

Neural Correlates of Purchasing Decisions in an Ecologically Plausible Shopping Scenario with Mobile fNIR Technology

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Abstract. In this paper we present our preliminary findings for the neural correlates of purchasing decisions made in a computerized setting as well as in an ecologically plausible supermarket environment. Participants who were randomly recruited from a database of typical customers maintained by a marketing consultancy company were given a specific budget and asked to make purchasing decisions for basic grocery items in two separate conditions. In the first condition, participants made their decisions in a computerized scenario, where in each trial a single product and its price were displayed for a fixed duration of time, and then the participants clicked on buttons to specify which products they wish to purchase. In the second experiment, participants made similar purchasing decisions while wandering around a custom-made grocery aisle with shelves including physical products. In both conditions participants' brain activities in their prefrontal cortices as well as their eye movements were recorded with a wireless fNIR device and a glass eye tracker respectively. In both conditions we observed higher mean oxygenation levels for the purchase decisions at the left dorso-medial prefrontal cortex. Despite the limited sample size, the oxygenation trends were similar in both purchasing situations. Our preliminary findings suggest that fNIR can effectively be employed to investigate neural correlates of purchasing behavior in ecological settings.

Keywords: Decision making · Neuroergonomics · Neuroeconomics · Optical brain imaging · Mobile fNIR

1 Introduction

Neuroeconomics has emerged as an interdisciplinary field to pursue the goal of developing a better understanding of the neurobiological factors that shape economic decisions [1]. In particular, neuroeconomics research seeks to further our understanding with regards to what variables are computed by the brain while humans are making different

kinds of decisions, and how those computations are implemented and constrained by underlying neurobiological processes, with the eventual goal of building biologically plausible models for human decision making [2]. Existing work in the field include decision making scenarios ranging from simple decision tasks such as choosing pizza over salad for lunch to decision making under uncertain, dynamically unfolding circumstances such as gambling tasks [3]. Although these studies include rather simplistic decision making scenarios due to the physical limitations imposed by brain imaging tools, they collectively identified important neural mechanisms underlying related cognitive and emotional processes such as reward evaluation, ambiguity/risk management and value comparison [4].

A number of brain imaging studies have focused on the role of the dopaminergic system in forming and updating expectations about rewards and value computation [4]. Monetary reward experience and evaluation processes have been found to activate several interconnected regions of this system, including the deep structures of the brain stem at ventral tegmental area (VTA) and the ventral striatum (vSTR), as well as the ventromedial prefrontal cortex (vmPFC) [5–7]. Especially the receipt of rewards were found to evoke activation in the vmPFC and the adjacent orbitofrontal cortex (OFC), which support the theory that these regions may be involved with computing the expected value of a reward [6]. Even activations observed at mPFC and striatum during passive viewing of products can be later used for predicting those consumer's choices involving those products [8]. In a recent study, Metereu and Dreher [9] found that the OFC/vmPFC region encodes a general unsigned anticipatory subjective value signal for both rewards and punishments.

Real world decision-making often involves uncertainty, which is another crucial factor that modulates the values attributed to choices. Imaging studies that involve uncertainties and risks in decision-making report activations in dorsolateral and lateral PFC, vmPFC, orbitofrontal cortex (OFC) and the anterior cingulate cortex (ACC) as well as subcortical regions including VTA, vSTR and amygdala [4, 10]. This distributed neural network is claimed to encode two components of a subjective value signal, namely expected value and risk probability [11]. The medial and lateral prefrontal cortex is claimed to play a role in integrating these two components [12]. The computations carried out in these regions are likely to be associated with subjective value signals, but not as robustly as the vmPFC/OFC regions. In particular, the dorso-lateral regions are argued to have a regulatory role on medial PFC during decision making scenarios [13]. However, the precise computational roles played by the dorso-medial and dorso-lateral areas remain to be an important issue in simple choice and reward processing paradigms in neuroeconomics [2].

Existing studies in neuroeconomics predominantly employ the fMRI method. Despite its superior spatial resolution, fMRI is an expensive and impractical neuroimaging technology for purchasing behavior studies in the field. In this paper, the functional near-infrared spectroscopy (fNIRS) method was employed to study purchasing behavior, which offers a low-cost, non-invasive and portable optical brain imaging

methodology. The aim of this study is to explore the plausibility of the fNIR methodology for neuroeconomics applications in the field, as well as to develop a neuro-physiologically informed predictive models of purchasing behavior based on fNIR measurements.

