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It's about the process, not the result: An fMRI approach to explore the encoding of explicit and implicit price information

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A R T I C L E I N F O

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A B S T R A C T

This research examines the neurophysiological correlates of consumers' price memory processes. We focus on the explicit and implicit dimensions of consumers' price knowledge and use an experimental functional Magnetic Resonance Imaging (fMRI) study to assess how the encoding of task-dependent price memory affects the choice process and neural activation. The findings of our study add to the field of consumer neuroscience by demonstrating how neural correlates of explicit and implicit task-dependent price memory can shed light on processes that guide consumer decision-making. Over the course of our experiment we found that consumers did not always make consistent decisions, but that their decisions were influenced by explicit components of price memory. Implicit price memory components seem to have a more supportive role in the decision-making process. In summary, we found that price memory is a dynamic construct that is influenced by unconscious and neurophysiological processes, and we conclude that a neurophysiological perspective can add value for consumer and marketing research.

1. Introduction

People's memories influence their decisions. As economics and marketing theory suggest, price memory and price knowledge are especially important variables for explaining shopping decisions (e.g., Estelami, Lehmann, & Holden, 2001; Olavarrieta, Hidalgo, Manzur, & Farías, 2012; Völckner, 2008). Against this background, it is not surprising that consumers' knowledge about individual prices has justifiably received extensive attention from marketing and consumer researchers (e.g., Dickson & Sawyer, 1990; Vanhuele & Drèze, 2002; Wakefield & Inman, 1993). Consumers encounter a continual stream of price information, from price tags on products in shops to prices on brochures and advertisements. Especially in the online world, people are bombarded with price information, whether they are shopping or simply comparing prices online, or whether they encounter online advertisements when using the web. Across offline and online channels, they make price-based decisions by comparing and observing prices. Within this decision process, some sort of price knowledge should help shoppers to distinguish between low and high prices of products they intend to buy. Taking this prevalence of consumer-price interactions as a basis (Vanhuele, Laurent, & Drèze, 2006), it might seem intuitive to expect that measures of customer price knowledge can be explained fairly well by now. However, despite decades of research in price memory, the question of why customers are able or unable to remember prices remains mainly unsolved (e.g., Gaston-Breton & Raghubir, 2013). Along this line, price knowledge should not depend solely on category, macro-economic, product-related, or socio-demographic factors, but also on neurophysiological factors that determine the ability of consumers to memorize product prices (Achrol &

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Table 1
Overview of selected* price knowledge-related studies from the fields of behavioral pricing and consumer neuroscience.

Author(s)	Domain/ Theoretical background (Research questions)	Research design (Variables)	Research design (Method)	Results
Vanhuele and Drèze (2002)	Behavioral pricing/ Triple code model of numeric information processing	Independent variables: - Characteristics of product category (price volatility; promotional frequency; price range; number of products) - Characteristics of consumer (proneness to searching for prices within a store; proneness to searching for prices between stores; shopping trip size/ household size) Dependent variable: - Accuracy of price knowledge - Extent of price recognition - Deal spotting capability	Experiment with 400 consumers in a supermarket. Product category: Groceries, cosmetics.	- 2,1% of respondents could recall the exact price. - 13,3% of respondents could recognize the right price (this value is corrected by probability of guessing). - 32,7% of consumers had a distinct deal spotting capability. - Promote frequency has a positive influence on price knowledge. - Price range of product category and number of products in this category have a negative influence on price knowledge. - Intensity of searching for prices within a store has a positive influence on price knowledge; comparisons between stores have no influence. - Shopping trip size respective to household size has no influence on price knowledge.
Mägi and Julander (2005)	Behavioral pricing/ Learning psychology (Objective and subjective knowledge)	Independent variables:- Out-of-store price search- Number of stores shopped- Length of residence in the market- Price consciousnessDependent variables:- Subjective price knowledge (i.e., what the consumer thinks s/he knows)- Objective price knowledge (i.e., measured accuracy)	Two data sets were used: proprietary price-index data collected from stores in one Swedish market area and a mail survey sent out to a random sample of residents in the same market.Data for the price index was collected in-store in the form of a weighted basket of about 300 common daily commodities.The survey consisted of 462 usable cases.	- Out-of-store price search, number of stores shopped, and length of residence in the market increase price knowledge. - Price consciousness has a larger positive effect on subjective than objective price knowledge.
Homburg et al. (2012)	Behavioral pricing/ Learning psychology (Explicit and implicit price knowledge)	Independent variables:- Customer satisfaction- Elapsed time since purchaseDependent variables:- Explicit price knowledge (Recall ability)- Implicit price knowledge (Deal spotting ability)	Study 1: 319 customer interviews after buying a durable good during the previous 12 months.Study 2: 223 customer interviews as in Study 1.	- Customer satisfaction has a negative impact on explicit price knowledge, but no substantial effect on implicit price knowledge. - The length of time between purchase and retrieval of the price information has a negative impact on explicit price knowledge but no substantial effect on implicit price knowledge. - Customer satisfaction has a moderating role, in that the higher the customer satisfaction level, the stronger the negative impact of elapsed time on explicit price knowledge.
Gaston-Breton and Raghubir (2013)	Behavioral pricing/ Price processing ability and motivation	Independent variables:- Age- Income- OccupationDependent variables:- Willingness to do memory task- Price recognition accuracy- Price recall accuracy	Field experiment among 683 shoppers manipulating an ability-related variable (familiar or unfamiliar currency) and a	- Consumers with the sociodemographic drivers of lower ability but higher motivation (older, less affluent, and lower occupational

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Table 1 (*continued*)

Author(s)	Domain/ Theoretical background (Research questions)	Research design (Variables)	Research design (Method)	Results
			motivation-related variable (normal or 50% higher prices).	categories) have worse price memory, especially when the prices are expressed in an unfamiliar currency (the ability-related manipulation).
Jensen and Grunert (2014)	Behavioral pricing/ Episodic and semantic memory processes	Independent variables:- Price consciousness- Value consciousness- Brand loyalty- Store loyalty- Price range- Deal share- Buying frequencyDependent variables:- Price recall- Price recognition- Deal spotting	Field experimental between-subjects design with three random samples (before, during, and after store visit) leading to 1204 interviewed shoppers.	- Consumers' price recall appeared quite inaccurate on entry, while mean price recall errors at the shelf and the exit were much lower after an opportunity to update item-specific price knowledge. - The findings show a positive effect of price and/or value consciousness on the level of price knowledge during and after store visit, but not before store visit. - No significant effect of brand loyalty on the level of price knowledge at the shelf or at the exit. - Significant positive effect of brand loyalty before the store visit. - Store loyalty had no effect on the level of price knowledge at any of the measurement points. - High buying frequency categories were associated with significantly higher levels of price knowledge at the shelf and the exit. - No significant ($p = .09$) effect of buying frequency before store visit. - High deal share categories were associated with significantly higher levels of price knowledge at the point of selection. - No effect of deal share at the exit and at the entrance. - Product categories characterized by a large price range were associated with significantly higher levels of price knowledge at the point of selection. - Highly significant negative relationship between price range and level of price knowledge before store visit.
Karmarkar et al. (2015)	Consumer neuroscience/ price primacy RQ: Can the sequence of product and price information influence mechanisms important to the decision-making process and, eventually, to	During two trials the brain activation of participants was measured with regard to: 1. Product primacy: product information was shown first, followed by the product together with the price information, and a decision phase	fMRI experiment with 17 participants with a product primacy task and a price primacy taskInternet study with 83 participants engaged in a product or price primacy task	- The sequence in which product and price information is presented can influence neural activation pattern, and in consequence can also change buying behavior. - Price primacy changed the evaluation process and yielded

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Table 1 (*continued*)

Author(s)	Domain/ Theoretical background (Research questions)	Research design (Variables)	Research design (Method)	Results
	purchasing decisions themselves?	2. Price primacy: The price was presented first, followed by the product and price information together, and a decision phase. In a survey study they also investigated whether price primacy specifically increases the choices for utilitarian products.		different activation patterns in the medial prefrontal cortex, before the decision was made. - Price primacy enhanced the focus on overall evaluations related to the monetary value of products. - Product primacy evoked activation pattern in relation to the attractiveness of a product. - These results could mean that price primacy could make people buy more bargain-priced products.
Knutson et al. (2007)	Consumer neuroscience RQ: What are the neural predictors of purchase?	Measured the brain activation during different stages of the buying decision process.Investigates prediction of purchase behavior on the basis of neural activation in the NaCC, the MPFC, the insula and self-reported variables (Preference and price differential)	26 subjects participated in a SHOP task while lying in the fMRI scanner	- Activation in the Nucleus Accumbens is associated with product preferences. - Activation in the MPFC is positively correlated with price differential. - Activation of the insula is negatively correlated with purchase decisions. - High prices yielded a higher activation in the Insula and a deactivation in the MPFC. - Activity in these regions before a purchase decision was made predicted purchases above and beyond self-report variables (preference and price differential).
Medina, Guerrero, Viedma-del-Jesús, & Aranda, 2020	Consumer neuroscience/ theory of social exchange, equity theory	Brain activity of prosocial and non-prosocial individuals was scanned while subjects of the study made purchase decisions including prices.	18 subjects participated in the fMRI study	- Prosocial consumers see the collective costs as more important, compared to non-prosocial consumers, who focus more on individual costs. - During the evaluation of prices, non-prosocial consumers exhibited higher activations in brain regions associated with reward, evaluation, and choice (e.g., MPFC, bilateral anterior insula, ACC, cerebellum and inferior frontal gyrus). - Whereas non-prosocial consumers base their decisions on prices, prosocial consumers prefer to have information additional to price in order to make their decisions.
Plassmann et al. (2007)	Consumer neuroscience RQ: What are the neural correlates of Willingness to Pay (WTP) computation?	Measured the WTP of participants with a Becker-DeGroot-Marshak auction while measuring brain activity with fMRI. Hungry subjects had to place bids on snacks.	19 participants participated in the fMRI study	- Activation in the medial orbitofrontal cortex and in the DLPFC is important for computation of the WTP.
Plassmann et al. (2008)	Consumer neuroscience/ appetitive and aversive goal values	Measured neural activity with fMRI while participants tasted wines that they believed to be different and sold at different prices.	20 participants tasted different wines and were provided with pricing information while in the fMRI scanner. They had to	- Activity in the mOFC is modulated through changes in the price of a wine.

