Doctoral Dissertation

Cognitive and Neurophysiological Bases of Monetary Processing

(Bases Cognitivas y Neurofisiológicas del Procesamiento Monetario)

International PhD candidate

Fernando Ojedo Collazo

Advisor

Pedro Macizo Soria

PhD in Psychology

Department of Experimental Psychology

UNIVERSIDAD DE GRANADA

University of Granada

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The content of this doctoral dissertation has been drawn up following the regulations of the University of Granada to obtain the International Doctorate Mention in the Psychology Doctoral Program. According to the regulation, the majority of the thesis has been written in English. A chapter including a summary and conclusions of the thesis is presented in Spanish (see Chapter XI).

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-PART 1-

Introduction

CHAPTER I

Representation of multi-symbolic magnitudes

Understanding how people represent information about quantities, either in a symbolic or non-symbolic way, is an important theoretical and applied issue for cognitive science and its application to everyday contexts. Quantities are used to carry out many actions in our daily lives that require counting, measuring and ordering. Number processing is a basic ability that is present in infants and in non-human animal species and seems to be the result of evolutionary processes (Semenza, 2008). Knowledge about numbers seems to be represented differently from other knowledge domains. Neuropsychological data of patients with damage to their left parietal lobe show that they are able to process and manipulate verbal information, but they have great difficulties processing and manipulating quantities (Cappelletti et al., 2001) independently of whether the quantities are visually presented or imagined (Gliksman et al., 2017).

How, then, are quantities represented in the cognitive system? For symbolic quantities composed of a single component, such as one-digit numbers, there is extensive evidence that they are represented as unitary units along a mental number line (e.g., Buckley & Gillman, 1974; Dehaene et al., 1990). Most of this evidence comes from the so-called distance effect (e.g., Moyer & Landauer, 1967), which refers to the finding that individuals are more efficient comparing the magnitude of two numbers when the distance between them is larger than when it is shorter. This effect is explained by assuming a mental number line in which the numbers are mentally displayed so that the comparison between two distant numbers is easier than the comparison between two numbers close in the mental line (Buckley & Gillman, 1974). The neural signal of mental line representation has also been studied by recording EEG signals during comparison tasks (Dehaene, 1996). Event-related brain potentials have identified a number of components associated with number comparison. First, P1, a positive modulation captured at posterior regions of the scalp, is related to non-specific visual processing. Second, the P2p, a positive modulation at right parietal–occipital–temporal sites, has been interpreted as an index of the distance effect (and of magnitude representation) to close numbers as compared with far numbers (Dehaene, 1996; Hyde & Spelke, 2009). A late positive component, P3 (a positive centro-parietal modulation arising at approximately 300 ms), is usually associated with memory updating (Polich, 2007) but also with magnitude representation and distance effects, since P3 is usually larger (and shows shorter latencies) for larger numerical distances (e.g., Cao et al. 2012; Dehaene 1996; Galfano et al., 2011). This has sometimes been interpreted as indicating less confident responses to closer distances (e.g., Dehaene, 1996). P3 is sensitive to individual differences in solving arithmetic problems (Núñez-Peña & Suárez-Pellicioni, 2012).

While there is broad consensus on the representation of single-symbol symbolic magnitudes, as explained above, this is not the case for the representation of multi-symbol magnitudes. By multi-symbolic magnitudes, we understand those representations of the magnitude formed by two or more components. The simplest and most common case might be two-digit numbers, but other representations of magnitude, such as prices or length measurements, would also be included in this category. Their common feature is that they are composed of two or more constituent symbols, such as decade and unit (e.g., 97), numbers and units of length (e.g., 9 metres), or numbers and monetary categories (e.g., 9 euros).