There are only a few fNIR studies published in the context of neuroeconomics. Existing fNIR studies have identified activation patterns in the prefrontal cortex during product selection [14], risk assessment [10], financial investment [15] and price prediction [16]. Mitsuda et al. [16] also proposed a support vector machine algorithm for classifying price/product pairings that were tagged as expensive or inexpensive by the participants with an accuracy of 70 %. The present study aims to contribute this line of inquiry by investigating activation patterns in the PFC of consumers during a more realistic, mundane purchasing scenario. In particular, we aimed to identify whether positive and negative purchasing decisions differ in terms of the neural activity they elicit in regions located at dorso-medial and dorso-lateral prefrontal cortex, and whether we can observe a similar pattern when participants make purchasing decisions while they walk around to freely inspect physical products located on a shelf.

The rest of the paper is organized as follows. The fNIR optical brain imaging technology and the experiment design are described in the next section. Next, we present our main findings regarding activation patterns observed at the dmPFC and dlPFC regions during purchasing decisions. The paper concludes with an overall discussion of the results and pointers for future work.

2 Materials and Methods

2.1 Functional Near-Infrared Spectroscopy

fNIR is a neuroimaging modality that enables continuous, noninvasive, and portable monitoring of changes in blood oxygenation and blood volume related to human brain function. Neuronal activity is determined with respect to the changes in oxygenation since variation in cerebral hemodynamics are related to functional brain activity through a mechanism known as neurovascular coupling [17]. Over the last decade, studies in the laboratory have established that fNIR spectroscopy provides a veridical measure of oxygenation and blood flow in the brain [18]. fNIR is not only non-invasive, safe, affordable and portable, it also provides a balance between temporal and spatial resolution which makes fNIR a viable option for in-the field neuroimaging.

fNIR technology uses specific wavelengths of light, introduced at the scalp, to enable the non-invasive measurement of changes in the relative ratios of deoxygenated hemoglobin (deoxy-Hb or HbR) and oxygenated hemoglobin (oxy-Hb or HbO) in the capillary beds during brain activity. Typically, an optical apparatus for fNIR Spectroscopy consists of at least one near infra-red light source and a detector that receives light after it has interacted with the tissue. Near-infrared light is known to diffuse through the intact scalp and skull, which makes it suitable for tracing relative changes in the concentration of specific chromophores in the neural tissue with non-invasive, spectroscopic methods [19]. Whereas most biological tissue (including water) are relatively transparent to light in the near infrared range between 700 to 900 nm, hemoglobin is a strong absorber of

light waves in this range of the spectrum. Within 700 to 900 nm, HbO and HbR are among the highest absorbers of infra-red light. This provides an optical window into neural tissue where one can approximate relative changes in the concentration of HbO and HbR based on how infra-red light is attenuated in neural tissue.

Photons that enter tissue undergo two different types of interaction: absorption and scattering [17]. Two chromophores, HbO and HbR, are strongly linked to tissue oxygenation and metabolism. The absorption spectra of HbO and HbR remain significantly different from each other allowing spectroscopic separation of these compounds to be possible by using only a few sample wavelengths. Once photons are introduced into the human head, they are either scattered by extra- and intracellular boundaries of different layers of the head (skin, skull, cerebrospinal fluid, brain, etc.) or absorbed mainly by HbO and HbR. A photo-detector placed on the skin surface at a certain distance from the light source can collect the photons that are scattered and thus have travelled along a “banana shaped path” from the source to the detector, which carry important information about the optical properties of the diffused neural tissue (Fig. 1). This raw light attenuation information is then converted into tissue oxygenation measures that quantify the relative changes in the presence of HbO and HbR within the banana shaped path by using a method called modified Beer Lambert law [20].

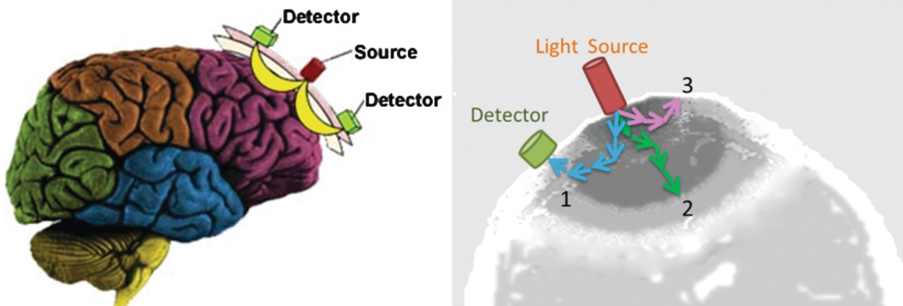


Fig. 1. The banana shaped path which includes the photons scattered back to the photo-detector (left). Representative paths (right), enumerated as 2 and 3 correspond to photons absorbed by the tissue and scattered out of the scalp without reaching the detector, respectively. (Color figure online)