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Table 1 (*continued*)

Author(s)	Domain/ Theoretical background (Research questions)	Research design (Variables)	Research design (Method)	Results
			enter taste pleasantness and taste intensity ratings.	- Activity in the mOFC also affects actual experienced pleasantness. - Higher prices also increased reported pleasantness of flavors.
Raposo et al. (2018)	Consumer neuroscience/ Price estimation Weber's law RQ: How does numerical processing modulate the neural basis of an estimation of the market price of goods?	Investigation of neurofunctional correlates of market price estimation with regard to the size and the precision of the estimate.	20 participants estimated the prices of everyday items while in the fMRI scanner	- Increasing price estimates took longer, yielded higher variability between participants, and increased activation in L medial and lateral PFC → if the estimated price is higher, more cognitive and neural demands are necessary. - Activity in the IPS and surrounding parietal lobules reflected the precision of those estimates. - Price estimation was in accordance with Weber's law. The standard deviation of price estimated was directly proportional to the mean price.
Weber, Aholt, Neuhaus, Trautner, Elger, Teichert	Consumer neuroscience/ reference dependence in real-market transactions H1: Does neural activity occur in brain regions associated with the processing of fear when selling an emotionally charged product. H2: No such neural activity occurs when purchasing a product with money in routine transactions. H3: The reward system will be activated after a decision has been made, if a high external reference price is provided in the context of satisfaction evaluation.	Measured the WTA (willingness to accept) and WTP of participants with a Becker-DeGroot-Marshak auction while measuring brain activity with fMRI. In the second experimental part, they measured brain activity during post-purchase satisfaction ratings based on different reference price information.	fMRI experiment with 16 participants with two parts: In part one, participants bought and sold a total of 64 MP3-songs via BDM-auctions. In part two, subjects assessed their purchase satisfaction for the songs that they bought in part one. Here, different reference price frames were presented, while the real savings was held constant.	- Part 1: - Subjects exhibited a significantly greater activation of the amygdala during selling, as compared to the buying condition. - In addition, a significant activation of the left caudate nucleus while subjects were selling songs was observed, as compared to the buying of songs. The contrast of buying vs. selling of songs revealed a stronger right parahippocampal gyrus activation. Part 2: - In the external reference price condition, participants showed significant activation in the anterior cingulate cortex, in comparison to activation during the original bidding condition. - In addition, when comparing the condition of "external reference price" to "original bidding," a significant difference in activation of the orbitofrontal cortex was observed.

*We selected studies that deal with price knowledge and/or price information processing, whether or not they simultaneously use explicit and implicit components.

Kotler, 2012; Kenning, Hartleb, & Schneider, 2011). By integrating consumer neuroscience methods and findings into marketing research, our article addresses this academic void.

We first provide a brief overview of the importance and conceptual basis of price knowledge in marketing and, more specifically, in behavioral pricing research. Next, we present our conceptualization based on prior research in consumer neuroscience, and develop specific research questions linking behavioral pricing and neuroscience research. Finally, we test the proposed research questions and demonstrate the marketing implications with a study conducted in an fMRI environment.

2. Theoretical development and conceptualization

2.1. Consumers' price knowledge in the behavioral pricing literature

Price plays two distinct roles in shoppers' evaluations of product alternatives (Völckner, 2008; Bornemann & Homburg, 2011). Price might be used as a measure of sacrifice (i.e., an amount of money a person must pay), but it also takes on the role of informational cue (i.e., quality and status inference). Accordingly, the price knowledge of individual consumers plays an important role in their buying decisions. Individuals differ, however, in their degree of price knowledge retrieval—while some consumers are very price sensitive and aware of their price knowledge, others do not base their decisions as much on price knowledge. For scholarly investigation of price knowledge, behavioral pricing researchers define price knowledge as the entire price-related information for a particular brand or product that the consumer has stored in his or her memory or organism, and which is elicited by the consumer when given the brand as a cue (Monroe & Lee, 1999; Olavarrieta et al., 2012). From this perspective, price knowledge represents an anchor against which the attractiveness of a price is evaluated in future price tasks (Koschate-Fischer & Wüllner, 2017; Vanhuele et al., 2006). Because price knowledge is a result of learning and memory processes (Estelami & Lehmann, 2001; Evanschitzky, Kenning, & Vogel, 2004; Kenning & Plassmann, 2005; Mazumdar & Monroe, 1990), it entails an explicit component (i.e., conscious recall of prices) as well as an implicit component (i.e., unconsciously stored information without explicit recall of information).

Consumer price knowledge has primarily been investigated by assessing consumers' ability to recall prices for specific consumer products that they are confronted with in the process of buying (see Estelami, Lehmann, & Holden 2001 for an overview from a marketing perspective). These studies show that many shoppers are unable to recall the price of a product they have just placed in their shopping cart, which was perceived as evidence of poor price knowledge among consumers. However, although the implicit price component represents a conceptual cornerstone of the price knowledge construct, very few studies consider explicit and implicit price knowledge simultaneously (see the first five studies in Table 1, which use a simultaneous focus on both price knowledge components). By adopting a multi-measure approach that also includes measures of (implicit) price recognition and deal spotting, the few studies that do use a simultaneous approach indicate that consumers know more about prices than prior studies suggest (Jensen & Grunert, 2014). Furthermore, they provide more differentiated insights into the determinants of price knowledge accuracy, with some determinants exerting influence on explicit price knowledge, but not on implicit (Homburg, Koschate-Fischer, & Wiegner, 2012).

The findings from studies combining explicit and implicit facets on price knowledge illustrate the differential impact of explicit and implicit processes on price judgments, and therefore on the importance of investigating the implicit processing of price information (Koschate-Fischer & Wüllner, 2017). Based on the literature review in Table 1, and to the best of our knowledge, there is no study on the question of how implicit price memory processes interact with explicit price memory processes to guide price decisions. The following section aligns this research question with the literature on consumer neuroscience.

2.2. Neurophysiological insights to understand consumers' price memory

The retrieval of price memory can be assumed to be an automatic process that is typically hard to articulate, as price-decisions may be unconscious (Sanfey & Cohen, 2004). Unconsciously stored information helps customers in purchase decisions, although they may not consciously remember specific prices, with one possible result of a feeling of attractiveness when confronted with a specific price, without the ability to name the actual price (Monroe & Lee, 1999). This conceptualization leads to the conclusion that customers might have some unconscious price knowledge without being able to recall product prices explicitly, eventually leading to significant heterogeneity in survey responses.

Methodological approaches in consumer research on price knowledge have tended to make use of survey measures to assess the level of consumers' price knowledge, and to determine how experimental manipulations influence that price knowledge (e.g., Estelami & Lehmann, 2001). The influence of unconscious and automatic processes is one important aspect of integrating price knowledge in the decision-making process, as well as being a research problem for this subject (Plassmann, Venkatraman, Huettel, & Yoon, 2015).

In this regard, the growing and emerging branch of consumer neuroscience (Karmarkar & Plassmann, 2019) aims to achieve a better understanding of the neurophysiological aspects that determine consumer choice processes. This is done by integrating neuroscientific methods, findings, and theories into marketing research (Camerer, Loewenstein, & Prelec, 2005; Hubert & Kenning, 2008; Karmarkar, Shiv, & Knutson, 2015; Plassmann, Yoon, Feinberg, & Shiv 2010; Venkatraman, Clithero, Fitzsimons, & Huettel, 2012). Neuroscience measurements may have an advantage over surveys and self-reports about potential biases (Camerer & Yoon, 2015; Kenning & Plassmann, 2005; Plassmann, Huettel, & Yoon, 2015; Plassmann et al. 2010).

Several studies from consumer neuroscience already exist that investigate different aspects of prices, such as consumers' willingness to pay (i.e., Plassmann, O'Doherty, & Rangel, 2007) and the decision parameter within buying processes in consumer behavior (i.e., Knutson, Rick, Wimmer, Prelec, & Loewenstein, 2007; Karmarkar et al., 2015). In addition, components of numerical cognitions offer further insights in connection to the processing of price estimates and information (Raposo, Frade, Alves & Marques, 2018).

First, prices are an integrative part of consumers' willingness to pay—of the maximum amount a person is willing to pay in exchange for a product (Plassmann et al., 2007). Within the valuation processes, preferences (i.e., liking a product) and associated costs refer to a subjective value, which in consequence drives a decision-making process (Bartra, McGuire, & Kable, 2013). Research shows that it is mainly activation in the medial orbitofrontal cortex (mOFC) and the dorsolateral prefrontal cortex (dlPFC) that are correlated with the computation of consumers' willingness to pay (Plassmann et al., 2007).

Second, in relation to subjective valuation (i.e., based on preferences (Plassmann et al., 2007)), explicit prices—for example within buying situations— act as important parameter in these decision-making processes (i.e., Knutson et al., 2007). Indeed, studies find that there are different neural circuits in the brain that respond to the processing of prices (Knutson et al., 2007). If consumers had to make purchase decisions that involved high prices, the medial prefrontal cortex (mPFC) (a brain region important for the integration of gains and losses) was deactivated. At the same time, the insula (a region that relates to the perception of pain and losses) was activated. Anticipatory activation in these brain regions independently predicted the buying decisions of participants (Knutson et al., 2007). The importance of price processing can be supported by a study on price primacy in which the price is presented before the product (Karmarkar et al., 2015). This study shows that the order in which product and price information are presented is significant, which could also be seen in an altered neural activation pattern, especially in the mPFC. If the price information was presented before the product information, people seem to focus more strongly on the monetary worth of a product, whereas viewing products first yielded evaluations associated with product attractiveness or desirability. Thus, participants found products in both conditions similarly attractive, but evaluated the value in a more critical way in the price primacy condition (Karmarkar et al., 2015). Nevertheless, prices are not only perceived as costs or losses, but can also be an indicator of high quality, as indicated by a study modulating activity in the mOFC which, in consequence, also increased the experienced utility during consumption of the product (Plassmann, O'Doherty, Shiv & Rangel, 2008) (see studies 6–11 in Table 1 for an overview of selected studies from the field of consumer neuroscience).