Regarding multi-symbolic magnitudes, an important question is whether the magnitude is represented in a holistic, compositional or hybrid manner, the latter being a combination of the other two. According to the holistic perspective, multi-symbolic magnitudes are represented as a unitary entity, assuming that they are retrieved as a whole and that each of the components that constitute the multi-symbolic magnitude is not independently analysed. In other words, this means that when comparing two-digit numbers (e.g., 74 vs. 51), the total magnitude of each number is retrieved directly for comparison without the independent contribution of either the decade or the unit when comparing the two numbers (Dehaene et al., 1990; Hinrichs et al.,1981). In contrast, from the compositional view, each component would be accessed separately and independently, and subsequently, the whole magnitude would be retrieved. When comparing two-digit numbers, the decades and units would be compared to access the magnitude of each number, and then it would be possible to perform the comparison and decide which number is larger (e.g., 74 vs. 51; 7 > 5 and 4 > 1) (Nuerk et al., 2001, 2004). Finally, as represented in Figure 1, the hybrid perspective assumes a representation that combines compositional and holistic representations (see Nuerk et al., 2011, for a review).

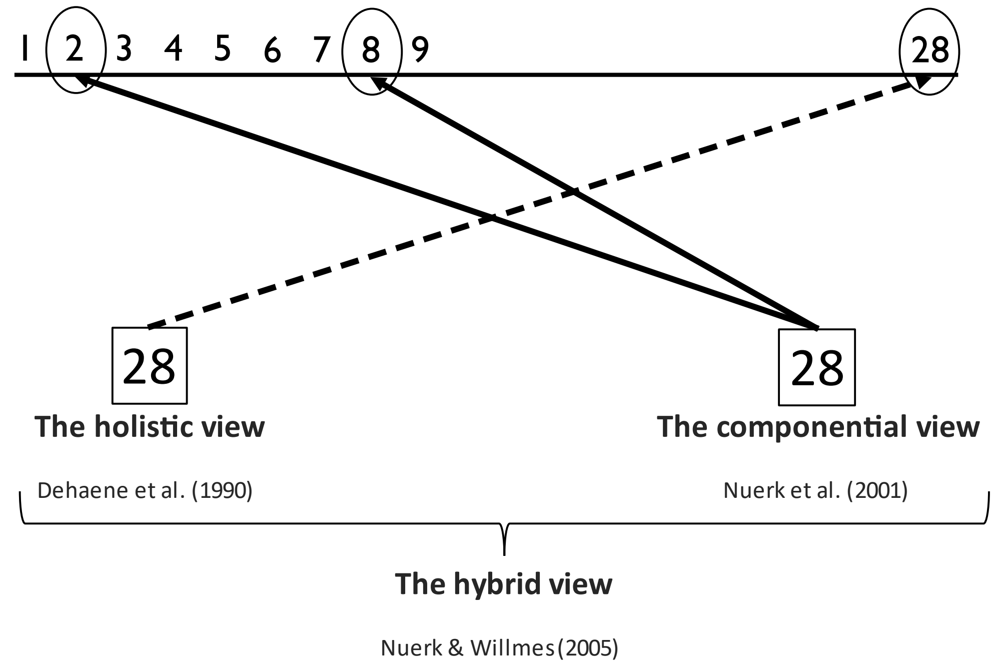

Figure 1. Diagram of the three different views of processing symbolic magnitudes of more than one component.