2.2 Experiment Setup

Participants. 21 participants (10 female) in the age range 19–45 ($M = 32.15$, $SD = 7.42$) participated in this study. 12 participants (5 female) were randomly assigned to the computerized purchasing task that included photographs of several grocery items, whereas the remaining 9 participants (5 female) completed a similar task in front of a rack of shelves including real grocery items. Participants were selected randomly among volunteers reached via the consumer database of ThinkNeuro. All participants were right-handed and none of them had a history of psychiatric disorders. Participants were paid 25 Turkish Liras (TL) for their participation and 20 TL as a bonus in compensation

for the items they selected to purchase during the experiment. The study was approved by the METU human subjects research ethics committee. Written informed consent was obtained prior to the experiment.

Experiment Design. The computerized purchasing task was comprised of 35 trials where participants were asked to make a purchasing decision for each individually displayed product based on the suggested price. In each block, the participants had 4 s for viewing a picture of the product, 4 s for viewing the picture and the price of the product, and 4 s to respond by pressing one of two buttons indicating a purchase or a pass, followed by a 8 s long fixation duration. Hence, each block lasted for 20 s, and the total duration of the experiment was about 12 min. The E-Prime software was used for the presentation of the experiment stimulus. The products consisted of snacks, beverages and cleaning supplies, which can be found in any local grocery stores (Fig. 2). The prices of the products were obtained from local groceries.



Fig. 2. An example product image used in the computerized purchasing task. The item was first displayed without the price tag (left), which is followed by the image with the price (right).

In the free shopping condition participants were given the same budget and asked to make their decisions by browsing through a rack of shelves including physical grocery items whose images were used during the computerized task (Fig. 3). In the first phase of the task, participants were asked to pick the selected item and place it in a shopping cart to indicate a purchasing decision. In the second phase of the experiment, experimenters asked each participant to find a specific item and put it on a desk. This search task was included in the experiment design as a control condition to compare against real purchasing decisions.

Participants in both conditions were informed that the experimenters would be able to provide them up to a total 40TL worth of the products that they selected. Subjects were also told that if they do not spend at least 40TL, they would receive only half of the unspent amount in an effort to reinforce buying behavior.



Fig. 3. A participant wearing the fNIR sensor as well as the ASL mobile eye tracker (left). A grocery store setup was used to investigate purchasing decisions in a more ecologically valid shopping scenario.

Materials, Apparatus and Software. While the participants were making purchasing decisions their eye movements were tracked with the help of an ASL mobile eye tracker, whereas the neural activity in their prefrontal cortex was monitored by a functional near-infrared spectroscopy (fNIR) system developed at Drexel University (Philadelphia, PA),

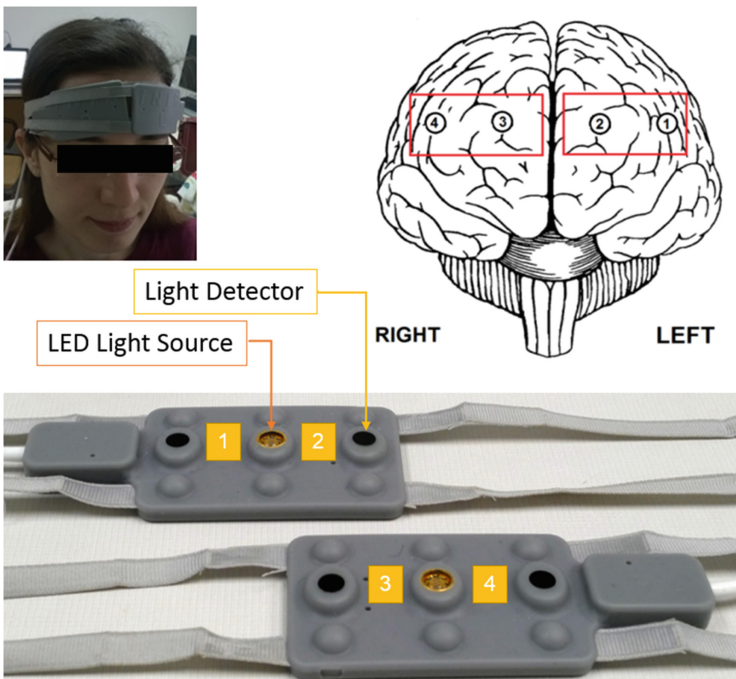


Fig. 4. The 4-channel split fNIR sensor (top, left), projection of the 4 measurement locations (optodes) on brain surface image (top, right), optodes identified on the split fNIR sensor (bottom). (Color figure online)