Third, in relation to an implicit processing of prices, research on numerical cognition, (especially with regard to aspects of price estimation) needs to be acknowledged. Current literature reveals that higher prices require more estimation time and yield increased activation in the medial and lateral PFC, which might indicate that more cognitive and neural resources are necessary for estimating high prices. Furthermore, activity in the interparietal sulcus (IPS) and surrounding areas reflect the precision of price estimates (Raposo et al., 2018).

Against this background and in accordance with behavioral research, an important aspect within these studies is the relative nature of price processing. This area of research bases decisions on price perception in relation to respective preferences for a given product (Knutson et al. 2007; Karmarkar et al., 2015). Thus, participants in the studies evaluated prices in comparison to their personal willingness to pay for the same product—modulated by a price differential (i.e., the difference between what the subject was willing to pay and the displayed price of the product; Knutson et al., 2007). The relative nature of price processing also holds true for price estimations, when participants were asked to estimate the price for a given product (Raposo et al., 2018). The evidence on price processing from these studies suggests that underlying memories (implicit and explicit), with regard to current and former price information, may play a crucial role in establishing preferences, decisions and estimates in valuation processes (Bartra et al., 2013; Knutson et al., 2007; Weber et al., 2007). However, the majority of the studies on this topic rely on an adjustment of preferences and perceived price values for a single same product, and are mainly focused especially on product preferences (Knutson et al., 2007; Karmarkar et al., 2015), but do not include a potential influence of formerly evaluated product-price decisions (Knutson et al., 2007). Weber et al. (2007) neural investigation on reference dependence in real-market transactions represents a notable exception: the authors show different neural activations associated with satisfaction statements when the evaluation is framed by a high external reference price instead of a lower internal reference price. In their study task, they do not model the reference prices used as memory-based anchors, but they explicitly integrate them into the experimental protocol. In contrast to that procedure, and scaling it to a broader scheme, evaluations of previous price information that were irrelevant for a current product-price decision could instead be relevant due to an "anchoring" of decisions, a process based on consumers' memory (Jacowitz & Kahneman, 1995; Weber et al., 2007).

With the prior research as a basis, we used an experimental fMRI study to assess how prices and components of task-dependent price memory, by integrating price differentials (the explicit component) and aspects of learned prices (the implicit component), affect the choice process and neural activation. With regard to these components of task-dependent price memory, we assumed that during our tasks, as part of the many decisions the participants would make in the course of our experiment, they would integrate the knowledge of the seen range of prices into their decisions, and would adjust their positive and negative choices. From the integration of task-dependent price memory components, we set out to clarify the following research questions (RQ):

Our first research question (RQ 1) pertains to our expectations with regard to neural activation in response to product-price decisions. Accordingly, we ask: Are there neural activity changes in brain regions associated with the integration of background (price) memory, decision-making, and information processing depending on a specific product-price decision?

The second research question (RQ 2) integrates our prospects with regard to neural activation in response to price differentials and the aspect of learned prices: Are there neural activity changes in regions associated with information and memory processing, but distinguishable between an explicit and implicit component?

3. Methodology

3.1. Participants

Eleven female and nine male subjects, all healthy and right-handed, participated in the fMRI study ($M_{age} = 41.85$ years, $SD = 3.884$, range = [35, 50]. There were no gender differences in age, $t(18) = -0.073$, $p = .942$). Using Yes/No indicators, participants were prescreened for familiarity with the target brand of the study, and for their current purchase behavior for that target brand. Thus, only participants who were familiar with the target brand and current customers of that brand were included. With regard to the fMRI-experiment, standard exclusion criteria for MR examinations were applied. All participants provided written informed consent prior to the scanning sessions. The participants were informed that the examination could potentially reveal medically significant

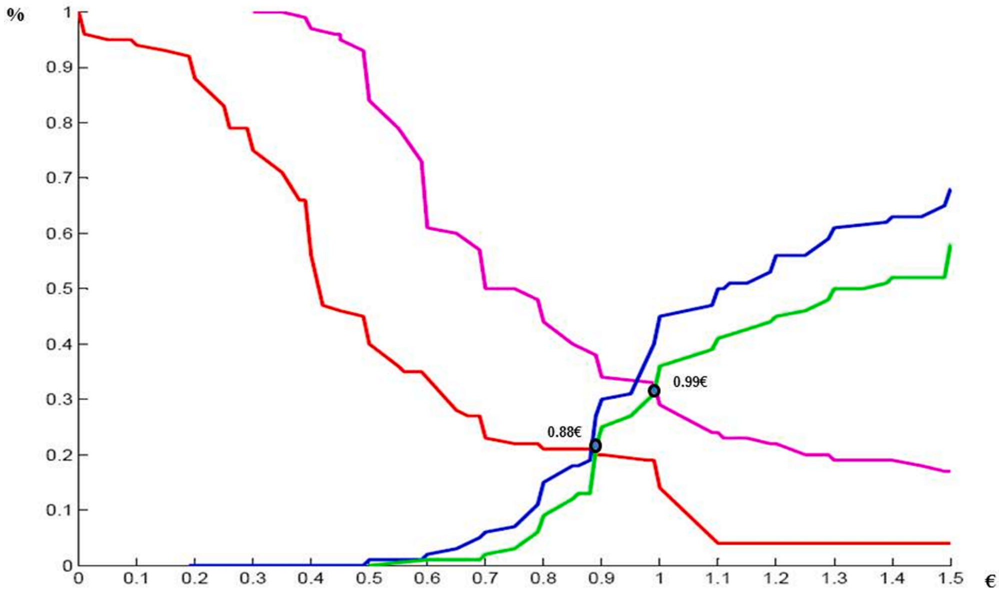

Fig. 1. Plotted price curves according to van Westendorp (1976) with *red line*: too cheap; *pink line*: cheap; *blue line*: expensive, *green line*: too expensive; *intersection of red/blue*: lower price threshold; *intersection of pink/green*: upper price threshold. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

findings, and they were asked whether they would like to be notified in such a case. An ethics commission approved this study.

After the experiment, participants completed a questionnaire with questions regarding 1) their buying frequency of the target brand (M = 3.4, SD = 1.10; with 1 = zero times to 5 = >3 times; no gender differences: t(18) = 0.160, p = .875); 2) their own responsibility for the purchase (M = 6.05, SD = 1.32; from 1 = totally disagree to 7 totally agree; no gender differences: t(18) = −1.577, p = .132); 3) their involvement with the product category (M = 5.6, SD = 1.31; from 1 = totally disagree to 7 totally agree; no gender differences: t(18) = −1.175, p = .255); and 4) their perceived price knowledge of the product category (M = 3.8, SD = 1.15; from 1 = totally disagree to 7 totally agree; no gender differences: t(18) = −1.722, p = .102).

3.2. Stimulus material

With regard to the stimulus material, we wanted to avoid confounding neural activation as a response to product preferences or attractive packaging (Hubert, Hubert, Florack, Linzmajer, & Kenning, 2013; Knutson et al., 2007; Stoll, Baecke, & Kenning, 2008). Therefore, we decided to concentrate on one target brand from one product category (a can of cat food), with slight variation only in product presentation (10 product variations). In order to determine realistic prices and price variability, in a pretest we asked 127 participants within the age group of 35 to 49 years to state their individual price perception (too cheap, cheap, expensive, or too expensive) for different product-price combinations. All participants were pre-screened for familiarity with and prior use of the brand. According to the method of van Westendorp (1976), we plotted the calculated price curves and price levels with regard to the individual price perceptions, and extracted the price range with specific lower and upper price thresholds. This resulted in a lower price-threshold of 0.88€ and an upper price-threshold of 0.99€ (see Fig. 1).

In order to have more variance in the fMRI-study, we took the lower-price threshold (0.88€) and subtracted 5%, 10%, and 25%. Accordingly, we added 5%, 10% and 25% to the upper-price threshold (0.99€). The outcome was a price range of nine prices, from 0.66 € to 1.24 €. Using the ten product variations and the nine prices for the fMRI-experiment, participants were asked to evaluate 90 different product-price combinations.

Importantly, we tried to rule out effects referring to structural features of numbers (i.e., the auditory verbal code and the visual Arabic code, as well as the analogue magnitude code) that have been shown to influence consumers' immediate memory for prices (Vanhuele et al., 2006).

3.3. Experimental setup

While we measured the brain activity of our participants, a product-price-decision experiment was applied, which is based on a common SHOP task (i.e., "Save Holdings Or Purchase"; see for example: Knutson et al., 2007). The task consisted of three major phases. In the first phase (*product perception*; fixed time interval of 4 s), only pictures of the product were shown. In the second phase (*price information*; fixed time interval of 4 s), participants saw the product image together with the price information (below), and in the third phase (*decision*; flexible time interval of 4 s (blanked out after decision)) participants again saw the product image and the price information, with two decision options. Participants had to decide (hypothetically) whether or not they would buy the product for the

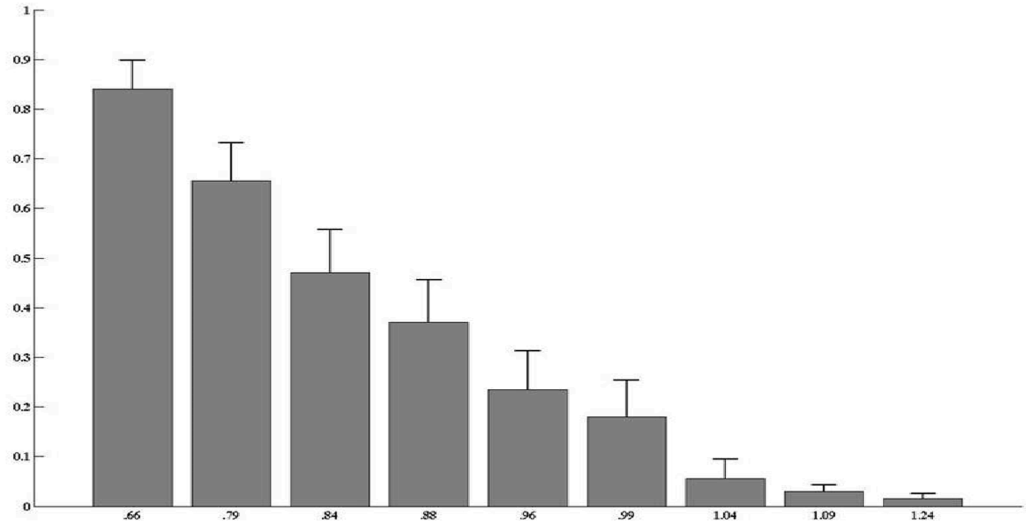

Fig. 2. Share of positive decisions for each price level from 0.66€ to 1.24€. Note: Product variations showed no effect on positive choices ($F(9, 80) = 0.126$, $p = .999$).

