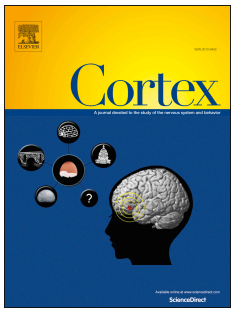

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Zero the hero: evidence for involvement of the ventromedial prefrontal cortex in affective bias for free items

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ABSTRACT

Recent evidence from psycho-economics shows that when the price of an item decreases to the extent that it becomes available for free, one can observe a remarkable increase of subjective utility toward this item. This phenomenon, which is not observed for any other price but *zero*, has been termed the zero-price effect (ZPE). The ZPE is attributed to an affective heuristic where the positive affect elicited by the free status of an item provides a mental shortcut biasing choice towards that item. Given that the ZPE relies on affective processing, a key role of the ventromedial prefrontal cortex (vmPFC) has been proposed, yet neuroscientific studies of the ZPE remain scarce. This study aimed to explore the role of the vmPFC in the ZPE using a novel, within-subject assessment in participants with either an acquired (lesion patients) or degenerative (behavioural-variant frontotemporal dementia patients) lesion of the vmPFC, and age-matched healthy controls. All participants were asked to make a series of choices between pairs of items that varied in price. One choice trial involved an equal decrease of both item prices, such that one of the items was priced zero. In contrast to controls, both vmPFC-lesion and behavioural-variant frontotemporal dementia patients showed marked reductions in zero-related changes of preference in pairs of gift-cards, but not for pairs of food items. Our findings suggest that affective evaluations driving the ZPE are altered in patients with focal or degenerative damage to the vmPFC. This supports the notion of a key role of the vmPFC in the ZPE and, more generally, the importance of this region in value-based affective decision-making. Our findings also highlight the potential utility of affective heuristic tasks in future clinical assessments.

KEYWORDS: Zero Price Effect, vmPFC, bvFTD, Decision-Making, Rationality, cognitive bias.

INTRODUCTION

To better account for real-life human behavior, a consensus emerged between economists and neuroscientists to drastically amend the former's utility maximization theory. The original theory postulated that individuals extract the most expected satisfaction from their economic decision (Von Neumann and Morgenstern, 1944). While more modern psychologically-amended formulations, such as Prospect theory (Kahneman & Tversky, 1979), propose that individuals make decisions based on perceived gains, this still fails to capture some human behaviors, and by extension, their underlying cognitive processes or biases.

As a significant illustration, the "zero-price effect" (ZPE) has been described in the economic literature as a major violation of economic rationality (Shampanier et al. 2007). The ZPE consists of the following phenomenon; consider a situation where people have to choose between two items: one is of a better quality and is *a priori* preferable to the second, but is also more expensive. It has been shown that a marginal and equivalent decrease in the prices of both items, so that the cheaper item becomes free, drastically increases the demand for the free item, even though it is *a priori* less preferred (Shampanier et al. 2007). At an individual level, what the ZPE reveals is an "irrational" perception of the utility of *free* items. Theories of decision-making, such as Utility Theory or Prospect Theory, postulate that decreasing marginally the relative prices of two items by the same amount such that the cheaper and non-preferred item becomes free should not change the order of preference between these items. Therefore, no substantial increase in demand for the now-free item should be observed and thus, no reversal of preferences. However, the ZPE clearly contradicts this view.

Several laboratory and field studies have replicated the ZPE, which is leveraged in business for sales promotion policies, demonstrating that preference toward the low-value item significantly increases when its price becomes free (Nicolau & Sellers, 2011; Driouchi et al., 2011; Hossain & Saini, 2015; Baumbach et al., 2016; Votinov et al., 2016; Ma et al., 2018). In Utility Theory terms, the ZPE could be due to a discontinuity in the perceived utility of money when it reaches zero. In psychological

terms, the ZPE has been interpreted as a special value attributed to a free product, which increases its intrinsic value (Shampanier et al., 2007). In this framework, items with no cost could indeed elicit a more positive affective response than those that are simply endowed with a lower price. This explanation, supported by studies exploring the ZPE through different experimental designs and contexts (e.g. Baumbach, 2016; Voltinov et al., 2016), overlaps with the notion of an affect heuristic, described as a mental shortcut where affect serves as a cue to guide decision making (Finucane et al., 2000; Slovic et al., 2007). In this view, a price equal to 0 would cause a positive affective reaction that would be used by most individuals as a cue to choose that item. This affective response should be substantially higher when an item's price drops, for example, from $1 to $0 as compared as when it falls (by the same magnitude) to a smaller positive price (i.e., from $2 to $1).

If the ZPE does indeed reflect an interaction between affective processes and the perception of value, then the ventromedial prefrontal cortex (vmPFC) may play a key role. Support for this notion comes from a large number of studies demonstrating critical involvement of this region in expecting and experiencing subjective values in numerous animal (Tremblay & Schultz, 1999; Lopatina et al., 2016; Noonan et al., 2010), functional imaging (O'Doherty et al., 2001; Kringelbach, 2005; Chib et al., 2009; Peters & Büchel, 2010; Howard et al., 2015; Lopez-Persem et al., 2020; see also these meta-analyses: Liu et al., 2011; Bartra et al., 2013; Clithero & Rangel, 2014) and human lesion studies (Jones & Mishkin, 1972; Camille et al., 2004; Pujara et al., 2009; Henri-Bhargava et al., 2012). In human studies, the role of the vmPFC in subjective evaluation, value expectation and comparison in diverse reward-driven decision-making contexts has been well-established during the last decades (for reviews, see Rudebeck & Murray, 2014; Hiser & Koenigs, 2019). By encoding subjective rewards independently of their category, the vmPFC has been assumed to perform the computing of rewards on a common scale. As such, it is considered to be the hub of subjective value processing within the core reward network (Sescousse et al., 2013; Levy & Glimcher, 2012; Clithero & Rangel, 2014). Related to its role in subjective valuation of stimuli, the vmPFC has a key role in affect processing through the integration of interoceptive signals such as heartbeat-evoked responses (Azzalini et al., 2021).

Dysfunction of the vmPFC has also been implicated in anhedonia and reward-related lack of motivation (Souther et al., 2022). These symptoms are commonly reported in psychiatric conditions and some neurological diseases such as the behavioural-variant frontotemporal dementia (bvFTD), which is characterized by significant vmPFC dysfunctions (Azzalini et al., 2021; Hiser & Koenigs, 2019; Sturm et al., 2017). Despite the central role of the vmPFC in value evaluation and affect processing, its role in affect heuristics remains underexplored. Of relevance, a study by Manuel et al. (2019) applied transcranial stimulation over the vmPFC and found that the vmPFC modulated interactions between reward and affect on a delay discounting task, by shifting decisions based on situational factors such as emotional salience. This suggests a potential role of the vmPFC during affect heuristics such as the ZPE. From this perspective, lesion studies may provide important insights regarding the role of the vmPFC in modulating the ZPE.

As sample sizes in lesion studies are frequently small given the inherent need to have localized lesions within the same brain area, a complementary approach is to include patients diagnosed with neurodegenerative diseases that affect similar regions. Regarding the vmPFC, bvFTD represents an ideal model as it is characterized by early vmPFC atrophy (Perry et al., 2006; Seeley et al., 2008; Bertoux et al. 2015a) and deficits in affective processing and reward processing (Bertoux et al., 2015b; Perry et al., 2015; Perry et al., 2017; Johnen & Bertoux, 2019). The significant atrophy in affective- and reward-relevant networks (which include the vmPFC) has been attributed to a wide range of behavioral abnormalities in this disease, including social and non-social decision-making (Bertoux et al., 2014; Perry & Kramer, 2015; Manuel et al., 2019; Sturm et al., 2017; Chiong et al., 2016; Wong et al., 2018; Rankin et al. 2020). As a novel lesion mapping approach to study complex brain-behavior relationships, the combination of a localized (acquired, circumscribed lesion) and a network approach (degenerative lesion) has been proposed (Baez et al., 2014; Hornberger & Bertoux, 2016; Melloni et al., 2016; Garcia-Cordero et al., 2019). This transnosographic approach offers important insights on neuro-cognitive mechanisms involved in observed phenomena, independently from disease-related mechanisms.