manufactured and supplied by fNIR Devices LLC (Potomac, MD; www.fnirdevices.com). The experimental setup consists of a flexible head-piece (sensor pad), a wireless control box for hardware management, and a computer that runs the COBI Studio software [21] for data acquisition. The filtering and conversion of raw fNIR signals into oxygenation measures were performed offline by using the fNIRsoft software [22]. Statistical tests on oxygenation measures were conducted with IBM SPSS v.23.

The fNIR sensor holds 2 light sources and 4 detectors (Fig. 4) to monitor oxygenation measures at 4 optodes located on the prefrontal cortex. The sensors have a source-detector separation of 2.5 cm, which allows for approximately 1.25 cm penetration depth to reach the cortical surface. This system can monitor changes in relative concentrations of HbO and HbR at a temporal resolution of 2 Hz. The locations of the regions on the cortical surface monitored by the sensor are displayed in Fig. 4, which correspond to Brodmann areas 9,10,44 and 45. These regions primarily include left/right dorsolateral prefrontal cortex (dlPFC) and left/right dorsomedial prefrontal cortex (dmPFC). Existing neuroimaging studies suggest that the prefrontal cortex has a special role in the processing of higher order cognitive functions such as working memory management, sequential processing of sensory and memory input, as well as response inhibition and decision making [23].

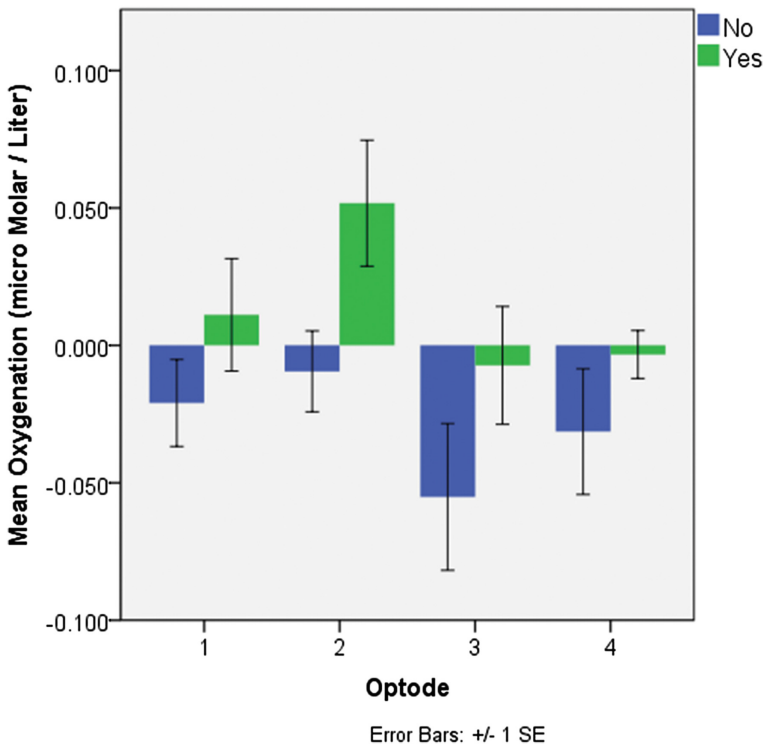


Fig. 5. The mean oxygenation values observed during purchase and pass decisions (Color figure online)

3 Results

In the computerized purchasing scenario, raw fNIR measures were obtained for buy/pass decisions over a total of 35 grocery items. Raw fNIR data (4 optodes \times 2 wavelengths) were low-pass filtered with a finite impulse response, linear phase filter with order 20 and cut-off frequency of 0.1 Hz to attenuate the high frequency noise due to respiration and cardiac cycle effects [24]. Saturated channels (if any), in which light intensity at the detector was higher than the analog-to-digital converter limit were excluded. Artifacts due to motion are detected and excluded by applying the sliding windows motion artifact filter [25]. fNIR data epochs for the rest and task periods were extracted from the continuous data using time synchronization markers. Blood oxygenation changes within each 4 optodes for the product, price and decision blocks were calculated using the modified Beer-Lambert Law for task periods with respect to rest periods at the beginning of each trial with the fNIRSoft software [22].

