. We need to investigate how much the time resolution can be minimized.

V. Conclusion and Future Work

This paper demonstrated the cognitive state analysis by using an eye tracker and an infrared thermal camera. We have developed an application to retrieve the change in the nose temperature from a commercial infrared thermal camera (FLIR ONE). We asked 12 high school students to read/solve learning materials in Physics and investigated the relation between sensor signals and surveys about their cognitive states. The changing of the pupil diameter was highly correlated with interest. Although the temporal resolution was not enough high for a realtime application scenario, the changing of the nose temperature represented their efforts for reading/solving learning materials.

This work investigated "when" additional information should be displayed on an anticipating textbook based on the measurement of cognitive states. We plan to implement dynamic changing on textbooks, and investigate two research questions. What kind of additional information can improve students' learning abilities? What is the best way to display additional information overcoming the split attention effect?

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