In this study, we aimed to examine the ZPE with clinical populations characterized by either an acquired (lesion patients) or a degenerative (bvFTD patients) lesion of the vmPFC, contrasting their choices to age-matched control groups. When considering the affect heuristic hypothesis and the key role of the vmPFC in subjective and affective evaluation, we predicted that changes of preference in favor of the free product would be greater in control participants than for participants with a vmPFC lesion.

METHODS

In this section, we report how we determined our sample size, all data exclusions, all inclusion/exclusion criteria, whether inclusion/exclusion criteria were established prior to data analysis, all manipulations, and all measures in the study.

Participants

Forty-six participants were included in this study. Given the rarity of patients with acquired focal brain lesion or bvFTD, the centers' recruitment capability determined the clinical sample sizes. The inclusion/exclusion criteria were established prior to the data analysis. Six participants with adult-onset brain lesions (Mean age=61.53±11.99, gender=3F/3M, education years=14.0±2.83) were recruited from the Cambridge Cognitive Neuroscience Research Panel (CCNRP) at the MRC Cognition and Brain Sciences Unit, Cambridge (UK). The inclusion criteria involved (1) lesions to be stable and chronic (sustained more than four years beforehand); (2) lesion location in the vmPFC. All individuals underwent MRI with a 1.5-T or 3-T scanner. MRIcro software (Rorden and Brett, 2000) was used for manual lesion tracing, volume calculation and visualization of lesion overlap. Images were normalized to the Montreal Neurological Institute (MNI) standard brain using SPM99 (Statistical Parametric Mapping; Welcome Department of Cognitive Neurology, London, UK). This group included individuals with meningioma resection (n = 4) and anterior communicating artery aneurysm (n = 2) as lesion aetiologies, which involved damage to one or more of the following regions of the vmPFC: gyrus

rectus/orbital gyrus, medial superior frontal gyrus, orbital regions of the superior frontal gyrus, pregenual/subgenual anterior cingulate cortex. Although some lesions extended dorsally to involve the superior or middle frontal gyri or anterior cingulate, or extended more laterally in the medial frontal cortex, all lesions overlapped in the vmPFC. Lesion location and overlap is shown in Figure 1(a). Patients had normal premorbid intelligence as assessed by the National Adult Reading Test (NART – Nelson, 1982) [NART predicted full scale IQ: 112.83±7.78] and a measure of fluid reasoning ability, the Cattell Culture Fair Intelligence Test, Scale 2, Cattell, 1951 [Cattell score: 29.17±9.91]. Exclusion criteria from the lesion panel and therefore the study involved any psychiatric disorder, the presence of a neurodegenerative condition or additional neurological disorder, or history of substance abuse.

Twenty patients with bvFTD were recruited from FRONTIER, the younger-onset dementia research clinic in Sydney, Australia (Mean age=62.15±8.85, gender=3F/17M, education years=11.8±2.73). All patients were assessed by an experienced behavioral neurologist and underwent neuropsychological assessment and structural brain magnetic resonance imaging (MRI). Inclusion criteria involved a diagnosis determined according to current international consensus criteria (Rascovsky et al., 2011). Exclusion criteria included concurrent psychiatric disorder, presence of other neurodegenerative conditions or neurological disorder, history of substance abuse, or the presence of a known genetic mutation causative for the disease. Seventeen patients were diagnosed with ‘probable’ bvFTD, while 3 met diagnostic criteria for ‘possible’ bvFTD. To increase the strength of the clinical diagnosis, all patients were followed for 36 months to ensure that the diagnosis remained unchanged. Nineteen of the bvFTD patients and 13 control participants underwent T1 MRI brain scans. Voxel-based morphometry analysis was used to quantify patterns of brain atrophy in the bvFTD patients compared to controls. Regions of brain atrophy in bvFTD patients relative to controls are shown in Figure 1(b). For further details regarding MRI acquisition and voxel-based morphometry analysis, see Appendix 1. Disease duration was estimated as the number of years elapsed since the reported onset of symptoms. The Frontotemporal dementia Rating Scale (FRS; Mioshi et al., 2010) was used to determine clinical disease stage. All bvFTD patients underwent general cognitive screening

using the Addenbrooke's Cognitive Examination, 3rd edition (ACE-III; Hsieh et al., 2013) to determine their overall level of cognitive functioning.

Twenty healthy control participants were enrolled in the study, including 7 participants seen at the Department of Clinical Neurosciences (Cambridge, UK) and 13 recruited through the healthy control volunteer registry at FRONTIER, Sydney (Mean age=62.96±6.92, gender=9F/11M, education years=13.06±2.40). All control participants also underwent general cognitive screening using either the ACE-III or ACE-R (Hsieh et al., 2013). Inclusion criteria involved an ACE score ≥88/100, English as the mother tongue, no cognitive complaints and no depressive or anxious complaints. Exclusion criteria involved no current psychiatric disorder & no past or current neurological disease.

Legal copyright restrictions prevent public archiving of the NART, Cattell and ACE-R, which can be obtained from the copyright holders in the cited references The FRS and ACE-III are freely publicly available on https://www.sydney.edu.au/brain-mind/resources-for-clinicians/dementia-test.html

The project was approved by the NRES Committee London – Queen Square (IRAS project ID: 159576) in Cambridge and the South Eastern Sydney Local Health District Ethics Committee in Sydney. All participants were volunteers and provided written informed consent prior to participation. No part of the study procedures or analyses was pre-registered prior to the research being conducted.

Figure 1. Lesion location and overlap for the 6 patients with VMPFC lesion (a) and regions of significant brain atrophy (displayed at p=.01) in bvFTD patients relative to controls (b).

Please insert Figure 1

Procedure

All choices presented in our study required participants to choose between two items (one of low-value, the other of high-value) from the same category with different prices, in a similar procedure to Shampanier et al. 2007. According to this procedure, the product pairs were designed so that the majority of participants would choose the high-value product, even if it was more expensive. We prepared 7 pairs from two categories, one involving monetary rewards (monetary condition) through gift-cards, and the other involving chocolates (food condition). All rewards were virtual, as people did not receive an actual pay-out from the task, nor were they compensated for their participation. However, they were instructed to make their choices as if real rewards depended on them. The different choices of the task are illustrated in Figure 2. The test had no time limit; thus, the participants could take as long as they wanted to choose between the low-value item (LVI) and the high-value item (HVI). As the study took place in Australia and the UK, a conversion of prices was made between cents/pence and dollars/pounds at the time of the experiment. For the chocolates, we also considered the difference in price between the UK and Australia, considering the actual price of the Lindt chocolate (the HVI) in both countries as a reference. In this section, we will detail all the choices in pence/pounds and cents/dollars, but for the sake of clarity, only prices in Australian dollars are reported in the Tables and Figures. Material is available online at https://osf.io/6fpxu/

Figure 2 – Experimental trials in monetary (left) and food (right) conditions which were designed to elicit a zero-price effect between the first (initial price) and second (zero-price) choice trials. In this illustration, on each trial, the item on the left is the low-value item (LVI) and the item on the right is the high-value item (HVI). Left-right item display was counterbalanced.

Please insert Figure 2

Monetary condition: Participants were asked to choose between two gift cards of 10 pounds/Australian dollars (the LVI) and 20 pounds/dollars respectively (the HVI), from Coles Group &

Myer (Australia) or John Lewis (UK). The monetary condition consisted of 3 choice trials, which were administered in the same order for all participants. On the first trial (initial price trial), "1 vs 8", the £/$10 card was priced 1 pound/dollars and the £/$20, 8 pounds/dollars. On the second trial (zero-price trial), "0 vs 7", both prices of the LVI and HVI were decreased by £/$1 compared to the first condition. A third, control trial was also presented (over price trial), where both prices, compared to the original pricing of the two items, were increased by 4 pounds/dollars (i.e. "5 vs 12"). Here, we thereby checked whether participants reversed their choices when prices were initially set higher (5 vs 12) than the initial prices (1 vs 8). If this were the case, we would not be able to determine whether choice-reversals in favor of the LVI in the zero-price trial are due to a simple decrease in price or to the free (0 priced) nature of the LVI. It should be noted that the HVI systematically has a better objective expected value (ranging from 7 to 13 pounds/dollars) than the LVI (ranging from 5 to 10). No ratings of attractiveness were performed for the gift cards as the card values were considered to be objective values.