Firstly, mean oxygenation measures for each participant was computed over the decisions they made for the 35 items during the experiment. Figure 5 below shows the average oxygenation levels observed at each optode for purchase and pass decisions made by the sample of 12 participants. Although the average oxygenation tends to be higher in the purchase cases, dependent t-tests conducted on each optode suggested that only at optode 2 this difference is statistically significant, $t(8) = 2.35$, $p < .05$.

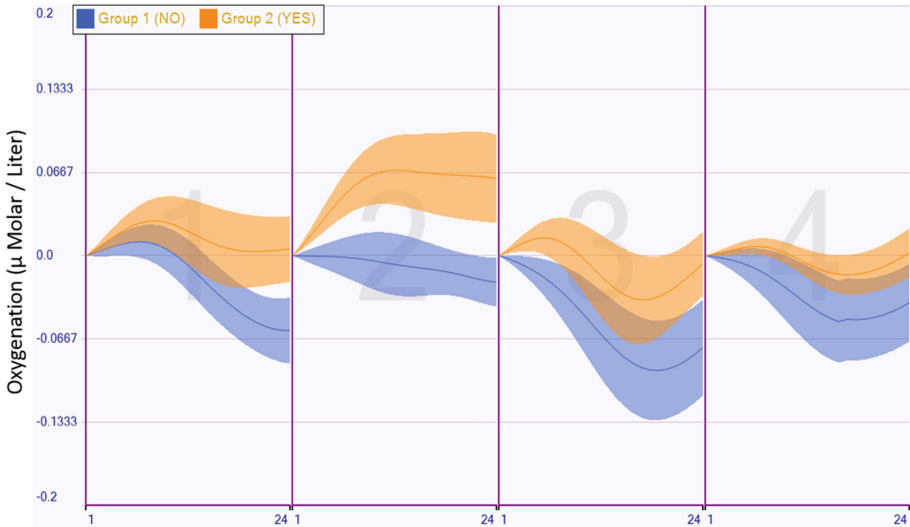


Fig. 6. The temporal trend of the oxygenation signal averaged over purchase (orange) and pass (blue) decisions of the 12 subjects. Shaded regions indicate standard error. The thick lines represent cell by cell averages computed across 12 subjects. (Color figure online)

Figure 6 below shows the temporal changes observed in the oxygenation values averaged over the whole sample of 9 subjects during the purchase and pass decisions.

The shaded regions signify the standard error. The largest separation between purchase and pass cases is observed in optode 2, which is close to the left dmPFC region.

In the free shopping condition we focused on identifying how the oxygenation trend changed within 10 s long blocks that end at the moment when the subject placed the item in her/his shopping cart. We employed the same block structure for the latter half of the experiment where subjects simply searched for the items the experimenter asked him/her to find. Figure 7 compares the mean oxygenation values observed during purchase and search blocks. Dependent t-tests conducted for each optode indicated that the difference between purchase and search is significant at optode 1, $t(9) = 2.02, p < .05$ (one-tailed), and optode 2 $t(7) = 2.11, p < .05$ (one-tailed).

