Brain and Cognition 125 (2018) 157–164

Contents lists available at ScienceDirect

Brain and Cognition

journal homepage: www.elsevier.com/locate/b&c

The neural bases of price estimation: Effects of size and precision of the estimate

Ana Raposo*, Sofia Frade, Mara Alves, J. Frederico Marques

Faculdade de Psicologia, Universidade de Lisboa, Alameda da Universidade, 1649-013 Lisboa, Portugal

ARTICLE INFO

Keywords:
Price estimation
Numerical processing
Size effect
Precision effect
Prefrontal cortex
Intraparietal sulcus

ABSTRACT

People are often confronted with the need of estimating the market price of goods. An important question is how people estimate prices, given the variability of products and prices available. Using event-related fMRI, we investigated how numerical processing modulates the neural bases of retail price estimation by focusing on two numerical dimensions: the size and precision of the estimates. Participants were presented with several product labels and made market price estimates for those products. Measures of product buying frequency and market price variability were also collected. The estimation of higher prices required longer response times, was associated with greater variation in responses across participants, and correlated with increasing medial and lateral prefrontal cortex (PFC) activity. Moreover, price estimates followed Weber's law, a hallmark feature of numerical processing. Increasing accuracy in price estimation, indexed by decreasing Weber fraction, engaged the intraparietal sulcus (IPS), a critical region in numerical processing. Our findings provide evidence for distinguishable neural mechanisms associated with the size and the precision of price estimates.

1. Introduction

We regularly need to estimate prices, whether to decide if a product has a fair value, to plan a budget or to make a bid. An intriguing question is how people estimate the market price of a good, given the variability of products and prices available. A buyer's judgment of an item's price is an important determinant of whether or not to purchase (Thomas & Morwitz, 2009). Hence, unravelling the neurocognitive underpinnings of our intuition for prices may advance knowledge on price cognition and its implications to everyday purchasing decisions.

Behavioural research has shown that given a product name, people can quickly provide a market price in a familiar currency. As proposed by Dehaene and Marques in their studies of price estimation, people's judgment of the market value of goods depends, at least in part, on numerical processing, i.e., our mental representation of magnitudes (Dehaene & Marques, 2002; Marques & Dehaene, 2004). Indeed, prices are a good example of a numerical property of products. Like other numerosities, prices are subject to two critical effects: the distance effect, i.e., the comparison between two prices is slower and more error prone when the prices are closer than further apart; and the size effect, i.e., comparison difficulty increases with increasing price (Cao, Li, Zhang, Wang, & Li, 2012; Dehaene & Marques, 2002; Moyer & Landauer, 1967). These effects reveal that the representation of quantities is approximate, rather than exact, and that larger quantities are increasingly less discriminable.

Previous studies have shown that price knowledge obeys Weber's law. The law states that the ability to psychologically discriminate numerical values depends on the ratio between the values being compared, rather than their absolute difference (e.g., adding 5 grams to 100 grams or adding 10 grams to 200 grams has the same perceived increase on weight, as the ratio is the same in both cases). Weber's law adequately predicts performance on numerical tasks (see Cantlon, Platt, & Brannon, 2009 for a review), including price judgment tasks (Webb, 1961). For example, Lambert (1978) reported that the frequency with which participants noticed a change in the price of a product did not depend on the absolute price change, but on its ratio to the item's price. Dehaene and Marques (2002) have shown that, when participants were asked to estimate prices for different items, the standard deviation of price estimates across participants was directly proportional to the mean price, such that the higher the price the larger the variability of the estimates. Importantly, it has been demonstrated that the ratio of the standard deviation to the mean, broadly known as Weber fraction, is stable across different price magnitudes (Dehaene & Marques, 2002). The Weber fraction is thus considered an index of an item's price estimation precision, with higher values indicating a "noisier" and less precise estimation of the item's price (Whalen, Gallistel, & Gelman,

* Corresponding author.
E-mail address: alraposo@psicologia.ulisboa.pt (A. Raposo).

https://doi.org/10.1016/j.bandc.2018.07.005
Received 11 August 2017; Received in revised form 5 July 2018; Accepted 6 July 2018
0278-2626/

1999). As such, the Weber fraction for a given product, calculated across participants, may be used as a proxy for the accuracy of the numerical representation of that product's price.

At a neural level, there is extensive evidence that the brain has specialized networks to process numerical quantities, notably in the intraparietal sulcus (IPS) and surrounding parietal regions (e.g., Butterworth, 2010; Cantlon et al., 2009; Cantlon, 2012; Cohen Kadosh, Cohen Kadosh, Kass, Henik, & Goebel, 2007; Dehaene, Piazza, Pinel, & Cohen, 2003; Dehaene, 2009; Emerson & Cantlon, 2014; Nieder & Dehaene, 2009; Nieder & Miller, 2004; Piazza, Izard, Pinel, Le Bihan, & Dehaene, 2004; Piazza, Pinel, Le Bihan, & Dehaene, 2007; Pinel, Piazza, Le Bihan, & Dehaene, 2004; Rivera, Reiss, Eckert, & Menon, 2005). Considered the core magnitude system, the IPS is systematically activated when quantity is manipulated, independently of notation (Piazza, Mechelli, Price, & Butterworth, 2006; Pinel, Dehaene, Riviere, & Bihan, 2001), and for various tasks, including mental arithmetic (Klein, Nuerk, Wood, Knops, & Willmes, 2009; Venkatraman, Ansari, & Chee, 2005), number comparison (Ansari, Fugelsang, Dhital, & Venkatraman, 2006), and digit detection (Eger, Sterzer, Russ, Giraud, & Kleinschmidt, 2003). The reliable activation of the IPS and neighbouring superior and inferior parietal lobules has been confirmed by various meta-analyses targeting number processing in humans (Arsalidou & Taylor, 2011; Sokolowski, Fias, Bosah Ononye, & Ansari, 2017; Sokolowski, Fias, Mousa, & Ansari, 2017). Interestingly, neuroimaging data have shown a weberian neural response in bilateral IPS. In an fMRI adaptation study, participants repeatedly viewed the adaptation stimuli (sets with a fixed number of dots), while deviant stimuli (sets of variable number of dots, along a continuum, spanning from half to double the adaptation values) were presented rarely. As predicted by Weber's law, IPS activation for deviant numerical stimuli was a direct function of the ratio between the deviant and the adaptation number (Piazza et al., 2004). Given its role in processing other numerical quantities, it is predictable that IPS also sustains our ability to estimate the market price of goods.