Food condition: Participants were asked to choose between two chocolates: a Woolworth's (Australia) or Sainsbury's (UK) "bauble" and a Lindt "Lindor" (in both countries). The Lindt chocolate is sold at a higher price in shops in both countries. The prices of these items were varied across four experimental or control choices. The food condition consisted of 4 choice trials, which were administered in the same order for all participants. On the first trial (initial price trial), "1 vs 68" (Australia) or "1 vs 24" (UK), the price of the bauble (LVI) was 1 cent (or 1 penny) and the Lindor (HVI) was 68 cents (24 pence). On the second trial (Zero price trial), "0 vs 67" (Australia) or "0 vs 23" (UK), both prices were decreased by 1 cent/penny compared to the first condition. This was followed by 2 controls choice trials: on a third trial (over price trial), "2 vs 69" (Australia) or "2 vs 25" (UK), the LVI and the HVI cost 2 cents (or 2 pence) and 69 cents (or 25 pence), respectively. This trial, as in the monetary condition, allowed us to check whether changes in prices above 0 induces preference changes. We also introduced a fourth trial (dropped price trial), "0 vs 53" (Australia) or "0 vs 16" (UK), in which the price of the LVI was 0 and HVI was 53 cents (or 16 pence) respectively. As compared to the initial equivalent decrease between 1 vs 68 to 0 vs 67 (or 1 vs 24 to 0 vs 23), this trial offered a

better bargain for those who initially preferred the HVI. The idea was to test whether the ZPE resists this asymmetric downwards shift in prices, or, in other terms, whether the attractiveness of a 0-price continues to overwhelm the attractiveness of the HVI combined with a surplus of utility benefit. After the food condition trials, participants rated on a 7-point Likert scale the attractiveness they personally felt with respect to the two chocolates, and then estimated the price of both chocolates in common shops (Woolworth's was taken as an example in Australia and Sainsbury's in the UK). These ratings were performed to check if, as expected, the HVI was perceived as more attractive and expensive than the LVI.

Data Analysis:

Behavioral data were analyzed with Matlab R2020b and R 3.6.2. There were no data exclusions. Inter-groups differences in demographics and global cognitive efficiency were analyzed using non-parametric Kruskal-Wallis ANOVA and Mann-Whitney U (for continuous variables) or Chi-squared (for binary variables) tests for pairwise comparisons.

As defined by Shampanier et al. (2007), a ZPE is observed when a participant chooses the HVI in the initial choice trial, when both prices are positive, but chooses the LVI in the zero-price trial, when prices are marginally decreased by the same amount so that the LVI becomes free. Since we used a within-subject design, data were analyzed using McNemar's test for changes in proportion of choice in favor of the LVI when the prices of both items marginally decreased. We applied the Yates correction when at least one theoretical frequency was smaller than 5%. This statistical test is well designed to compare the marginal frequencies of dichotomous responses performed in a paired sample of participants. We ran these statistical tests for the monetary and food conditions and for each group (bvFTD and Controls), except in the vmPFC lesion group where the Exact Fisher Test was used instead, because of the small sample size. To complement these analyses, we also used the two-proportion Z-test to compare the proportion of ZPE between control and patients and the Fisher Test when comparing groups of patients together. The Wilcoxon Signed Rank test was used to compare the

ratings within each group. Additional analyses, such as logistic regression, were also used to assess the impact of covariates (e.g. ACE) on the results. Matlab and R analyses' scripts used for the study are available online at https://osf.io/6fpxu/

The conditions of our ethics approval do not permit public archiving of anonymized study data. Readers seeking access to the data should contact the lead author (MB) or the NHS Ethical committee (the NRES Committee London - Queen Square for data acquired at the University of Cambridge and the South Eastern Sydney Local Health District Ethics Committee for the data acquired in Sydney). Access will be granted to named individuals in accordance with ethical procedures governing the reuse of sensitive data. Specifically, requestors must meet the following conditions to obtain the data: researchers undertaking other ethically approved research & completion of a formal data sharing agreement under a national or international collaboration.

RESULTS

Demographics & clinical variables

There was no difference in age and education level (years) across the groups (χ^2=.637; p=.73 and χ^2=4.56; p=.10, respectively). There were no differences in the groups' sex ratio (χ^2=5.045; p<.08). As expected, the ACE score was different (Z=4.285; p<.0001) across the groups, with control participants outperforming patients (Mean=94.55±3.35 vs 82.04±9.95; Z=-3.002; p<.005). However, this difference was driven by patients with bvFTD (Mean=80.15±9.4) given that patients with vmPFC lesion had normal ACE performance (Mean=91.5±7.14; Z=.574; p=.65).

Monetary condition:

As reported in Figure 3, faced with the offer "1 vs 8" (initial price trial), 45 % of control participants chose the LVI. These results were 55% in the bvFTD group and 66.66% in the vmPFC-lesion group. The proportion of choices on the initial price trial did not differ statistically between controls

and patients ($\chi2=0.310$; df = 1; p=.58) or between controls vs bvFTD ($\chi2=0.1$; df=1; p=.75) or controls vs vmPFC (odds ratio=0.423, IC95%=[0.031, 3.775]; p=.65), or between bvFTD vs vmPFC (odds ratio=1.339, IC95%=[0.187, 16.084]; p=1). When both prices marginally decreased (zero-price trial), demand for the now-free LVI increased by 40% in the control group (i.e. for a total of 85% of choices in favor of the LVI), 10 % (65% of choices in favor of the LVI) in the bvFTD group and 0% (66.66% of choices in favor of the LVI) in the vmPFC-lesion group. Results are detailed in each group in the following paragraphs and Table 1.

Figure 3. Proportion of choices in favor of the low-value item (LVI) & the high-value item (HVI) for each group in each choice trial of the monetary condition. * indicates a significant change among the different items between the initial price and zero-price trials, based on the contingency tables.

Please insert Figure 3

Table 1. Contingency table reporting the number of participants of each group choosing the low-value item (LVI) or the high-value item (HVI) in the initial price and zero-price choices in the monetary condition. In red, the ZPE.

Control group (n=20)			
	Zero price trial		
Initial price trial	**LVI ($10)**	**HVI ($20)**	Total
LVI ($10)	8 (consistent choice)	1 (inverse of ZPE)	9
HVI ($20)	9 (ZPE)	2 (consistent choice)	11
Total	17	3	20
bvFTD group (n=20)			
	Zero price trial		
Initial price trial	**LVI ($10)**	**HVI ($20)**	Total
LVI ($10)	11 (consistent choice)	0 (inverse of ZPE)	11
HVI ($20)	2 (ZPE)	7 (consistent choice)	9
Total	13	7	20

vmPFC group (n=6)	Zero price trial		
Initial price trial	**LVI ($10)**	**HVI ($20)**	Total
LVI ($10)	3 (consistent choice)	1 (inverse of ZPE)	4
HVI ($20)	1 (ZPE)	1 (consistent choice)	2
Total	4	2	6

The McNemar's test highlighted a significant impact of a marginal decrease in price between the initial price trial ("1 vs 8") and zero-price trial ("0 vs 7") choices on the relative number of choices of the LVI in control participants ($\chi2=6.40$, p=.01; with Yates correction: $\chi2=4.90$, p=.02). 81.8% of participants (9 participants out of 11) who chose the HVI on the initial price trial then chose the LVI on the zero-price trial, therefore displaying a ZPE. Overall, 45% of participants (9/20) thus showed a pattern consistent with the ZPE, 5% showed the reverse pattern (1/20), 40% chose the LVI in both offers (8/20) and 10% (2/20) chose the HVI in both offers.

Regarding the bvFTD patients, the McNemar's test highlighted no significant impact of a marginal decrease in price between the initial price trial ("1 vs 8") and zero-price trial ("0 vs 7") on the change in proportion in favor of the LVI ($\chi2=2$, p=.16; with Yates correction: $\chi2=.5$, p=.48). 22.2% of participants (2 participants out of 9) who chose the HVI on the initial price trial chose the LVI during the zero-price trial, therefore displaying a ZPE pattern. No participant (0%) exhibited the reverse pattern. Overall, 10% of participants (2/20) thus showed a pattern consistent with the ZPE, 0% showed the reverse pattern (0/20), 55% consistently chose the LVI in both offers (11/20) and 35% (2/20) consistently chose the HVI in both choices.