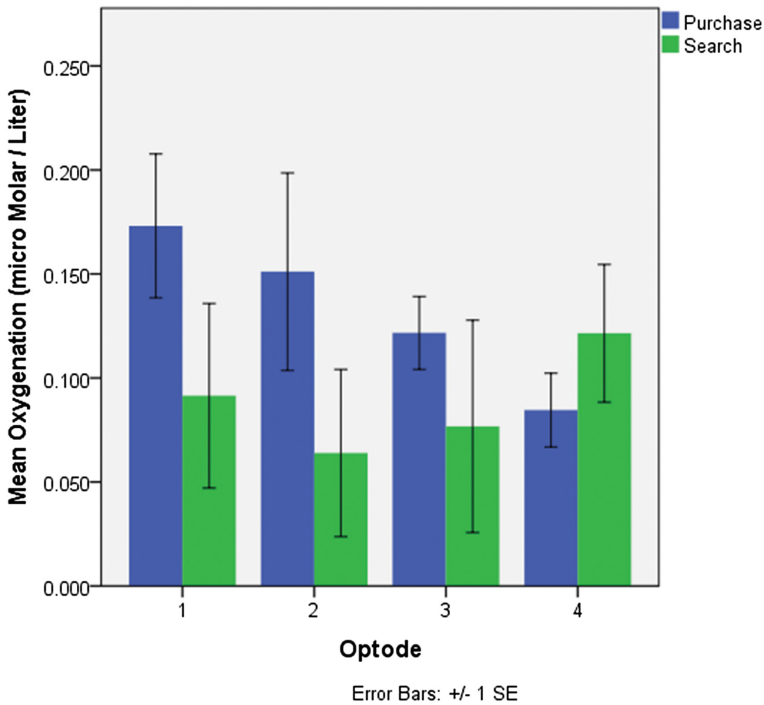


Fig. 7. The mean oxygenation values observed during purchase and search actions in the shopping condition. (Color figure online)

Figure 8 shows the time course of the oxygenation signals observed during purchase and search tasks averaged across 9 subjects. The purchase decisions tend to elicit higher levels of activity in the left dlPFC and left dmPFC.

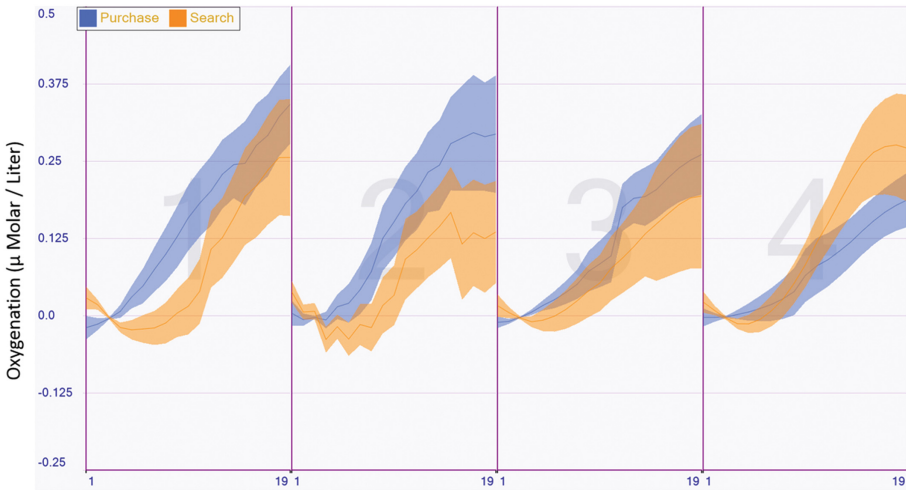


Fig. 8. The temporal trend of the oxygenation signal averaged over purchase (orange) and search (blue) tasks of the 9 subjects. Shaded regions indicate standard error. The thick lines represent cell by cell averages computed across 9 subjects. (Color figure online)

4 Discussion and Future Work

Overall, we have detected a significant increase in optode 2 in the case of purchasing decisions during both computerized and free shopping conditions. These results are consistent with the findings of a previous study where we employed a 16 channel fNIR sensor in the computerized condition [26]. Our previous study as well as the findings of existing fMRI studies suggest that decisions that result in a purchasing action significantly increase the neural activity at the frontopolar regions, which are closely related to OFC and vmPFC that modulate the computation of subjective values. Trials that resulted in a purchase tend to elicit a high level of activity in frontopolar as well as in the neighboring left and right dmPFC regions. Our findings with the wireless fNIR device that can monitor 4 optodes over the implicated regions are consistent with this trend. We also found a considerable increase in dmPFC during a purchase action as opposed to a pass or a search action. Finally, our results with the smaller split sensor suggest a stronger difference in the left hemisphere between purchase and no-purchase decisions.

In conclusion, this study demonstrated that fNIR can be used to monitor activations in the prefrontal cortex during purchasing decisions in the field. In the future, we aim to better exploit these suggestive statistical regularities to test the robustness of a predictive model of purchasing behavior in ecologically realistic settings. To that end, we plan to extend our sample size and incorporate eye movement metrics in an effort to build a multimodal model with reasonable predictive power for estimating the likelihood of a purchasing decision given the immediate neural and ocular trends.

Acknowledgments. The authors would like to thank Dr. Hasan Ayaz for his guidance and help during the analysis and processing of fNIR signals. This research and development project was supported by The Scientific and Research Council of Turkey, TUBITAK-1501 grant to ThinkNeuro (Project No: 3140565).

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