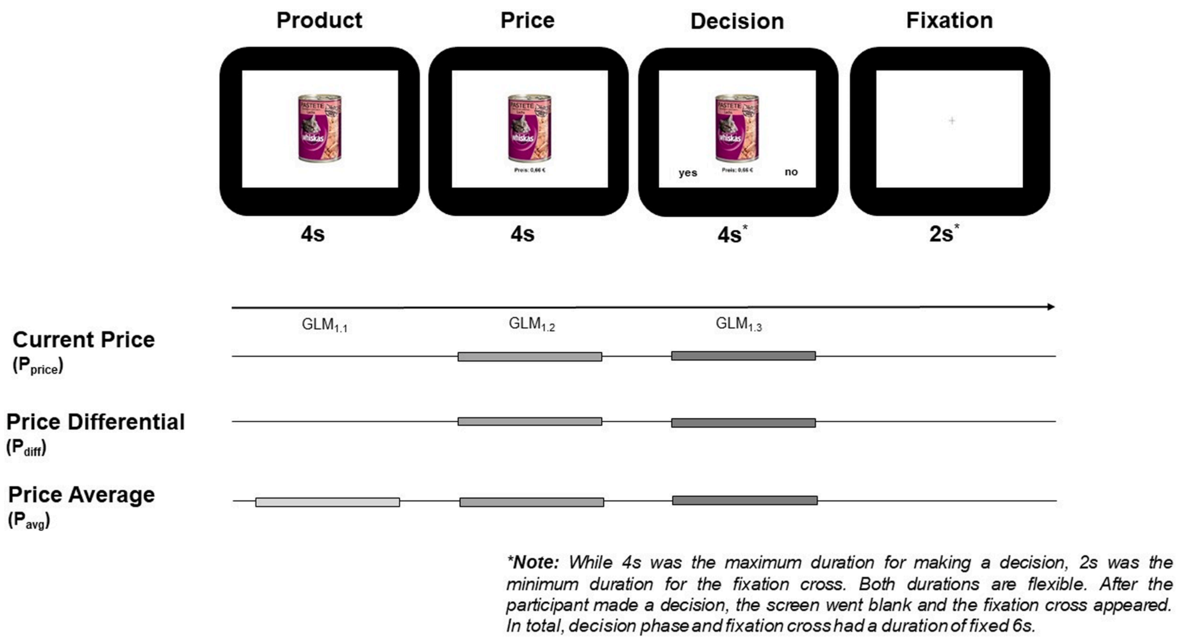

Fig. 3. Overview of a product-price combination trial (product, price, and decision phases) and the corresponding parametric modulators for the subsequent fMRI analyses with only P_{avg} modeled with the product phase (where no current price level is shown) and with $P_{price,\ diff,\ and\ avg}$ modeled within the price and decision phases.

given price. They were directed to press one of two corresponding buttons on a magnetic resonance compatible response box, indicating whether or not they would consider buying the product shown for the given price. We recorded the responses by using COGENT software. After participants pressed the button, the image disappeared and they saw a fixation cross (minimum time interval of 2 s) for the rest of the duration (=time interval fixation cross plus remaining decision time). They were then presented with the next product perception/price information decision combination, and the displays continued in the same form. Within the fMRI-experiment, the images were projected on a transparent screen with an LCD beamer, and were viewed from the other side via a 45° mirror mounted on an element phase array coil. Further, the images were selected for equal size, position, background, and luminance in order to prevent external confounding visual stimulation.

After the experiment, we calculated the mean assessment (share of positive choices) for each price level [0.66€ to 1.24€], with 0 = 0% positive choices to 1 = 100% positive choices. In general, price levels evidenced shares of positive choices>0% (see Fig. 2 for a

Table 2
Individual shares of positive decision for each participant and price level (between 0 and 1).

Participant	0.66	0.79	0.84	0.88	0.96	0.99	1.04	1.09	1.24
1	1	0.8	0.8	0.7					
2	0.9	0.2	0.1			0.1	0.1	0.1	0.1
3	1	0.2	0.1	0.1					
4	0.8	0.8	0.8	0.9	0.9	0.8	0.8	0.1	
5	1	0.7	0.2	0.1					
6	1	1							
7	1	0.5	0.1						
8	0.8	0.8	0.8		0.1				
9	1	1	0.9	0.9	0.1	0.1			
10	0.4	0.4	0.6	0.4	0.5	0.4	0.1	0.1	0.2
11		0.3	0.9	0.4	0.8	0.2			
12	1	0.9	1	1	0.9	1		0.2	
13	0.9	0.1							
14	1	0.9	0.8	0.8	0.2				
15	1	1	0.1						
16	0.6	0.5	0.6	0.6	0.4	0.1	0.1		
17	0.7	1	0.8	0.8					
18	0.7	1	0.8	0.7	0.8	0.9		0.1	
19	1	1							
20	1								

distribution of share of positive decisions).To check for behavioral differences in positive judgments between the selected prices, we entered the shares of positive choices for each price level and gender as between subject factors into a one-way ANOVA (with price level: [0.66€:1.24€]) corrected for repeated measures using the Greenhouse-Geisser (GG) correction criterion. We found a significant main effect for price; $F(3.011, 54.189) = 26.150$, $p < .001$, $\eta p2 = 0.592$, but no main effect for gender; $F(1, 18) = 0.243$, $p = .628$, $\eta p2 = 0.013$, as well as no interaction effect of price*gender; $F(3.011, 54.189) = 0.074$, $p = .425$, $\eta p2 = 0.023$.

Additionally, we created and assessed three price parameters for use as parametric modulators within the fMRI analyses. First, the *price parameter (P_{price})* reflects the current absolute price at a given product-price combination. Thus, P_{price} (t) = price level (t). Second, based on the assumption of participants' explicit price recall (an explicit component of price memory) (Monroe & Lee, 1999), we created a *price differential parameter (P_{diff})* similar to an n-back task (Conway et al., 2005; Jaeggi. Buschkuehl, Perrig & Meier, 2010). The price differential (P_{diff}) is defined as the difference between a participants' price memory of the price level of a product-price combination previously seen, and the current product-price combination. Thus, P_{diff} (t) = price level (t−1) – price level (t). While a positive price differential ($P_{diff} > 0$) corresponds to a cheaper product in the current trial (t), a negative price differential ($P_{diff} < 0$) corresponds to a more expensive product in the current trial (t). Third, based on the assumption of a participants' implicit price learning through the experiment (an implicit price memory component) (Monroe & Lee, 1999), we created a *price average parameter (P_{avg})*. The price average *(P_{avg})* is defined as the average of all price levels seen in a product-price combination, exclusive of the current trial (t). Thus, P_{avg} (t) = mean (price level (1:t−1)). On this basis, we focus on the memorization process of consumers by using the operationalization of our price knowledge components, extending prior research on comparison processes of external and internal reference prices (Weber et al., 2007), knowledge outputs in the form of computed price knowledge measures (cf., behavioral studies in Table 1), and preference-dependent price evaluations (e.g., Knutson et al., 2007).[1] Fig. 3 gives an overview of the experimental procedure and subsequent use of the parametric modulators for the fMRI analyses with regard to the different phases.

3.4. FMRI data acquisition

Data acquisition. The study was executed on a 3 T fMRI-scanner (Magnetom Trio, SIEMENS, Erlangen, Germany). Gradient echo T2*-weighted echo-planar images (EPIs) with blood oxygen level–dependent (BOLD) contrast were acquired. The data set used in this study consisted of 36 transversal slices of 3.6 mm thickness without a gap, a field of view of 230 mm × 230 mm, and an acquired matrix with 64 × 64 (i.e., isotropic voxels with 3.6 mm edge length). Contrast parameters were a repetition time (TR) of 3000 ms, an echo time (TE) of 50 ms, and a flip angle of 90°. Whole-brain high-resolution T1-weighted structural scans (1 × 1 × 1 mm) were acquired from every subject.

Data preprocessing. We conducted the data analysis with the SPM12 freeware (Friston, 1996; Friston et al., 1994; Wellcome Trust Centre for Neuroimaging, London, UK, http://www.fil.ion.ucl.ac.uk/spm/software/spm12) using MatLab as a working base. Functional images were realigned and resliced to the mean image of the session, slice-timing (TA = 2.917; interleaved-ascending slice order, referenced to the middle slice) corrected, coregistered to the participants' T1-weighted high resolution structural image and normalized (new normalization in SPM12) to the individual mean EPI template before segmenting according to the individual T1 scan. Normalized images were smoothed with an 8-mm width at half isometric Gaussian kernel. Intensity normalization and high-pass

[1] We want to express our gratitude to one of the anonymous reviewers, who brought to our attention this important differentiating factor regarding existing research on price knowledge.