In the vmPFC-lesion group, the Fisher exact test revealed no significant impact of a marginal decrease in price between the initial price trial ("1 vs 8") and zero-price trial ("0 vs 7") on the change in proportion in favor of the LVI (odds ratio: 2.45, p=1). Only two participants preferred the HVI in the initial price trial and only one participant displayed a behavior consistent with the ZPE by choosing the LVI in the zero-price trial. Overall, 16.67% of participants (1/6) showed a pattern consistent with the

ZPE, 16.67% showed the reverse pattern (1/6), 50% consistently chose the LVI in both choices and 33.33% (2/6) consistently chose the HVI in both choices.

There was thus a significantly higher proportion of ZPE in the control group ($\chi2=4.944$; df=1; p<.001) compared to the patients, and no difference between patients with bvFTD and patients with focal lesion (odds ratio = 0.570; ic95%= [0.025, 39.262]; p = 1). These results were replicated using a binary logistic regression using a generalized mixed-linear model, and are presented in the Appendix 2.

In the control trial (over price trial), we did not observe any significant change of proportion in favor of the LVI between the over price and the initial price trials in control participants, when the prices of both items increased by $4 ($\chi2=0$, p=1). Results are presented in Appendix 3. Here, only 10% (2 out of 20 control participants) changed their initial choice, 40% of participants (8/20) chose the LVI across both offers and 50% (10/20) systematically chose the HVI. A similar result was observed in patients with bvFTD, i.e. we did not observe any significant impact on change proportion between the over price and initial price trials ($\chi2=0.2$, p=.66; with Yates correction: $\chi2=0$, p=1). The same result was observed in the vmPFC group (odds ratio=Infinite, p=.40).

Food condition:

As reported in Figure 4, when presented with the initial price choice ("1 vs 68" in Australia – which is the equivalent of "1 vs 24" in the UK), 20% of control participants chose the LVI. In patient groups, 55% of bvFTD patients and 100% of the patients with vmPFC-lesion did so. The proportion of choices was statistically different between controls and patients ($\chi2=7.645$; df = 1; p<.01). Strong statistical trends with borderline p values were also obtained when comparing controls vs bvFTD ($\chi2=3.840$; df=1; p=.05) and controls vs vmPFC (odds ratio = Inf, IC95% = [0.793, Inf]; p=.06). There was no difference between patients' groups (odds ratio = Inf, IC95% = [0.420, Inf]; p=.30). When both prices marginally decreased, in the zero-price trial, the proportion of choices for the LVI increased by 15%

(from 20% to 35%) in the control group, by 15% (from 55% to 70%) in the bvFTD group but did not increase (from 100% to 100%) in the vmPFC-lesion group.

Figure 4. Proportion of choices in favor of the low-value item (LVI) & the high-value item (HVI) for each group in each choice trial of the food condition.

Please insert Figure 4

Table 2: Contingency table reporting the number of participants of each group choosing the low-value item (LVI) or the high-value item (HVI) in the initial price and zero-price trials, in the food condition.

Control group (n=20)			
	Zero price trial		
Initial price trial	**LVI**	**HVI**	Total
LVI	4 (consistent choice)	0 (inverse of ZPE)	4
HVI	3 (ZPE)	13 (consistent choice)	16
Total	7	13	20
bvFTD group (n=20)			
	Zero price trial		
Initial price trial	**LVI**	**HVI**	Total
LVI	10 (consistent choice)	1 (inverse of ZPE)	11
HVI	4 (ZPE)	5 (consistent choice)	9
Total	14	6	20
vmPFC group (n=6)			
	Zero price trial		
Initial price trial	**LVI**	**HVI**	Total
LVI	6 (consistent choice)	0 (inverse of ZPE)	6
HVI	0 (ZPE)	0 (consistent choice)	0
Total	6	0	6

As reported in Table 2, in the control group, the McNemar's test highlighted no significant impact of a marginal decrease in price between the initial price and the zero-price choices ("1 vs 68" and "0 vs 67" offers or "1 vs 24" and "0 vs 23" in the UK) on the change in proportion in favor of the LVI (χ^2=3.00, p=.08; with Yates correction: χ^2=1.33, p=.25). Among the 16 participants who chose the

HVI, only 3 (18.8%) opted for the LVI in the zero-price trial, i.e. after the prices of both chocolates decreased by ¢1 (or p1 in UK). Four participants (20%) consistently chose the LVI across the two offers and 13 (65%) always chose the HVI. In summary, 3 out of 20 participants of the control group (15%), exhibited a pattern consistent with the ZPE. In the bvFTD group, we did not observe any significant impact of a marginal decrease in price between the initial price ("1 vs 68") and zero-price ("0 vs 67") trials (respectively equivalent to the "1 vs 24" and "0 vs 23" offers in the UK) on the change in proportion in favor of the LVI (χ^2 = 1.80, p=.18; with Yates correction: χ^2 = .80, p=.37). Among the 9 participants who chose the HVI on the initial price trial, 4 (44.44%) opted for the LVI in the zero-price trial. Five (25%) participants consistently chose the HVI across both trials and 10 (50%) always chose the LVI. In the vmPFC group, as all partIcipants had chosen the LVI in the initial price choice ("1 vs 68", or "1 vs 24" in the UK), we did not detect any ZPE in the zero-price trial. There was no significant difference in the proportion of ZPE in the control group (χ2=0.000; df=1; p=1) compared to the patients, and no difference between patients with bvFTD and patients with focal lesion (odds ratio = inf.; ic95%= [0.188, inf.]; p =.54). These results were replicated using a binary logistic regression using a generalized mixed-linear model and are presented in the Appendix 2.

Regarding the control trials, in controls, we observed no change in proportion for the LVI between the over price ("2 vs 69") and the initial price "1 vs 68" (respectively "2 vs 25" and "1 vs 24" in the UK) trials, since no participants reversed their choices (Appendix 3). A somewhat similar picture emerged with bvFTD patients, where change of proportion in favor of the LVI between the over price and initial price trials was not observed (χ^2 =3.00, p=.08; with Yates correction: χ^2=1.33, p=.25). In the vmPFC-lesion group, only one participant opted for the HVI in the over price trial and reversed their choice for the LVI during the initial price condition. The remaining participants systematically chose the LVI for both conditions. As a final control (Appendix 4), we compared the choice in favor of the LVI between the initial price "1 vs 68" and the dropped price "0 vs 53" trials (or "1 vs 24" then "0 vs 16" in the UK). The McNemar's test revealed no significant impact on the change in proportion in favor of the LVI in controls (χ^2=2.00, p=.16; with Yates correction: χ^2=0.50, p=.48) or in bvFTD patients (χ^2=1.80,

p=.18; with Yates correction: χ^2=.80, p=.37). For the vmPFC group, every participant chose the LVI on both price trials.

Results from the ratings of attractiveness and price completed by the participants for both the HVI and LVI are presented in Appendix 5. Overall, the HVI was rated as being significantly more attractive than the LVI in the control and patients' groups. HVI price was rated as being significantly higher in control and patients' groups. A *post-hoc* regression analysis was then conducted to check if the rated attractiveness had any role in the probability of choosing the HVI (Appendix 6). This showed that it significantly impacted controls' choice but not patients.

Post-hoc analyses were conducted to check if a general cognitive deficit could account for the differential observation of the ZPE across groups. These analyses, presented in Appendix 7, show that general cognitive performance (as measured by the ACE) had no effect in controls' or patients' choice of items on the Zero price trial.

DISCUSSION

The aim of this study was to investigate the ZPE in two clinical populations characterized by vmPFC dysfunction. By applying a lesion approach to examine the role of the vmPFC in the affective mechanism underlying the ZPE, our study is the first to explore the ZPE in a clinical context. In line with our predictions, we found a significant ZPE in controls in the monetary condition, but not in patients with an acquired or a neurodegenerative lesion of the vmPFC. In particular, the majority of control participants who initially chose the higher valued item subsequently switched their preferences to the lower valued item when its price was reduced to zero, whereas this change in choice behaviour was observed significantly less frequently in bvFTD and not at all in vmPFC-lesion patients. We discuss in more detail below the theoretical and clinical implications of these findings.