The idea of purely holistic processing has been ruled out by the extensive evidence supporting compositional processing and has been reported in the past few years (Huber, Bahnmueller, et al., 2015; Huber, Cornelsen, et al., 2015; Macizo, 2017; Macizo et al., 2010; Macizo et al., 2011a; Macizo & Herrera, 2008, 2010, 2011a, 2011b; Macizo & Herrera, 2013a; Moeller et al., 2013; Nuerk et al., 2001). The main source of evidence against pure holistic processing comes from the compatibility effect (Nuerk et al., 2001). This effect refers to the fact that in a comparison task, participants are faster on compatible magnitude comparison trials (e.g., 96 vs. 72; 9 > 7 and 6 > 2) than on incompatible comparison trials (e.g., 52 vs. 28; 5 > 2 but 2 < 8), indicating that each element of the magnitude plays a role in the comparison. Thus, the compatibility effect provides evidence that it is difficult to explain from the assumptions of the holistic theory since the effect is observed even when the distance between the pair of numbers to be compared (24 in the example) is equated. In contrast, and in support of the compositional model, the compatibility effect suggests that the magnitude of the decades and the units composing two-digit numbers are compared separately. These comparisons might produce conflicts when the decades and units point to opposite responses, as is the case with incompatible number pairs (63 vs. 48, where 6 > 4 but 6–8) (see Macizo, 2017). The compatibility effect provides evidence not only that participants process the decades and the units separately (componential processing) but also that this process proceeds in parallel for the two quantities (decades and units) since the effect would not be evident if participants first compared the decade and then the unit. In this case, a comparison of the decade would suffice to perform the comparison for both compatible (97 vs. 82) and incompatible (63 vs. 48) trials (9 > 8 so 97 > 82, and 6 > 4 so 63 > 48, respectively). Similar to the distance effect (Dehaene, 1996), the neural markers of the compatibility effect have also been identified by EEG recordings in comparison tasks with compatible and incompatible trials. Overall, incompatible trials produce a negative modulation over central-parietal regions at 350–450 ms time windows. This negative deflection has been interpreted as an N400 component related to conflict resolution (e.g., Schwarz & Heinze, 1998; Szucs & Soltész, 2007).

As mentioned, the compatibility effect has been a key element in investigating the processing of multi-symbolic magnitudes (see Huber et al., 2016, for a generalized model of multi-symbol magnitude processing). Therefore, it is important to emphasise that this effect has been found not only with two-digit numbers but also when other types of magnitudes are compared. For example, Huber, Bahnmueller, et al. (2015) observed a compatibility effect in a comparison task in which participants had to make comparisons between pairs of physical magnitudes. In this case, participants were more efficient at processing compatible trials (e.g., 9 cm vs. 5 mm; 9 > 5 and cm > mm) than those trials labelled incompatible (e.g., 9 cm vs. 5 mm; 9 > 5 and cm > mm). Another example of the compatibility effect in multi-symbolic magnitudes has also been observed in negative numbers, which are composed of a number and a polarity sign, with better performance observed in compatible (-53 vs. +97) than incompatible (-97 vs. +53) trials (Huber, Cornelsen, et al., 2015). These results suggest that compositional processing would take place regardless of the type of components that constitute the multi-symbolic magnitudes.

Nevertheless, support for the compositional model is not complete, despite the evidence ruling out the presence of holistic processing in some conditions. In fact, there is evidence indicating some holistic processing and, therefore, supporting the idea of the hybrid perspective. For example, even classic magnitude comparison studies with two-digit numbers showing compatibility effects have also shown that the distance between the quantities indicated by the two digits might have an influence on the performance of the participants (Nuerk et al., 2001). Subsequent studies have consistently observed how the overall distance influences the performance of participants in magnitude comparison tasks (logarithmic of the absolute distance, Moeller, Nuerk & Willmes, 2009; Nuerk et al., 2001, 2005; overall absolute distance, Moeller, Nuerk & Willmes, 2009; Nuerk et al., 2004; distance of the logarithmic magnitudes, Moeller, Nuerk & Willmes, 2009). Hence, the presence of compatibility and distance effects in these studies suggests that both compositional and holistic processing might be taking place. In addition, further evidence of the hybrid view is provided by studies with artificial neural networks, which suggests that the data could be explained through both purely compositional models and hybrid models (Moeller et al., 2011). Conversely, some studies have proposed the coexistence of both types of processing, indicating that the occurrence and prevalence of each type of processing may be determined by different factors.

An example of a factor that modulates the observation of compositional or holistic processing is the intentionality of the participant while processing magnitudes. Compositional processing is observed equally when the magnitudes are processed automatically and when they are processed intentionally; however, evidence of holistic processing has been observed more easily when people process magnitudes intentionally than when they process them automatically (Ganor-Stern et al., 2007).