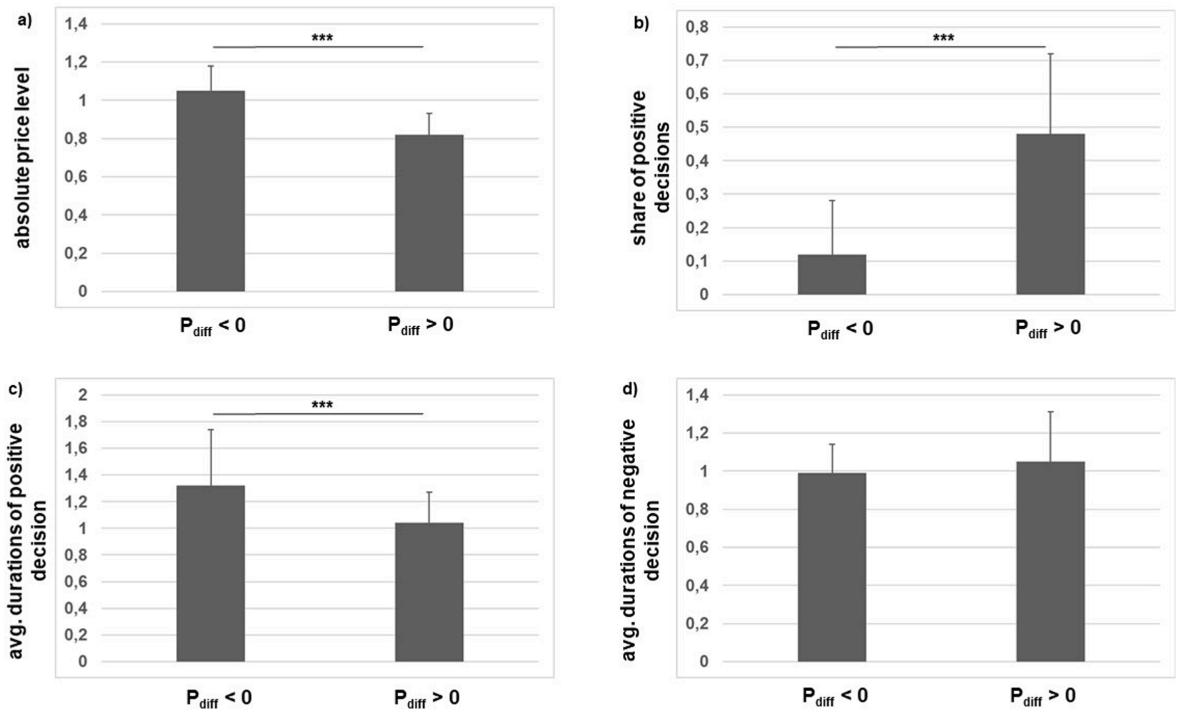

Fig. 4. Test for significant differences between negative and positive price differentials (P_{diff}) for a) the absolute price level, b) share of positive decisions, c) avg. duration of positive decisions and 4) avg. duration of negative decisions.

temporal filtering (using a filter width of 128 s) were also applied to the data.

4. Analyses and results

4.1. Behavioral analyses and results

First, by plotting shares of positive decisions for each price level and participant, we could observe inconsistent judgments, which indicates the assumed integration of price memory generated within the experiment. While mainly consistent decisions would imply an equal or lower share of positive decisions for a higher price level as compared to a lower price level (i.e., share of positive decision for 0.79€ should be equal to or smaller than the share of positive decisions for 0.66€), inconsistent decisions would deviate from this behavior (see Table 2 for an overview).

Second, based on a differentiation between negative price differentials ($P_{diff} < 0$) and positive price differentials ($P_{diff} > 0$), we checked for significant differences of 1) the absolute price level, 2) share of positive decisions, 3) average duration for positive decisions, and 4) average duration for negative decision with regard to the respective product-price combination in a current trial (t). We found significant differences between positive price differentials ($P_{diff} > 0$) and negative price differentials ($P_{diff} > 0$) for: 1) current prices ($t(79) = 8.64$, $p < .001$); 2) share of positive decisions ($t(79) = -7.91$, $p < .001$); and 3) average duration for positive decisions ($t(66) = 3.55$, $p = .001$). We did not find significant differences for 4) the average duration of negative decisions ($t(79) = -1.03$, $p = .308$). (See Fig. 4).

4.2. FMRI data analyses and results

Main analyses. With regard to the fMRI main analysis, we estimated mixed-effect general linear models of the BOLD activity within three steps.

First, for each subject, we estimated three general linear models ($GLM_{1.1}$ (product phase), $GLM_{1.2}$ (price phase), and $GLM_{1.3}$ (decision phase)) (see Fig. 2), with robust WLS (Diedrichsen & Shadmehr, 2005) and the following independent variables.

For $GLM_{1.1,}$ independent variables are: (R1) indicator variable for the product presentation (product phase), (R2) indicator variable for product presentation parametrically modulated by the price average (P_{avg}), (R3) indicator variable for price information (price phase), (R4) indicator variable for decision trials (decision phase), and (R5–R11) six movement regressors and session constant. Regressors R1-R3 were modeled using boxcar functions with a duration of 3.5 s. Regressor R4 was modeled using a boxcar function with durations equal to the subject's response time in that trial. Each of the regressors of interest (R1–R4) were convolved with a canonical hemodynamic response function.

Table 3
Overview of regions with activity corresponding to the contrasts of interest.

Parameter	Region	Side	No. of voxels	BA	MNI Coordinates of peak voxel			T-score
GLM$_{1.1}$: Product Perception								
P_{avg}	No significant voxel cluster at $p < .001$ (uncorrected)							
	Medial frontal gyrus	L	96	10	−14	48	12	3.67*
	Medial frontal gyrus	L	13	10	−4	56	4	3.41*
	Superior frontal gyrus	L	22	10	14	54	2	3.22*
GLM$_{1.2}$: Price Information								
P_{price}	Precentral gyrus	R	31		58	−4	38	−4.63
	Cingulate gyrus	R	16		12	18	40	−4.29
	Cingulate gyrus	L	7	(32)	−14	8	44	−4.05
	Medial frontal gyrus	L	25		−12	−24	52	−4.60
	Precentral gyrus	L	11		−22	−22	66	−3.95
P_{diff}	Inferior occipital gyrus	L	54		−28	−88	−10	−4.56
	Inferior occipital gyrus	R	7	18	34	−86	−10	−3.80
	Inferior frontal gyrus	R	5		38	24	−6	−4.00
	Putamen	L	46		−30	−8	8	4.72
	Precentral gyrus	L	39		−58	6	10	4.47
	Insula	L	5		−30	6	12	3.82
	Middle frontal gyrus	R	19	10	44	48	14	−4.32
	Inferior frontal gyrus	R	161	9/46	50	18	24	−5.65
	Supramarginal gyrus	L	90	40	−38	−44	38	−4.84
	Precentral gyrus	R	17	6	42	−8	38	4.21
	Precuneus	L	153		−22	−64	38	−4.60
	Superior parietal lobule	R	58	7	32	−56	54	−4.32
	Medial frontal gyrus	R	7	8	6	50	48	−3.99
P_{avg}	**Insula**	L	18	13	−26	20	−4	4.01
	Caudate	R	10		20	22	0	3.87
	Caudate	L	19		−22	32	−2	4.16
	Medial frontal gyrus	L	12	(10)	−18	48	8	4.09
	Medial frontal gyrus	L	11		−8	−26	60	4.06
GLM$_{1.3}$: Decision trial								
P_{price}	No significant voxel cluster at $p < .001$ (uncorrected) with $k = 5$ or at $p < .005$ (uncorrected) with $k = 10$							
P_{diff}	Inferior occipital gyrus	R	9	18	36	−86	−8	−3.89
	Middle occipital gyrus	L	28		−36	−88	0	−4.49
	Superior temporal gyrus	R	14	22	46	−14	−6	4.18
	Precentral gyrus	L	67		−58	2	10	5.15
	Cingulate gyrus	R	20		14	−4	34	−4.76
	Precuneus	R	7		28	−66	36	−3.69
	Precentral gyrus	L	19		−42	−18	42	4.13
	Precentral gyrus	L	17	4	−20	−26	56	4.07
P_{avg}	No significant voxel cluster at $p < .001$ (uncorrected; $k = 5$) or at $p < .005$ (uncorrected; $k = 10$)							

*Note: These regions were extracted with $p < .005$ [uncorrected] and an extent threshold of $k = 10$ voxel.

For GLM$_{1.2,}$ independent variables are: (R1) indicator variable for the product presentation (product phase), (R2) indicator variable for price information (price phase), (R3) indicator variable for price information parametrically modulated by the current price (P_{price}), (R4) indicator variable for price information parametrically modulated by the price differential (P_{diff}), (R5) indicator variable for price information parametrically modulated by the price average (P_{avg}), (R6) indicator variable for decision trials (decision phase), and (R7–R13) six movement regressors and session constant. Regressors R1-R5 were modeled using boxcar functions with a duration of 3.5 s. Regressor R6 was modeled using a boxcar function with durations equal to the subject's response time in that trial. Each of the regressors of interest (R1–R6) were convolved with a canonical hemodynamic response function.

For GLM$_{1.3,}$ independent variables are: (R1) indicator variable for the product presentation (product phase), (R2) indicator variable for price information (price phase), (R3) indicator variable for decision trials (decision phase), (R4) indicator variable for decision trials parametrically modulated by the current price (P_{price}), (R5) indicator variable for decision trials parametrically modulated by the price differential (P_{diff}), (R6) indicator variable for decision trials parametrically modulated by the price average (P_{avg}), and (R7–R13) six movement regressors and session constant. Regressors R1-R2 were modeled using boxcar functions with a duration of 3.5 s. Regressors R3-R6 were modeled using a boxcar function with durations equal to the subject's response time in that trial. Each of the regressors of interest (R1–R6) were convolved with a canonical hemodynamic response function.

Second, we calculated first-level single-subject contrasts for GLM$_{1.1}$ with regard to regressor R2 versus baseline; for GLM$_{1.2}$ with regard to regressors R3-R5 versus baseline; and for GLM$_{1.3}$ with regard to regressors R4-R6 versus baseline.

Third, for each of the first-level contrasts from GLM$_{1.1\text{-}1.3}$, we estimated second-level mixed-effects analyses by computing a one-sample *t*-test on the coefficients of each single-subject contrast. Results are reported and visualized at a level of $p < 0.001$ (uncorrected) with an extent threshold of $k = 5$ by using the xjView toolbox (https://www.alivelearn.net/xjview). Anatomical localizations were visualized by overlaying the t-maps on a structural T1-template provided by the xjView toolbox (https://www.alivelearn.net/xjview).