In clinical neurosciences, the role of affect in decision-making is well established and vastly studied (Bechara et al., 1994; Loewenstein & Lerner, 2003; Rolls & Grabenhorst, 2008). The term affect heuristic was coined by psychologists to define the 'mental shortcut' in which people make decisions heavily influenced by affect, which may not necessarily match with their past decisions. As an example, choice inconsistencies observed through the Allais' paradox (Bertoux et al. 2014) could well illustrate the affect heuristic through a shift observed in the responses of control participants after the introduction of an element supposedly eliciting this affective response. This affect heuristic has been requisitioned in various forms of decision theories, such as the regret theory (Loomes & Sugden, 1982) or the disappointment theory (Gul, 1991) and our results support its role in the ZPE, as it was originally proposed (Shampanier et al., 2007).

Given the well documented involvement of the vmPFC in affect processing, our findings in the monetary condition support the notion that the vmPFC plays a key role in the ZPE. Since its original study, all replications of the ZPE have supported the role of a positive affect elicited by the zero-priced item (Nicolau & Sellers, 2011; Driouchi et al., 2011; Baumbach et al., 2016; Votinov et al., 2016; Ma et al., 2018). Only two studies so far, however, have explored the underlying neural mechanisms of the ZPE or its affective component. The first study explored event-related potentials of the ZPE but their topographical correlates were not discussed (Ma et al., 2018). The second study opted for an fMRI approach in 11 participants and emphasized the role of the medial prefrontal cortex in the affective cueing of free items (Votinov et al., 2016). Interestingly, the BA10 region identified by Votinov et al., 2016 partly overlaps with the lesion and atrophy mapping in our study (see Appendix 1). By applying a lesion approach, we demonstrate that damage to the vmPFC (due to a focal or progressive lesion) is associated with lower susceptibility to the affect heuristic and, therefore, lower occurrence of the ZPE. This alteration in decision-making behaviour is in line with a large number of studies that have evidenced the role of the vmPFC area in affect processing, through a wide range of measures and approaches (Jones & Mishkin, 1972; O'Doherty et al., 2001; Sescousse et al., 2013; Kringelbach, 2005; Chib et al., 2009; Peters & Büchel, 2010; Levy & Glimcher, 2012; Bartra et al., 2013; Howard et al.,

2015). More recently, transcranial stimulation of the vmPFC has been found to modulate the interactions between reward and affect in economic choices (Manuel et al., 2019), which is a context at stake in our study as well.

Interestingly, a different picture emerged in the food condition of our study. The majority of controls and patients did not show a significant ZPE. While unexpected, our findings suggest that the items chosen in this condition were not suitable for assessing the ZPE in a within-subjects design. Firstly, as all patients with vmPFC-lesion had chosen the low-quality chocolate in the initial choice trial, when prices of both items were both positive, it was not possible to observe a ZPE on the following choice trial. While our results indicating a lower frequency of ZPE in the bvFTD group initially appear in line with our hypothesis, the ZPE was only observed in a minority of control participants. In addition, similarly to patients with a focal lesion, patients with bvFTD mostly chose the low-quality chocolate in the initial choice trial. When considering patients' behavior in this condition's trial, their initial choice of the low-quality chocolate may have prevented the ZPE to be observed, due to this ceiling effect. Considering these limitations, in this specific experimental condition involving chocolate stimuli, we thus cannot draw any conclusions on either the absence or presence of ZPE. The monetary condition was chosen as the primary condition of our study because the gift card stimuli have an associated objective value, and their expected value could be objectively manipulated. On the other hand, the food condition was included in our study to challenge the robustness of the effect through a different kind of reward. However, we did not anticipate a major difference in the perception of relative attractiveness between the items across the two conditions, nor did we expect a bias of selection toward the low-quality item in patients during the initial choice. While the difference between two monetary values – two prices – is indeed objectively perceived, the different levels of attractiveness between two chocolate brands arguably leaves room for greater individual differences in subjective appraisal and subsequent bias. A gift-card is indeed a one-dimensional object: a monetary item that can be exchanged later for any other consumable. By contrast, non-monetary, directly consumable items, especially food items, present a complex array of variable characteristics at the participant level

such as the favorability of brands, satiety, taste differences and preferences, nutritional preferences, etc. (Plassmann et al., 2012; Cohen et al. 2021; Nitsch & Kalenscher, 2020), which can make their mutual comparisons more difficult to process, especially in the context of affective and cognitive difficulties. Here, it is worth noting that one participant reported experiencing anosmia, and therefore did not pay attention to the taste of food, and two reported not liking or knowing the chocolate brands. Furthermore, as we did not control for time of testing or participants' hunger levels, differences in satiety and its potential impact on the food condition cannot be ruled out. Importantly, our regression analyses indicated that in the food condition, the probability of choosing the most expensive chocolate in the "Initial price" condition significantly and positively depended on the perceived difference in attractiveness between the two chocolate items in controls, but not in patients (see Appendix 5). In this context, if the attractiveness of the higher quality chocolate is perceived to be substantially greater than of the lower quality chocolate, the affective response associated with the free status (i.e. zero-priced) of the latter may be insufficient to shift the individuals' preference in its favor. A final point regarding our design is that the selection of the chocolates' prices between the UK and Australia was performed by considering the price of the high-value item as a reference. However, the Lindt chocolate being more expensive in Australia than in the UK, this introduced a difference in magnitude across controls coming from the UK and those coming from Australia that may have prevented the observation of the ZPE in the Australian participants specifically (0% ZPE in Australian controls vs a 43% ZPE in UK controls). Future studies that account for individual differences in food-related stimuli are therefore needed to clarify whether the ZPE can be observed using a within-subjects design.

From a clinical perspective, our findings highlight the potential utility of the ZPE task in providing a quick assessment of a cognitive bias that may be absent due to vmPFC damage. So far, cognitive biases have mostly been considered in clinical sciences in terms of potential factors affecting clinicians and their decision-making processes in the diagnosis or care of patients (e.g. Saposnik et al., 2016; Dobler et al., 2018). A recent shift in research, however, has started to focus on cognitive or affective biases in psychiatric (Livet et al., 2020) or neurological patients (Bertoux et al., 2014;

O'Callaghan et al., 2016). Notably, the latter two studies showed that "irrational" behaviors (i.e. those that go against Utility Theory) that are expected in controls could be strikingly reduced in patients with bvFTD. For example, controls tend to favor maximum reliability over likely utility in the Allais' Paradox experiment (Bertoux et al., 2014), and they do consider the social background of others before deciding the amount of money they are willing to share with them in a modified Ultimatum game (O'Callaghan et al., 2016). However, in patients with bvFTD specifically, maximum expected utility seems to prevail. Our results lend support to this notion, in revealing that the behavior of vmPFC-lesion or bvFTD patients more closely matches with the predictions of classical economic decision-theory, as opposed to the behavior of healthy controls, which appear to defy these "rational" predictions via their susceptibility to affect heuristics. Beyond questioning the concept of rationality, this paradox of "lesional rationality" could potentially be leveraged in clinical settings to provide novel markers of affective or cognitive impairment due to vmPFC integrity. To date, clinical measures of affective processing mostly rely on facial emotion recognition, decision making or interoception – in a framework where affect is envisaged as an interoceptive response to the inner or outer environment, guiding either the emotion categorization or the decision (Barrett & Satpute, 2019; Salamone et al., 2021). When considering the different tests of affective processing, one could anticipate several limitations to their translation for use in in clinical contexts. For example, emotion recognition tests involve a number of processes (e.g. exploratory gaze strategy, visual perception, decoding of elementary expression – or acting units – configurations, semantic processing) that may differentially explain poor performance (Grainger & Henry, 2020; Bertoux et al., 2020). A complex interaction of diverse cognitive processes is also at play in decision-making tasks, such as the Iowa Gambling Task (Bechara et al. 1994), or delay discounting tasks (Bertoux et al. 2015; Beagle et al., 2020), such that test performance relies not only on reward processing, but also on episodic memory, working memory and executive functioning. In addition, the use of such tasks requires significant time commitment and their accurate completion requires – in the case of the IGT - an elaborated understanding of the task that is far from being systematic, even in controls (Bertoux et al., 2013; Kloeters et al., 2013). Finally,

interoceptive tasks may allow identifying impaired visceral responsiveness to affective items (Birba et al., 2022), but despite their relevancy to bvFTD, they require complex equipment and analyses to be reliable (although see Fittipaldi et al., 2020). As they could provide a quicker, more efficient and much purer method to test affect processing, measures of affective heuristic (or affective biases) stemming from psycho/neuroeconomics could be thus of interest for clinical practice.