Individual differences in sex and hemispheric asymmetry have also been observed in the way magnitudes are represented. Thus, the sex of individuals seems to be a factor that influences the compatibility effect (Harris et al., 2018). In particular, it has been observed that the compatibility effect is stronger in women than in men. Likewise, some studies have observed hemispheric asymmetry in the compatibility effect, finding stronger effects in two-digit numerical comparison tasks in the right hemifield (left hemisphere) than in the left hemifield (right hemisphere). At the same time, it was observed that sex hormones modulated the hemispheric asymmetry of the compatibility effect. Testosterone was specifically found to be negatively related to the hemispheric asymmetry of the compatibility effect in women (Pletzer, Jäger, & Hawelka, 2019).

Further factors that have been noted as modulators of the compatibility effect are spatial navigation strategies and individual differences in visual hierarchical analysis. In the case of spatial navigation strategies, they have been positively related to the compatibility effect so that the better the participants performed in a navigation task with landmark-based instructions, the stronger the compatibility effect was observed in the numerical comparison task (Pletzer, Harris, & Scheuringer, 2019). Moreover, in relation to individual differences in visual hierarchical analysis, a relationship was found between the compatibility effect in a numerical comparison task and the global advantage in a global–local processing task (Pletzer, Scheuringer, Harris, & Scherndl, 2021). Specifically, it was observed that participants with a smaller global advantage effect were more likely to have a stronger decade-unit compatibility effect. The question, therefore, is whether the two types of processing really coexist or whether the evidence of holistic processing depends on particular conditions and, alternatively, whether the compositional model is able to explain most of the data.

One further question about the processing of multi-symbolic magnitudes is whether the compatibility effect and the results related to it would also apply to magnitudes composed of more than two components, that is, to numbers composed of three digits or more, or to multi-symbolic magnitudes composed of two-digit numbers and a third symbol indicating magnitude. However, few studies have addressed this question (Bahnmueller et al., 2015, 2016, 2021; Huber et al., 2013; Klein et al., 2013; Korvorst & Damian, 2008; Man et al., 2012; Meyerhoff et al., 2012). For example, Korvorst and Damian (2008) studied the compatibility effect on three-digit numbers by including two compatibility effects: the hundred-decade compatibility effect and the hundred-unit compatibility effect. In this study, a comparison task was used in which there were trials (862 vs. 359) denominated as hundred-decade compatible (8 > 3 and 6 > 5) but hundred-unit incompatible (8 > 3 but 2 > 9). Moreover, there were other trials (846 vs. 351) with incompatible hundred-decade magnitudes (8 > 3 but 4 > 5) and compatible hundred-unit magnitudes (8 > 3 and 6 > 1). Both hundred-decade and hundred-unit compatibility effects were observed, indicating fully compositional processing in which each component was processed independently. Interestingly, although both compatibility effects were observed, they differed from each other, with the hundred-decade compatibility effect (30 ms) being stronger than the hundred-unit effect (10 ms). This could point to parallel processing but be mediated by the position of each component that constitutes the number.

However, studies looking at the processing of multi-symbolic magnitudes composed of more than three components have also observed compatibility effects, but they are not as clear as in studies with three components. Meyerhoff et al. (2012) evaluated the processing of 4- to 6-digit numbers. They used a comparison task in which pairs of numbers consisting of four and six digits were used and compatibility effects were manipulated across different digits. For example, incompatibility could be observed at the beginning (e.g., **67**4583 vs. **91**4583, 6 < 9 but 7 > 1) or the end of the numbers (e.g., 8712**36** vs. 8712**54**, 3 < 6 but 6 > 4). However, in his study, a compatibility effect was observed when presented at the beginning of the numbers but not when the compatibility was located at the end of the numbers. These results suggest two significant facts. The first is that longer numbers are also processed compositionally and in parallel; otherwise, it would not be possible to observe any compatibility effect. The second is that processing is not fully parallel since the compatibility effects occur only at the beginning. If processing were fully parallel, compatibility effects would also be observed in conditions in which the compatible/incompatible digits were located at the end of the numbers. The authors interpreted their pattern of results by proposing that in the case of long multi-digit numbers, a chunking process occurs in which in the first part of the numbers are grouped together and processed in parallel, and only then is a second chunk processed in parallel as well. Clustering can explain the compatibility effect for the first digits since it would be the results of comparing the first chunks of the two numbers to be compared and the absence of the compatibility effect when comparing the second chunks of the numbers and since at this point it would already be known which magnitude is larger and therefore there would not be further conflict.