Results. With regard to GLM$_{1.1}$ (product phase), no significant cluster was observed for the price average (P_{avg}) as parametric

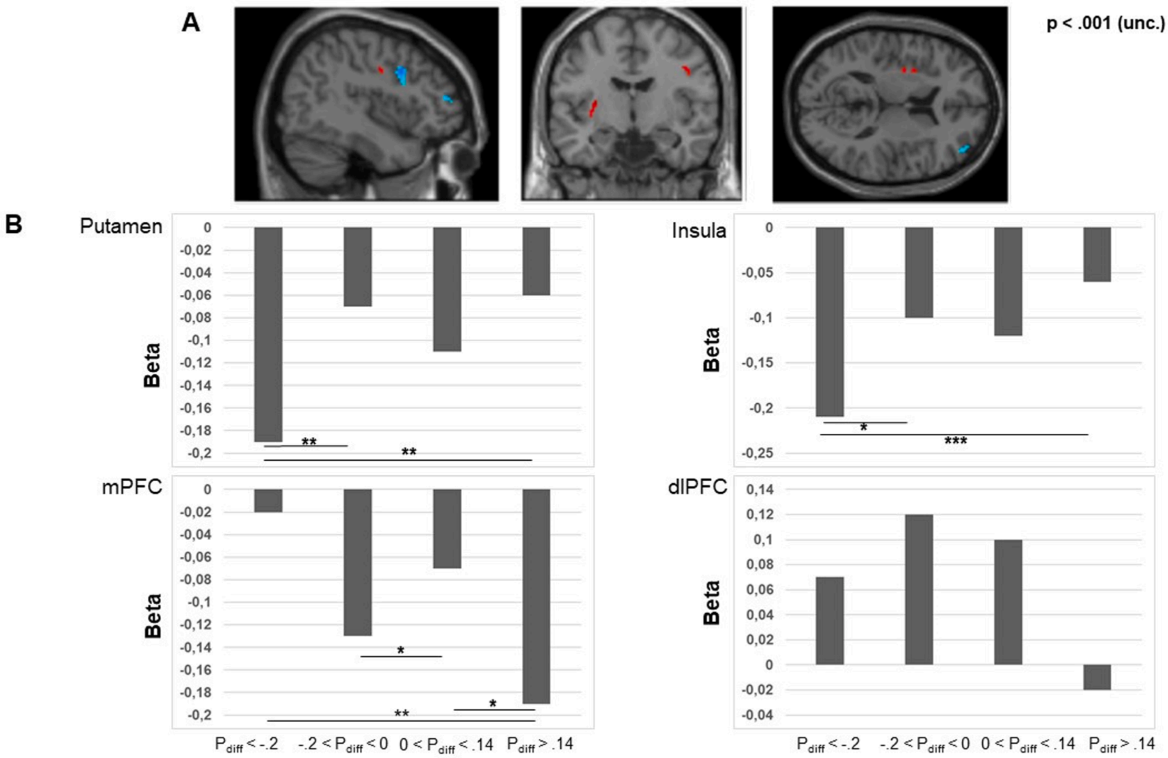

Fig. 5. (A) Activated regions correlating with values of the price differential during the price phase ($GLM_{1.2}$) are related to left putamen (−30,−8,8), left insula (−30,6,12), right mPFC (44,48,14), and right dlPFC (42,10,38). (B) Beta plots for these four areas showing differences with regard to quartiles of the price differential extracted from $GLM_{2.1}$within the putamen, insula, and mPFC, but not the dlPFC. Significance levels for paired t-tests: *$p < .05$, ** $p < .01$, ***$P < 0.001$.

modulator for $p < .001$ (uncorrected). However, if we applied a more liberal threshold of $p < .005$ (uncorrected) with an extent threshold of $k = 10$, we found a positive correlation of the left medial prefrontal gyrus (BA 10) with increasing values of price average (see Table 3).

With regard to $GLM_{1.2}$ (price phase), regions with activity correlated with the current price (P_{price}) were observed mainly within the left and right cingulate gyrus and the left medial frontal gyrus. Regions with activity correlated with values of a price differential (P_{diff}) were, in addition to others, the left putamen, the left insula, the right middle frontal gyrus (BA10), and the right inferior frontal gyrus (BA9). Regions with activity correlated with values of the price average (P_{avg}) were the left anterior insula (BA 13), the right caudate, and the left caudate (see Table 3).

With regard to $GLM_{1.3}$ (decision phase), neither the P_{price} nor P_{avg} showed significant correlated activity for both, with a threshold level of $p < .001$ (uncorrected; $k = 5$) and $p < .005$ (uncorrected, $k = 10$). Regions with activity correlated with the price differential (P_{diff}*)* are associated mainly with areas of visual and language processing, such as the observed activation within the right inferior occipital gyrus (BA 18) and the right superior temporal gyrus (BA 22) (see Table 3).

Post-hoc analyses. First, post hoc tests of neural activity changes in regions of interest (ROIs) identified by the second-level group mixed-effects analyses for $GLM_{1.2}$ (price phase) with regard to the price differential (P_{diff}) (putamen, insula, mPFC (BA10) and dLPFC (BA9)) and with regard to the price average (P_{avg}) (insula (BA 13) and caudate) were computed. By running three additional GLMs $_{(GLM2.1\text{-}2.3)}$ modeled with robust WLS (Diedrichsen & Shadmehr, 2005) that separated regressors within (1) $GLM_{2.1}$ with regard to the price phase by distinguishing four unique price differentials (R2-R5)(based on quartiles: $P_{diff} < -0.2€$; $-0.2 <= P_{diff} < 0$; $0 <= P_{diff} <= 0.14$; and $P_{diff} > 0.14$) ($GLM_{2.1}$); within (2) $GLM_{2.2}$ with regard to the decision phase by distinguishing negative (D−) and positive decision (D+) (R3-R4); and within (3) $GLM_{2.3}$ with regard to the decision phase by distinguishing negative and positive choices (D−, D+) for negative price differentials ($P_{diff} < 0$) and positive price differentials ($P_{diff} > 0$) (R3-R6).

Second, we then calculated the first-level single-subject contrasts of interest for $GLM_{2.1}$ (R2-R4), $GLM_{2.2}$ (R3-R4) and $GLM_{2.3}$ (R3-R6) and extracted the parameter estimates for an independent regions-of-interest (ROI) based on results from the analysis of our first model by following the procedure in Litt, Plassmann, Shiv, and Rangel (2011). In more detail, for each subject *j* we identified a peak voxel for the contrast of interest by selecting the voxel within the region of interest that exhibited peak activity for the contrast in a mixed-effects analysis that included all subjects except *j* (see Litt et al., 2011). For each subject we computed an average parameter estimate over the sessions using a spherical mask centered on the MNI coordinates with an 8 mm radius (see e.g., Karmarkar et al., 2015; Knutson et al., 2007).

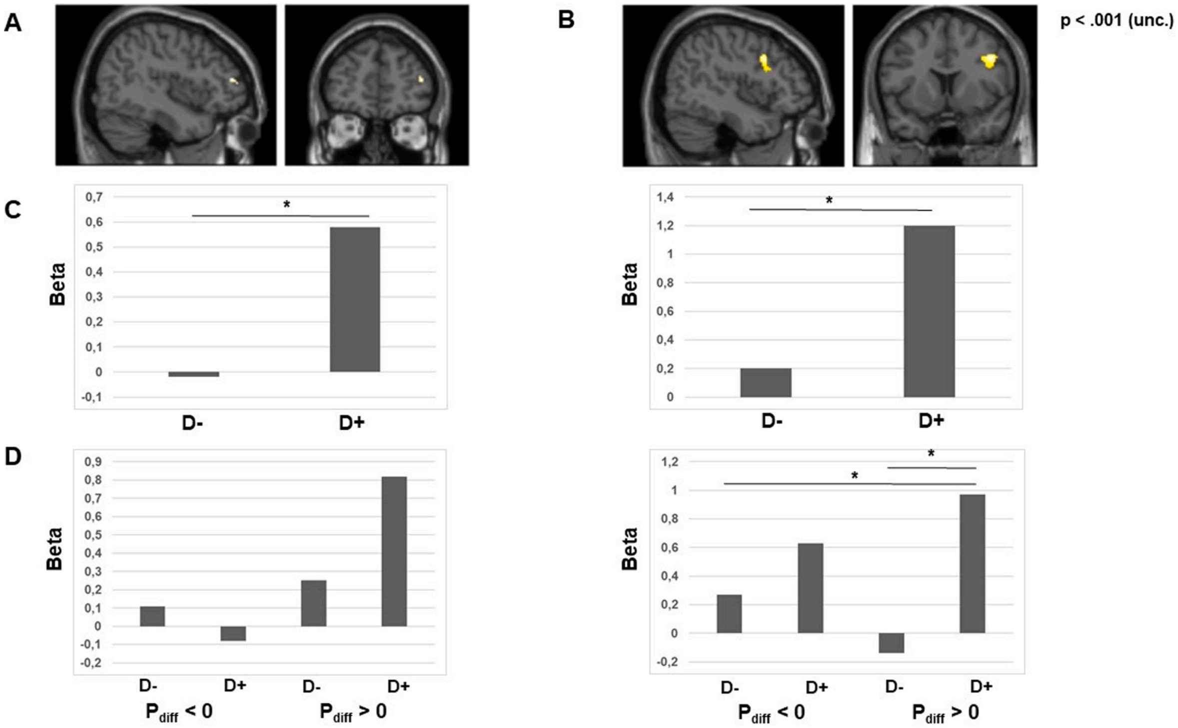

Fig. 6. (A) Activated right mPFC (44,48,14) correlated with values of the price differential during the price phase ($GLM_{1.2}$). (B) Activated right dlPFC (42,10,38) correlated with values of the price differential during the price phase ($GLM_{1.}$ (C) Beta plots for these two areas showing differences with regard to negative decisions (D−) and positive decisions (D+) extracted from $GLM_{2.2}$. (D) Beta plots for these two areas showing differences with regard to negative decisions (D−) and positive decisions (D+) for negative ($P_{diff} < 0$) and positive price differentials ($P_{diff} > 0$) extracted from $GLM_{2.3.}$ Significance levels for paired t-tests: *p < .05, ** p < .01, ***P < 0.001.