In the present fMRI study, we investigated the neurofunctional correlates of market price estimation, focusing on two numerical dimensions: the size and precision of the estimates. In line with previous research that shows that larger magnitudes are represented in a fuzzier, less exact manner (as evidenced by the size effect), we expect that higher prices will be more difficult to estimate, as participants must indicate a specific price within a range of values that are less discriminable than lower prices. Moreover, the computation of prices may also be influenced by factors that are extrinsic to numerical dimensions. Among these, buying frequency and market price variability have been shown to have an impact on market price estimation (Dehaene & Marques, 2002; Giuliani, D'Anselmo, Tommasi, Brancucci & Pietroni, 2017; Marques & Dehaene, 2004). Specifically, it is harder to estimate the price of products that are less frequently purchased as well as prices with greater variation in the marketplace, as revealed by longer response times (RTs) and greater variability across participants' responses. Importantly, both buying frequency and market price variability are strongly related with price magnitude, since products with higher prices tend to have lower buying frequency and greater market price variability. As such, both the approximate nature of numerical processing (with increasingly "noisier" representations as the values get larger) and purchasing factors (notably, buying frequency and market price variability) may increase the processing demands associated with the estimation of higher prices. Greater cognitive control may be necessary in order to select a specific price among a range of subjectively closer values and to manipulate multiple price representations associated with greater market price variability. Areas engaged in cognitive control, notably lateral and medial prefrontal cortex (PFC; Ansari et al., 2006; Emerson & Cantlon, 2014; Rivera et al., 2005) would be expected to demonstrate a positive correlation with increasing price estimates. Thus, it is of interest to investigate price estimation effects in regions outside the IPS.

Regarding the precision of the estimates, following previous studies, we will use the Weber fraction as an index of the price estimation accuracy. We hypothesize that a more precise representation of the price, indexed by a smaller Weber fraction, will engage the IPS, the neural signature of the mental representation of numbers.

Table 1
Descriptive statistics of the items' rating judgments and price estimation measures obtained in the behavioural study.

	Mean (SD)	Range
Rating judgments (7-point scales)		
Familiarity	5.36 (1.26)	2.57–6.89
Imageability	6.33 (0.67)	3.50–6.86
Subjective liking	4.86 (1.05)	2.18–6.86
Market price variability	3.35 (1.26)	1.29–6.36
Buying frequency	3.26 (1.18)	1.04–5.32
Price estimation measures		
Price estimates (in €)	25.87 (81.66)	0.13–530
Weber fraction	0.49 (0.21)	0.15–1.23
RT (in ms)	4185 (629)	3217–6286

2. Method

2.1. Participants

Twenty healthy participants (17 females, M = 19.65 years, range: 19–29 years) took part in the study. All were right-handed, native speakers of Portuguese, and had no history of neurological impairment or head injury. They all gave informed written consent to the experimental procedure, which was approved by the local ethics committee. All participants were university students and received a course credit as compensation for their participation.

2.2. Materials

Sixty-four everyday items were selected from a database of previous studies (Dehaene & Marques, 2002; Marques & Dehaene, 2004). Items denoted a broad range of products including groceries (e.g., biscuit pack), toys (e.g., video game), apparel (e.g., sport shoes), household items (e.g., light bulb), entertainment (e.g., movie ticket), electronics (e.g., laptop computer), and transportation (e.g., bus ticket). Product labels were made up of two words, presented in the written form, and no number words were used.

The features of these items and their impact in the price estimation task were evaluated in a separate behavioural study. In this study, a group of 28 participants (16 females, M = 23.96 years, range: 18–35 years), who did not take part in the fMRI study, provided their market price judgments of each product, by typing the estimated price on the keyboard. RTs were measured from the onset of the product presentation to the onset of typing a response. After the price estimation task, participants rated on a 7-point scale each item on several dimensions including familiarity (1 = very unfamiliar to 7 = very familiar), imageability (1 = very low imageability to 7 = very high imageability), subjective liking (1 = do not like 7 = like very much), market price variability (1 = very low market price variability to 7 = very high market price variability) and their own buying frequency of the product (1 = rarely ever buy to 7 = buy very often). As it can be seen in Table 1, the selected products presented relatively high levels of familiarity (i.e., participants reported knowing the items, with no product being rated as unfamiliar) and imageability (i.e., people reported being able to imagine the product from the labels provided). For the other dimensions, the full range of the scale was used, with items varying in subjective liking, market price variability and buying frequency.

Correlation analyses between these dimensions and the log