Nonetheless, a number of modifications would be required to allow translation of our findings into clinical practice. The choice of the general design of any future task assessing the ZPE is an important point to consider. Adapting the ZPE to a clinical population required a key methodological difference between our study and the original studies (Shampanier et al. 2007). While the original study used a between-subject design, we opted for a within-subject approach. Although the within-subject design was more challenging in terms of replicating the ZPE, given its *a priori* assumption of choice consistency within-subjects (Nitsch & Kalenscher, 2020), this modification was required to test how affective processes influence behavioral consistency in this particular setting. The following points should also be considered in future studies. Firstly, testing the ZPE relies on binary choices which provide indicators that are not ideal for clinical practice, for which scaled measures provide more information (e.g. regarding the severity of impairments). A possible recommendation would then be to add more monetary choice trials in the test. This would allow assessing the ZPE with more reliability while allowing to disqualify pair of choices marked by an initial selection of the low-quality item, which prevent the observation of the ZPE in the second choice. Second, it could be relevant to add more categories of items (e.g. cultural activities, electronic goods, etc.), then averaging the choices made across the different conditions, similar to what was done in Votinov et al. (2016). However, we already reported a discrepancy in the ability of our two conditions to allow an effective observation of the ZPE, and discussed earlier the limitations of the second condition relying on food items. Further experimental investigation of the ZPE should also consider the interaction between the intrinsic characteristics of the stimulus items as well as individual differences in the participants' preferences. For example, it should be noted that the age (62 years on average), country (Australia & UK) and level

of education (13 years on average) of our participants, which differed from the Shampanier et al. (2007) participants (mostly MIT students), may have contributed to the divergent findings. The potential influence of demographic factors on the impact of affective heuristics on decision-making will be an important area of future enquiry.

In this study, we hypothesized the specific role of the vmPFC in the affect heuristic that underpin the ZPE. This hypothesis was formulated on the basis of extensive evidence supporting the role of the vmPFC in subjective valuation, value comparisons and affect processing of different stimuli across multiple reward-related decision-making contexts (Levy & Glimcher, 2012; Bartra et al., 2013; Rudebeck & Murray, 2014; Hiser & Koenigs, 2019). While our findings support the hypothesis that vmPFC damage is associated with dampening of the affective bias toward free products, we acknowledge that reward or value processing in the brain extends beyond this sole region, with the involvement of additional key regions, such as the amygdala, hippocampus, insula and striatum (Liu et al., 2011; Sescousse et al., 2013; Rudebeck et al., 2013). It should be noted that these regions were also atrophic in our bvFTD group, and degeneration of the white matter tracts connecting these regions has also been observed in other studies of this dementia syndrome (Elahi et al., 2017). While our study took an original transnosographic approach to demonstrate a specific role for the vmPFC in the ZPE (see also Baez et al. 2014), we cannot rule out the potential influence of atrophy in other brain regions. As such, future studies should include a fourth comparison group including patients with focal lesions in a region other than the vmPFC. Ideally, future studies should also incorporate within-subject multiple trials test designs and neuroimaging analysis. Concurrent psychophysiological measures such as heart-beat or electrodermal sensitivity may also be of value, to further explore the neurobiological mechanisms underlying the ZPE.

In summary, our study investigated the neural substrates of affective processes that influence decision-making. We established that the vmPFC plays a key role in the affective bias driving the ZPE, by demonstrating abnormal decision-making in patients with focal and neurodegenerative lesions of

this brain region. While this paradigm requires further refinement before translation into clinical practice, our findings underline the potential utility of adapting experimental psycho-economic tasks to assess the integrity of the vmPFC or abnormal affective processing in clinical populations.

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APPENDIX 1

Neuroimaging procedures and contrast between controls & bvFTD patients

Patients with bvFTD and controls from Sydney underwent a whole-brain structural MRI on a 3T Phillips MRI scanner with a standard quadrature head coil (8 channels). 3D T1-weighted images were acquired as follows: coronal orientation, matrix 256 × 256, 200 slices, 1 mm^2 in-plane resolution, slice thickness 1 mm, echo time/repetition time = 2.6/5.8 ms, flip angle α = 8°. Pre-processing of neuroimaging data, including normalisation, segmentation, modulation and smoothing, was completed with the FSL voxel-based morphometry according to https://fsl.fmrib.ox.ac.uk/fsl/fslwiki/FSLVBM (Good et al., 2001; Smith et al., 2004).

Voxel-wise general linear models (GLM) were applied to investigate differences in grey matter intensity via permutation-based non-para- metric testing (Nichols and Holmes, 2002) with 5000 permutations per contrast. Group differences in grey matter intensity were tested for significance at $p<.05$, corrected for multiple comparisons via Family-Wise Error (FWE) correction across space. A cluster extent threshold of 200 contiguous voxels was applied for group comparisons. Relative to controls, bvFTD patients showed characteristic patterns of regional brain atrophy (see Appendix Table 1).

Appendix Table 1. Voxel-based morphometry results showing regions of significant grey matter intensity decrease in bvFTD patients compared to controls.

Regions	Hemisphere (left, right, bilateral)	MNI Coordinates			Number of voxels
		X	Y	Z	
Temporal pole, orbitofrontal cortex, parahippocampal gyrus (anterior, posterior), fusiform cortex (anterior, posterior), hippocampus, amygdala, putamen, insular cortex, central opercular cortex	Left	-44	24	30	3840
Angular gyrus, supramarginal gyrus, parietal operculum cortex	Right	58	-48	46	2331
Frontal pole, frontal medial cortex, paracingulate cortex	Bilateral	6	66	-16	2245
Lateral occipital cortex, cuneal cortex	Right	20	-58	64	1271
Superior parietal lobule, lateral occipital cortex	Left	-30	-48	62	553
Superior parietal lobule, postcentral gyrus	Right	28	-40	54	361
Angular gyrus, superior parietal lobule	Left	-54	-52	48	333
Temporal pole	Right	46	12	-14	255

APPENDIX 2

Replication of findings through a binary logistic regression using a generalized mixed-linear model

In this analysis, we explored the probability to choose the HVI by performing a binary logistic regression using generalized mixed-linear models with trials (Initial, Zero price, Overprice) and group effects (controls, patients) as fixed effect and participants as random effect. To measure how the trials impact the probability to choose the HVI with respect to the group condition, we added an interaction term with these two covariates, such that:

$$y \sim 1 + PRICE + GROUP + PRICE * GROUP + (1|participant)$$

We ran this regression for the food and gift card condition separately. The reference level for each regression was the control group in the initial price condition. We did not analyze the interaction between trials (PRICE) and group (GROUP) because this was not appropriate given our hypotheses (i.e. the ZPE was only expected in controls). However, this interaction was explicitly declared in the model in order to be able to compare the results of the control group (or patients, after relevelling the model) between the initial price and the overprice trials, then between the initial price and the zero price trial. Not declaring this interaction in the model would have introduced a bias in the model, and we would not be been able to observe the impact of the trial on the probability to choose the HVI whatever the group, or the impact of the group on the probability to choose the HVI, whatever the trial. For both analyses, the following parameters were in use.

Model information	
Number of observations	138
Fixed effects coefficients	6
Random effects coefficients	46
Covariance parameters	1
Distribution	Binomial
Link	Logit
Fit method	Laplace

The covariance parameter corresponds to the standard deviation of the random effect associated with the participant predictor, which has an estimated value of 13.822 for the monetary condition and 20.329 for the food condition.

Monetary condition

This analysis confirms our analysis reported in the Manuscript. More specifically, (1) In the Monetary condition, the control group had less chance to choose the HVI in the "Zero price" trial compared to the "Initial price" trial (tStat=-3.306; DF=132; p<.0001). This result refers to the ZPE. (2) This difference is not observed between the "Initial price" trial and the "Overprice" trial (tStat=0.0; DF=132; p=1). (3) To examine if we observed a ZPE in patients, we relevelled this model with the patients' group in the "Initial price" trial as the reference level. We did not observe any significant difference between the "Initial price" and the "Zero price" trials (tStat=-0.914, DF=132; p>.30).