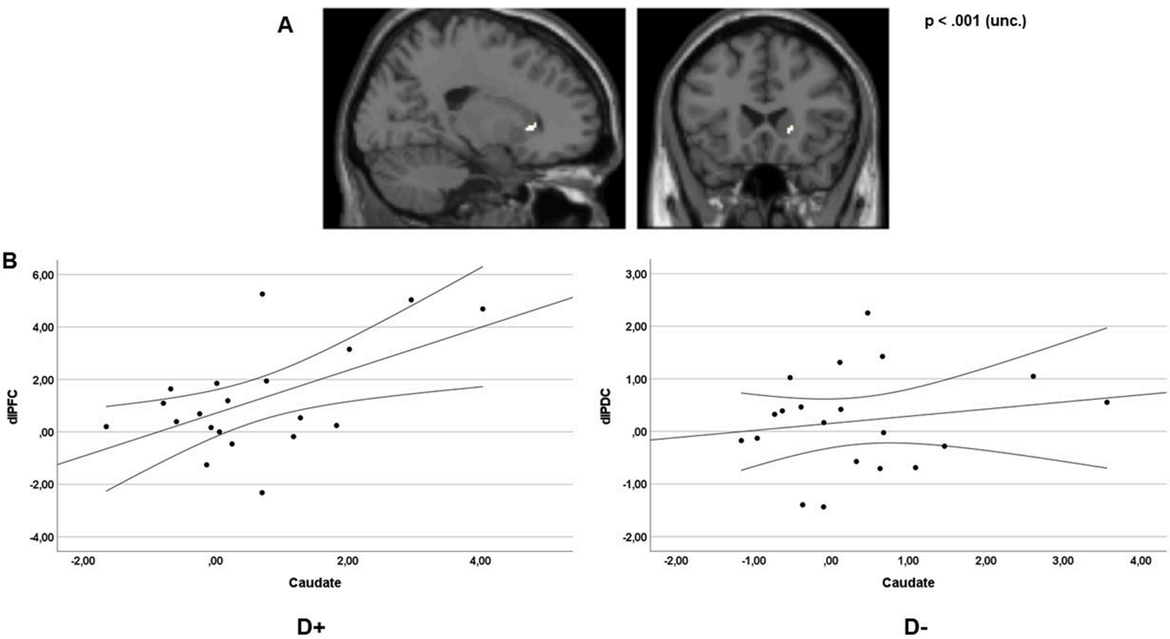

Fig. 7. (A) Activated right caudate (20,22,0) correlated with values of the price average during the price phase ($GLM_{1.2}$). (B) Beta plots for this area correlated with beta plots of the activated dlPFC showing significant correlations with regard to positive decisions (D+) (r = 0.40, p = .038) (left) but not negative decisions (D−) (r = 0.26, p = .284) (right) extracted from $GLM_{2.2.}$

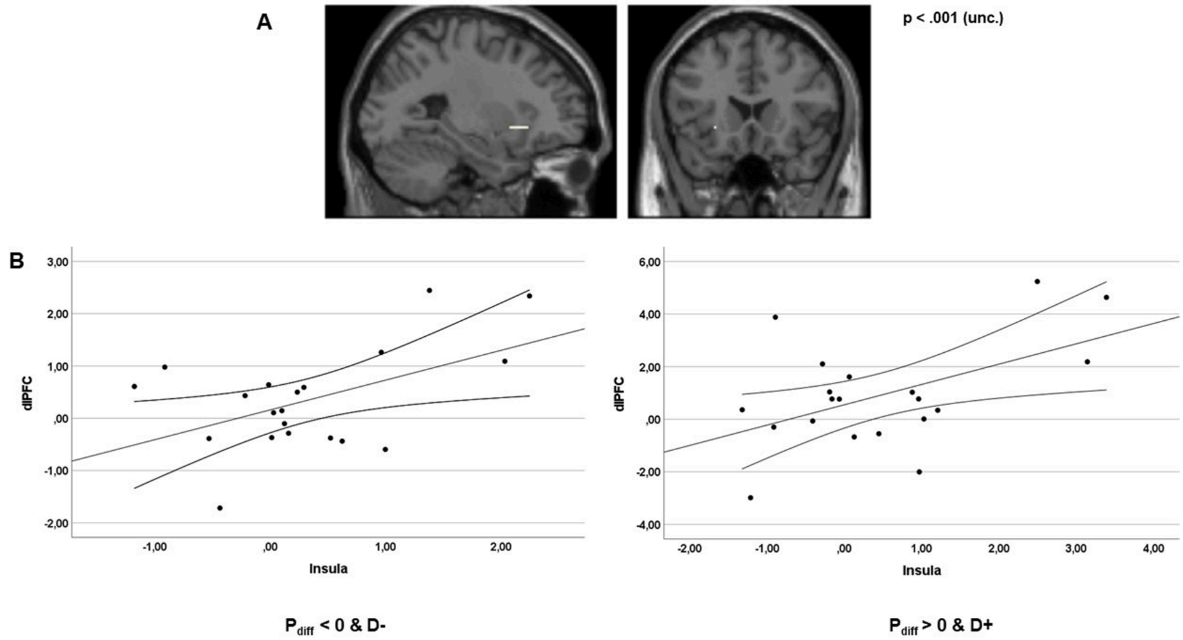

Fig. 8. (A) Activated left anterior insula (−26,20,−4) correlated with values of the price average during the price phase ($GLM_{1.2}$). (B) Beta plots for this area correlated with beta plots of the activated dlPFC showing significant correlations with regard to negative decisions (D−) and negative price differentials ($P_{diff} < 0$) ($r = 0.51$, $p = .023$) (left), and with regard to positive decisions (D+) and positive price differentials ($P_{diff} > 0$) ($r = 0.51$, $p = .021$ (right) extracted from $GLM_{2.3}$.

Third, we then averaged the set of extracted beta values (one for each subject), plotted for each regressor of interest, and tested for significance by applying paired-sample t-tests. The main results of interest are visualized in Figs. 5–8 (see Table A1 in the Appendix for all results).

5. Discussion

We used fMRI to investigate how prices how the encoding of task-dependent price memory affects the decision-making process and corresponding neural activation. Our expectation going into the experiment was that, along with the many decisions required through the course of the experiment, participants would assemble task-dependent price memory from the range of prices seen, which would help them to adjust their positive and negative choices.

First, in accordance with other studies using a SHOP task (Karmarkar et al., 2015; Knutson et al., 2007), main activations within the price phase are associated with subsequent negative and positive decision trials. Primarily, activations correlated with the price differential in the price phase ($GLM_{1.2}$) are associated with behavioral responses and decision trials. This indicates that processing of prices seen for the first time (within the price phase), with dependence on previous price information, influences subsequent choices (within the decision phase) (Karmarkar et al., 2015; Knutson et al., 2007).

Second and as expected, explicit and implicit aspects of price knowledge are associated with the decision-making processes. Explicit memory modeled as a price differential (P_{diff}) appears to be directly connected to respective decision trials (see Figs. 4-6), while implicit memory generated through learned prices (P_{avg}) seems to have a stronger supportive role, but does not directly influence decision trials (see Figs. 7-8). This neuroscientific evidence connects well to findings from behavioral pricing, as well as from consumer neuroscience research, wherein explicit price knowledge or high external reference prices are more strongly connected to economically relevant constructs reported by consumers, such as customer satisfaction (Homburg et al., 2012; Weber et al., 2007). In addition, self-reported constructs representing a stronger associative learning mechanism such as price consciousness are more strongly connected to implicit price knowledge (Mägi & Julander, 2005).

Third, the lateral parts of the middle frontal cortex (mPFC) and, especially, of the dorsolateral prefrontal cortex (dlPFC) appear to play a major role in informing subsequent decision-making processes (see Fig. 6). While the putamen, the insula, and the mPFC seem to be responsible for processing different levels of price differentials, the dlPFC shows no significant differences in processing various price differentials in the price phase, implying a general processing of price differentials (see Fig. 5). However, by investigating concrete decision trials in the decision phase—distinguishing between negative and positive decisions—activation in the dlPFC not only seems to have an influence on decisions in general (e.g. stronger DLPFC activation in relation to positive decisions) (see Fig. 6C), but has a primary influence on decisions, with regard to negative and positive price differentials (see Fig. 6D).

Both regions (lateral parts of the mPFC and dlPFC) show evidence of relevance during processing price estimates (Raposo et al., 2018), which in our task could be an evaluation of current prices by taking previous prices into account. The dlPFC is associated with using reward information to control behavior (Plassmann et al., 2007; Wallis & Miller, 2003), which is an indication of activation that is particularly related to positive decisions (see Fig. 6). The dlPFC has been shown to be activated in n-back tasks (Owen, McMillan, Laird, & Bullmore, 2005; Rodriguez-Jimenez et al., 2009; Rottschy et al., 2012)—an indication of the price differential (an explicit memory component) essentially influencing product-price evaluations. Furthermore, the dlPFC is associated with working memory (Levy & Goldman-Rakic, 2000) and implementation of cognitive control (MacDonald, Cohen, Locke, Stenger, & Fiez, 2000). This control function might indicate why a participant made a positive decision despite a negative price differential. In particular, this control function might indicate, that the participants sometimes accepted higher prices compared to those in the previous trial, because they may have been influenced by the learned prices/price differentials during the overall experiment (see Figs. 7 and 8).

Fourth, activated regions corresponding to the price average (P_{avg}) within the price phase (the anterior insula and caudate) seem to have a stronger supportive role in relation to decision processes, as evidenced by their significant correlations with the dlPFC (see Figs. 7 and 8). While activity within the *caudate* correlates with activation within the dlPFC for positive decisions, there is no significant correlation for negative decisions (see Fig. 7). In general, the caudate is often associated with reward expectations, emotions, motivated behavior, and action planning, as well as learning and feedback processing (Delgado, Locke, Stenger, & Fiez, 2003; Haruno & Kawato, 2006). Regarding processes of goal-directed behavior, the caudate is involved in reinforcement of an action and supports action-outcome learning. As well, it is activated when the outcome is perceived to be dependent on behavior (action-outcome involvement) (Chiu, Jiang, & Egner, 2017; Grahn, Parkinson, & Owen, 2008; Tricomi, Delgado, & Diez, 2004; Tricomi & Fiez, 2004). Therefore, the integration of learned information from previous trials (P_{avg}) seems to support the processing of positive price differentials relevant for subsequent positive choices.

Observation of the anterior insula reveals a more differentiated picture. Here, significant correlations were detected for negative decisions and a negative price differential, or for positive decisions and a positive price differential. This signals a more complex role of insula activation within price perception and processing. The insula cortex connects the temporal and frontal lobes in the brain (Yaple, Yu, & Arsalidou, 2020). In general, it seems to play an important role for decision-making and learning (Heekeren, Marrett, & Ungerleider, 2008; Palminteri et al., 2012; Singer, Critchley, & Preuschoff, 2009; Thielscher & Pessoa, 2007). With regard to decision-making, studies show that the insula cortex is involved in perception, attention, and cognitive control (Bechara, 2005; Heekeren et al., 2008; Nelson et al., 2010; Sterzer & Kleinschmidt, 2010). It has been observed to be important for driving attentional resources in order to make complex choices (Heekeren et al., 2008), and for reference-based evaluations of risk (De Martino, Kumaran, Holt, & Dolan, 2009). For example, Menon and Uddin (2010) conceptualize anterior parts of the insula as an important part of a “salience network”, because it detects salient events, as well as integrating and mediating dynamic interactions between larger brain networks that are associated with externally oriented attention and internally oriented cognition (Menon & Uddin, 2010). Therefore, it seems that specific learned prices (i.e., high prices, Jensen & Grunert, 2014) trigger salience processes within the insula, which in consequence strengthen the perception of negative price differentials or positive price differentials related to subsequent negative or positive decisions. These observations indicate that a potential negative decision with negative price differentials will be strengthened by implicit price memory confirming potential high prices in the past. In the same way, a potential positive decision with positive price differentials will be strengthened by implicit price memory.

6. Implications

Existing research on non-conscious influences has demonstrated that several external cues in the environment trigger consumer behavior and decision-making, even without consumers being aware of the triggers (e.g., Fitzsimons, Chartrand, & Fitzsimons, 2008). In this study, we show that a physiological state can also influence important decision determinants at a non-conscious level. Classical economic theories on pricing, particularly, suggest the presence of stable preferences for alternative product choices. However, abundant evidence exists to show that consumer preferences are dependent on various situational and contextual factors, as well as on elicitation methods (Dhar, Nowlis, & Sherman, 2000; Mishra & Mishra, 2010; Mishra, Mishra, & Nayakankuppam, 2007). We add to these research findings by suggesting that, due to specific neural activation patterns, price memory is a dynamic construct that is influenced by situational and physiological aspects.

Explicit price memory is more strongly connected to price acceptance and rejection. When customers are accustomed to buying a product, they judge a given product price against a previously seen or remembered price. Given that consumers today are being targeted by a vast range of different promotional mechanisms (e.g., Cheng & Cryder, 2018), particularly those mechanisms that are developing through digitalization and the advent of dynamic pricing (Scheidegger, Linzmajer, & Rudolph, 2020), it is not surprising that these internal reference points do not act as perfect information sources. In addition, choice overload in contemporary retailing leads to imperfect external reference points when consumers try to use price information at the shelf (e.g., Chernev, Böckenholt, & Goodman, 2015). Although price transparency has increased in recent years, consumers have difficulty building explicit price knowledge as a central decision determinant. This reasoning supports the findings from behavioral pricing studies. Explicit price knowledge is limited, but at the same time this limitation does not necessarily follow from underestimating explicit price knowledge that is based on experimental research methods. Explicit price knowledge might be poor in general, given the high number of product prices that consumers must make decisions on every day. From a theoretical perspective, attention may be key to consumers’ informed price decisions.

Implicit price knowledge supports consumers’ price decisions as an emotional gatekeeper. What consumers have learned through prior exposure to given product prices serves as an emotional signal supporting how they explicitly judge what they see. This process of associative learning accompanies consumers throughout their lives, and has the potential to prevent them from accepting odd prices, even if they appear reasonable in a given context. In an extension of studies on behavioral pricing, it can be inferred that factors influencing the neural ability to learn associatively may play a decisive role in impacting the significance of this gatekeeper effect (e.g., Witte et al., 2009). From a theoretical perspective, it is not surprising that most of the determinants investigated in past studies on implicit price knowledge did not show significant effects, as they did not integrate variables affecting the ability to memorize prices implicitly.

With regard to managerial implications of these observations, first, drivers of explicit price knowledge can be used to set higher prices. As Homburg et al. (2012) found, higher customer satisfaction drives lower explicit price knowledge. Given the relevance of explicit price knowledge for pricing decisions, managers could reason that higher customer satisfaction leads to an opportunity to set higher prices.

Second, pricing managers should take into account that consumers' price memory is not limited to an explicit component, which is repeatedly reported to be relatively poor for a wide range of products and across business sectors. One might conclude from these previous studies that price adjustments (e.g., setting higher prices) can be made easily without recognition by consumers. As price is one of the central profit drivers for companies, it is conceivable that pricing managers are interested in transferring these results into practice. However, this study shows that without a clear conceptualization integrating both the explicit and implicit components of consumers' price memory, managers might rapidly destroy price images of their products, as implicit price knowledge might enable customers to judge the attractiveness of prices or price changes.

Third, in times of increasing price transparency, companies may want to differentiate themselves by giving consumers decision aids that take into account the ability-dependent implicit component of price memory.

6.1. Limitations and future research

As in every research project, this study has limitations and unanswered questions that offer avenues for further research. First, the interplay of explicit and implicit price memory processes needs further exploration, e.g. investigating to what degree these components contribute to subsequent choices. We used a dynamic process model in our fMRI study, but future investigations may want to quantify the influence of distinct forms of memory in a real-life setting—that is, at the point of sale in retail environments.

Second, unconscious processes affecting the ability to remember information from information processing might help to explain the greater variance in customers' price knowledge. In this situation, specific hormone balances might influence the ability to remember prices at different points in time. In addition to unconscious processes, emotions are likely to affect price information processing, so that it might be hypothesized that prices can be remembered better if specific emotions are triggered during the confrontation with prices. Because we aimed to ensure that price acted as the crucial decision criterion, our experimental setup employed no variability in brand and product category, and used a pre-screened sample. But future research could incorporate products and price ranges with a higher impulsive potential to discover the interplay of prices with specific emotions.

These and related research gaps might offer favourable and interesting links for further research on consumers' price memory and its influence on subsequent choices. In general, our primarily experimental setup will profit from further academic scrutiny in the field. We wanted to show that consumer and marketing research on the determinants of constructs that have not been well understood can profit from the integration of neuroscience methods and findings. If this consumer neuroscience approach is to succeed, future survey studies will need to show its potential in the broader field by combining neuroscience methods and findings with traditional methods in marketing research.

6.2. Conclusion

This research examines the neurophysiological correlates of consumers' price memory and helps to provide further understanding of the different aspects of consumers' price-dependent decision-making. We focus on different aspects of consumers' price memory and demonstrate the complexity of the antecedents of price-dependent decision-making. The findings of our study add to the field of consumer neuroscience by demonstrating how neural correlates of explicit and implicit task-dependent price memory can shed light on processes that guide consumer decision-making. Qver the course of our experiment we found that consumers did not always make consistent decisions, but that their decisions were influenced by explicit price memory (price differential). Here, especially, activation in the dlPFC seems to be important for making a decision and for integrating explicit price information in the decision phase. More implicit price memory (price average) has a supportive role in the decision-making process, as it can be seen in activation of the anterior insula and the caudate in correlation with the dlPFC.

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Appendix

See Fig. A1 and Fig. A2.

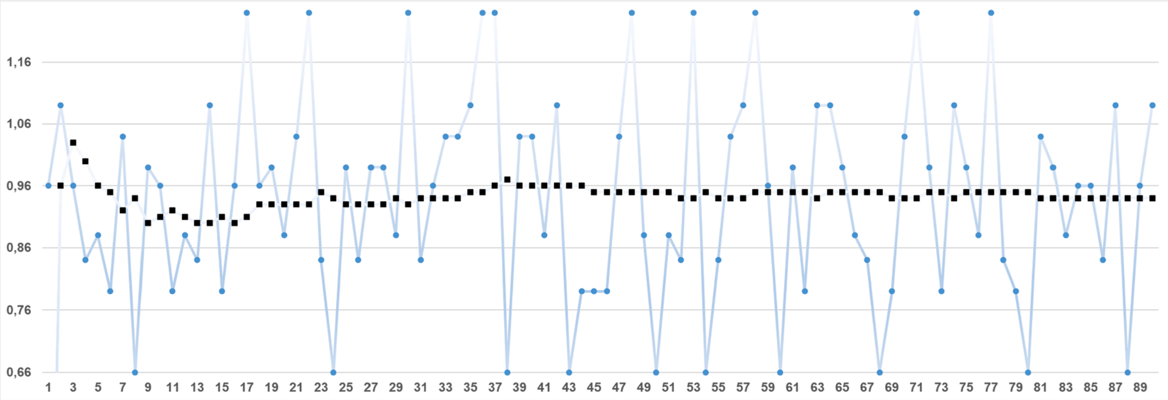

Fig. A1. Visualization of absolute price level (P_{price}; blue [0.66€, 1.24€]) and corresponding price average (P_{avg}; black). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

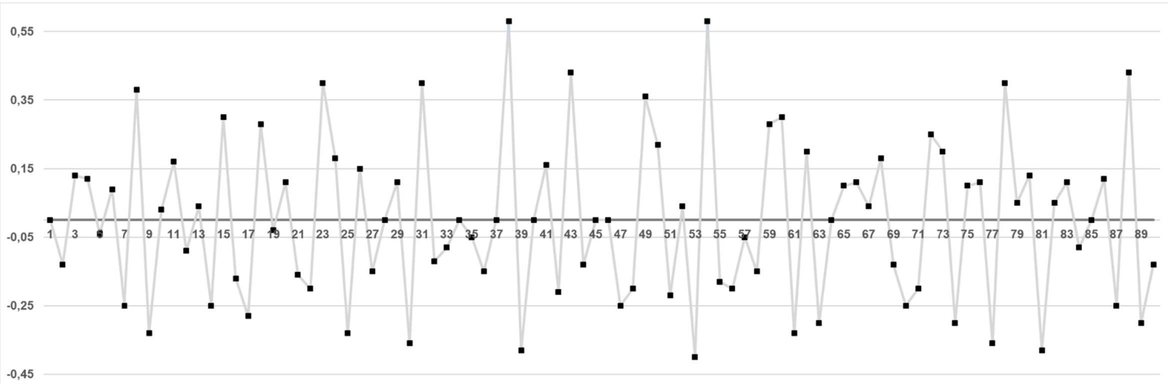

Fig. A2. Distribution of Price Differentials (P_{diff}).

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