Food condition

These findings confirm the results reported in the Manuscript. More specifically, (1) In the Food condition, the probability to choose the HVI in the "Zero price" trial as compared to the "Initial price" trial is not different for the control group (tStat=-1.136; DF=132; p=.26). Therefore, we did not observe any ZPE here. (2) We did not observe any difference between the "Initial price" and the "Overprice" trials (tStat=-0.0; DF=132; p=1). (3) In order to examine if we observed a ZPE for the patients in the Food condition, we relevelled this model with the patients group in the "Initial price" trial as the reference level. We did not observe any significant difference between the "Initial price" and the "Zero price" trials (tStat=-1.903; DF=132; p=.07).

APPENDIX 3

Contingency tables according to each group (money condition) between the initial price and the over price trials

Control group (n=20)			
	Over price trial		
Initial price trial	**LVI**	**HVI**	Total
LVI	8 (consistent choice)	1	9
HVI	1	10 (consistent choice)	11
Total	9	11	20
bvFTD group (n=20)			
	Over price trial		
Initial price trial	**LVI**	**HVI**	Total
LVI	8 (consistent choice)	3	11
HVI	2	7 (consistent choice)	9
Total	10	10	20
vmPFC group (n=6)			
	Over price trial		
Initial price trial	**LVI**	**HVI**	Total
LVI	3 (consistent choice)	1	4
HVI	2	0 (consistent choice)	2
Total	5	1	6

Contingency tables according to each group (food condition) between the initial price and the over price trials

Control group (n=20)			
	Over price trial		
Initial price trial	**LVI**	**HVI**	Total
LVI	4 (consistent choice)	0	4
HVI	3	13 (consistent choice)	16
Total	7	13	20
bvFTD group (n=20)			
	Over price trial		
Initial price trial	**LVI**	**HVI**	Total
LVI	11 (consistent choice)	0	11
HVI	3	6 (consistent choice)	9
Total	14	6	20
vmPFC group (n=6)			
	Over price trial		
Initial price trial	**LVI**	**HVI**	Total
LVI	5 (consistent choice)	1	6
HVI	0	0 (consistent choice)	0
Total	5	1	6

APPENDIX 4

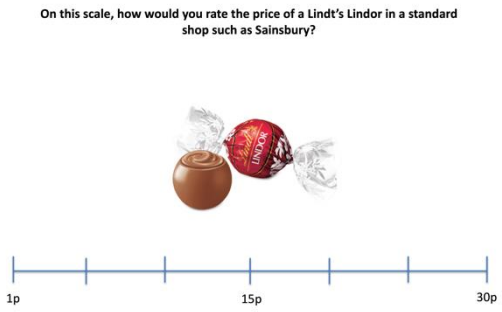
Contingency tables according to each group (food condition) between the initial price and the dropped price trials

Control group (n=20)			
	Dropped price trial		
Initial price trial	**LVI**	**HVI**	Total
LVI	4 (consistent choice)	0	4
HVI	2	14 (consistent choice)	16
Total	6	14	20
bvFTD group (n=20)			
	Dropped price trial		
Initial prices trial	**LVI**	**HVI**	Total
LVI	10 (consistent choice)	1	11
HVI	4	5 (consistent choice)	9
Total	14	6	20
vmPFC group (n=6)			
	Dropped price trial		
Initial price trial	**LVI**	**HVI**	Total
LVI	6 (consistent choice)	0	6
HVI	0	0 (consistent choice)	0
Total	6	0	6

APPENDIX 5

Examples of the ratings performed are presented on Figure 5. Comparisons between LVI and HVI ratings were performed through Multiple Wilcoxon tests with multiple comparison corrections (FDR).

Price rating (screenshot - HVI)



Attractiveness ratings (screenshot - LVI)

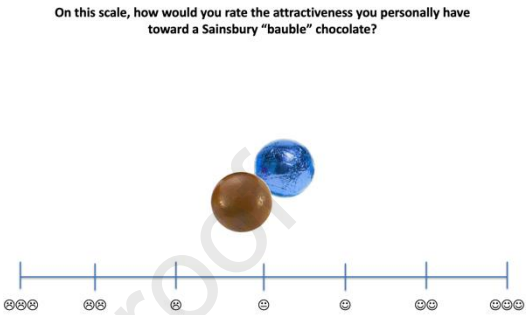


Figure 5 - Examples of the price (left) and attractiveness (right) ratings for the high-value item (left) and low-value item (right) for UK participants.

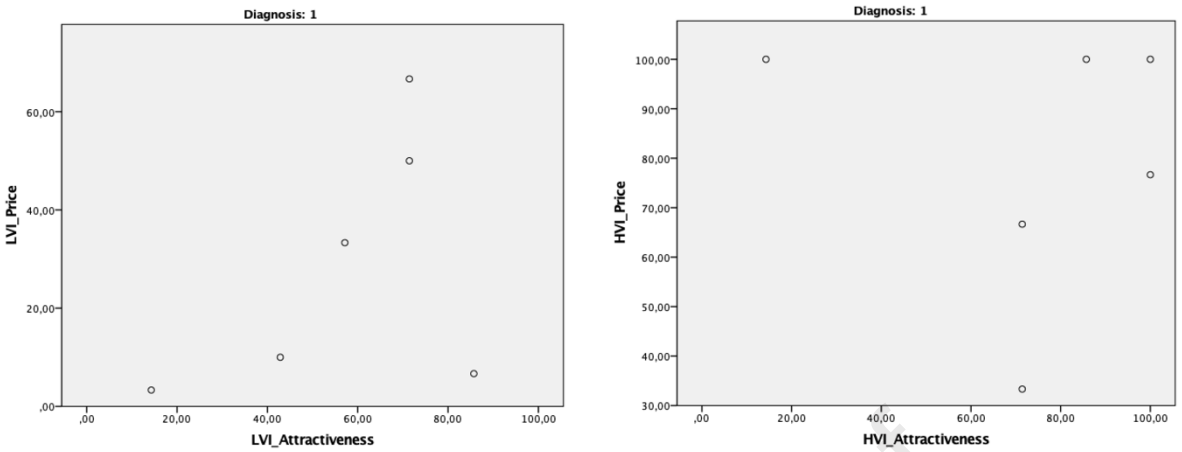
Results regarding the ratings are presented on Figure 6. All prices have been rescaled to assure data standardization across participants from different country. There was a significant difference between the ratings of price ($p<.001$; Sum of pos. ranks 0.000; Sum of neg. ranks -210.0) and attractiveness ($p<.001$; Sum of pos. ranks 20.50; Sum of neg. ranks -189.5) for LVI and HVI in controls, with LVI < HVI in both results. The same results were observed in bvFTD patients ($p<.001$ for price ratings and $p<.01$ for attractiveness) and in vmPFC patients ($p<.05$ and $p=.05$ respectively for price and attractiveness). Findings are illustrated on Figure 6.

Please insert Figure 6

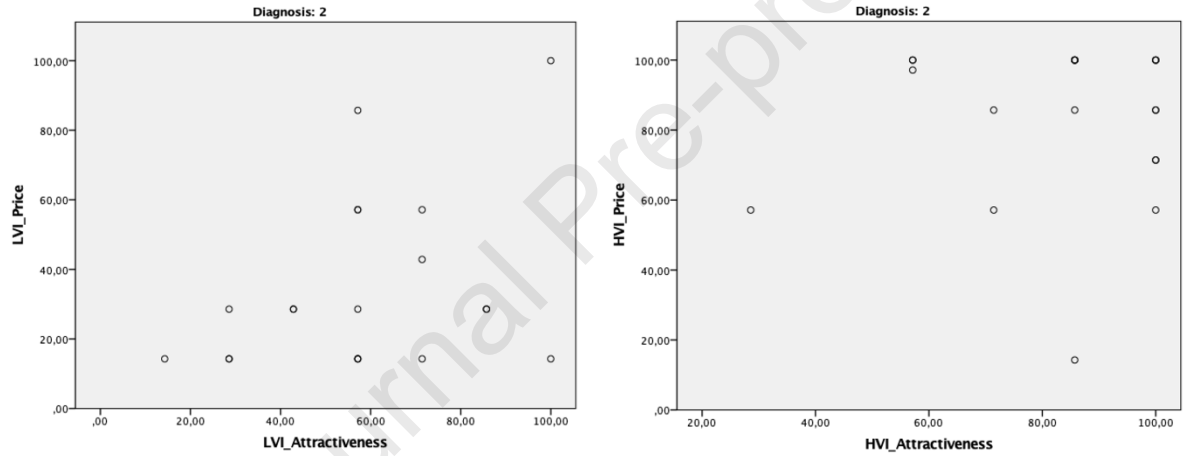
Figure 6 - Price and attractiveness ratings for the low-value item (LVI – blue squares) and high-value (brown triangles) item (HVI) for controls, bvFTD patients and vmPFC patients. ** indicates p<.01; * indicates p<.05

No significant correlation (R's<.31; p's<.17; based on Spearman coefficient) between LVI's price ratings and attractiveness and between HVI's price ratings and attractiveness was observed in any group, as showed on Figure 7.

vmPFC patients



bvFTD patients



Controls

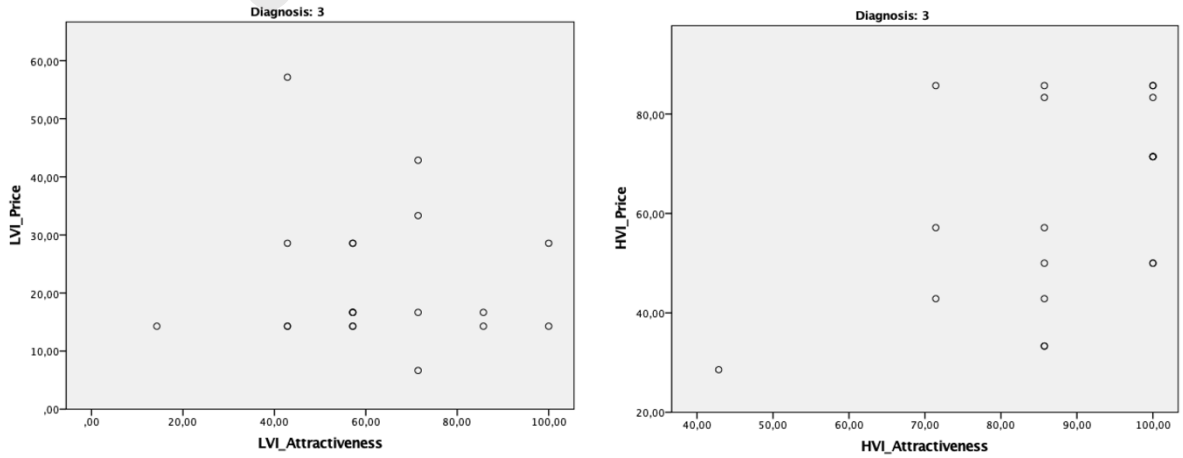


Figure 7 – Plots of correlation between low-value item's (LVI) or high-value item's (HVI) rated price and attractiveness in patients with vmPFC lesion, bvFTD and controls.

APPENDIX 6

Interaction between chocolates' attractiveness & probability of choosing the HVI

We ran a logistic regression to evaluate the probability to choose the HVI chocolate with respect to two factors: (1) the differential attractiveness between the HVI and LVI chocolates and (2) the clinical status (control vs patients). Since only 6 participants where in the vmPFC-lesion group, we decided to merge all the data from the vmPFC-lesion and bvFTD patients, in order to have a patients' group of 26 participants. The attractiveness of the chocolates was evaluated by a 7-point Likert scale (measuring the attractiveness each participant personally felt with respect to the two chocolates). We note, Delta_A, the differential attractiveness such that: Delta_A = rating(HVI) – rating (LVI). Through this logistic regression we asked the following questions: (Question 1) does differential attractiveness has a significant impact on the probability to choose the HVI chocolate in the condition "initial prices"? (Question 2) Does this differential attractivity has a similar impact in each group in the condition "initial prices"? We ran the following model:

P(choose HVI) ~ DIFFERENTIAL ATTRACTIVITY + DIFFERENTIAL ATTRACTIVITY:GROUP

Where GROUP is a dummy variable taking the value 1 for patients and 0 for controls. Our reference level was then the controls' group. Regarding control participants (question 1), differential attractiveness has a significant impact on the probability of choosing the HVI chocolate (b=0.066, SE=0.024; tStat=2.707; p<.01). Moreover, it seems that this impact was not of significantly lower importance for patients (b=-0.005, SE=0.024; tStat=-1.937; p=.05) (question 2), although a trend can be observed. For this analysis, the Intercept was (b=-0.718, SE=0.478; tStat=-1.503; p=.13), the degrees of freedom (n=43), the dispersion N=1. To examine the extent to which differential attractiveness impacted on the probability of HVI chocolate choice in patients, we ran the same model, with the patient group as the reference level. We observed a non-significative statistical trend for the impact of differential attractiveness on the probability of HVI chocolate choice (b=-0.019, p=.16) in patients.

We then compared the impact of the attractiveness differential on the probability of choosing the HVI between the bvFTD and the vmPFC groups in the Initial price condition, running the following logistic regression:

P(choose HVI) ~ DIFFERENTIAL ATTRACTIVITY + DIFFERENTIAL ATTRACTIVITY:GROUP

Where GROUP includes bvFTD and vmPFC. Here vmPFC is the reference level. First, the differential of attractiveness has no impact on the probability to choose HVI for the vmPFC group (beta= -5.342, SE = 1.416, tStat=-3.771, p=1). Second, the impact of the differential attractiveness on the probability to choose HVI is not different between the bvFTD and the vmPFC groups (beta= 5.375, SE = 1.416, tStat=3.795, p=1).

APPENDIX 7

Impact of general cognitive efficiency on the occurrence of the ZPE

Two analyses were performed to discard the potential effect of a general cognitive deterioration on the choices performed in the two conditions. For these analyses, the ACE total score was considered.

The first analysis was restricted to the Monetary condition (where the ZPEs have been observed) and in bvFTD patients, because it is the only group in which the ACE score could be below the ACE threshold for dementia (i.e 82). When considering this threshold, one ZPE can be observed among the n=8 patients who had performed above (i.e. >82, with min=83, max=96), and one ZPE can be observed among the n=12 patients who had performed below (< or 82, min=66, max=81). When we performed a median-split of the patients' ACE scores (median=79), the same result can be observed (i.e. same proportion of ZPE in patients with higher cognitive impairments).

The second analysis was based on a logistic regression. We examined the potential effect of the ACE score to explain the reversal of choice during the Zero price trial in both condition (Monetary and Food). In the Monetary condition, the ACE has no effect in controls' decision (beta=0.217, SE=0.164; t=1.320; p=.19) or patients' decision (beta=-0.001, SE=0.063; t=-0.008; p=.99). In more details, the ACE score had no effect on the decision for patients with bvFTD's (beta= 0.025, SE= 0.084, tstat= 0.299, p=.76) or with focal lesion of the vmPFC (beta= -16.832, SE= 5.425, tstat= -3.102, p=1). The same results were observed in the Food condition in controls (beta=0.093, SE=0.208; t=0.449; p=.65) and patients (beta=0.089, SE=0.069; t=1.293; p=.19). Again, the ACE score had no effect on the decision for patients with bvFTD's (beta=0.160, SE= 0.091, tstat= 1.762, p=.08) or with focal lesion of the vmPFC (beta= -16.832, SE= 5.425, tstat= -3.102, p=1).

(beta=0.160, SE= 0.091, tstat= 1.762, p=.08) and for patients with focal lesion of the vmPFC

(beta=3.289, se= 5.425, tstat= 6.063, p=1)

CONTRIBUTIONS

VL: Formal analysis, methodology, interpretation, writing – original draft. **SW:** Data curation, investigation, formal analysis, methodology, writing – review & editing. **CO**: Data curation, investigation, writing – review & editing. **SE:** Data curation, coordination of the Cambridge Cognitive Neuroscience Research Panel, writing – review & editing. **MH**: Data curation, supervision, interpretation, writing – review & editing. **TL:** interpretation, writing – review & editing. **OP**: Data curation, supervision, interpretation, writing – review & editing. **SBG**: Conceptualization, methodology, supervision, interpretation, writing – original draft, writing – review & editing. **MB**: Conceptualization, data curation, investigation, methodology, formal analysis, project coordination, interpretation, writing – original draft, review & editing.

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