The clustering hypothesis could also explain the results observed with three-component multi-symbolic magnitudes formed by a non-numeric symbol (e.g., minus or plus) and a two-digit number. Thus, in the previously discussed study by Huber, Cornelsen, et al. (2015) with two-digit numbers, the authors considered not only the compatibility between the decade and the polarity sign but also the compatibility between the unit and the sign. As mentioned, they observed a compatibility effect between the decade and the polarity sign, with better performance for compatible trials (-53 vs. +97) than for incompatible trials (-97 vs. +53). However, the compatibility effect between the unit and the polarity sign was not evident. The interaction between compatibility and decade unit was interpreted as evidence in favour of fully compositional and parallel processing of these multi-symbolic magnitudes.

In sum, magnitude comparison studies suggest that the compatibility effect is pervasive and it is found not only with two-digit numbers but also multi-symbolic magnitudes, including longer numbers and combinations of numbers and symbols.

In the next section, we focus on a very special type of symbolic magnitude as it is represented by the symbolic price.

CHAPTER II

The prices as a different multi-symbolic magnitude

As mentioned, most studies on the representation and processing of multi-symbolic magnitudes indicate that compatibility effects are not exclusive of multi-digit magnitudes and are also applicable to other representations of symbolic magnitudes. In addition, they suggested that compositionality is an important principle for processing many symbolic magnitudes (although holistic processing might also take place). In contrast, the first studies performed using prices as multi-symbolic magnitudes suggested that this magnitude might be processed differently from other magnitudes. Specifically, they did not seem to be processed in a compositional way (Cao et al., 2012). Cao et al. (2012) designed a price comparison task in which different prices were presented on the screen (e.g., 6 yuan) and participants had to indicate whether they were higher or lower than a standard price established at the start of the task (five jiao) (Chinese prices are composed of a number and a monetary category; one yuan = 10 jiao). They manipulated the distance between two prices as an index to dissociate between holistic and compositional processing. As previously discussed, the distance effect refers to the fact that the time required to compare two numbers varies inversely with the distance between them (e.g., Moyer & Landauer, 1967). Thus, the trials were defined in terms of whether they were far or close in the mental number line while considering either the total distance of the price magnitude (holistic processing) or the distance between the digits that composed the prices (compositional processing). For example, when distance was defined in terms of holistic or total distance, trials such as one yuan or four yuan would be considered as close-distance prices, and trials such as six yuan or nine yuan would be considered as far-distance prices, always compared to the value of the standard price to be compared, which was five jiao. On the other hand, when the distance was defined uniquely by the distance between the two digits of the prices to be compared, close-distance trials would be those of four yuan and six yuan, while far-distance trials would be those of one yuan and nine yuan (always compared to the standard price of five jiao). Hence, if the distance effect was observed for total or holistic trials, this would support the holistic perspective. If the distance effect was found when the distance was defined in terms of digits only, this would reinforce the compositional perspective because it would indicate that the digits were being compared separately. The results indicated holistic processing since participants were slower and less accurate when prices were higher or lower than the standard price when distance was defined holistically. However, when distance was defined only in terms of that between price digits, no distance effect was observed. Furthermore, electrophysiological activity was recorded during the task, observing a greater positivity for more holistic distances than for short distances in the period of 350–450 ms, with the difference being located in the posterior scalp. As mentioned, P3 has been previously associated with the distance effect (Dehaene, 1996), although its meaning is not entirely clear (i.e., working memory updating or as more difficult decisions). However, in the context of magnitude comparison, Cao et al. (2012) interpreted it as a reflection of magnitude processing. Hence, neither the behavioural nor the electrophysiological analysis showed a distance effect when the reference was the distance between the digits that composed the prices. Therefore, the authors concluded that prices had not been processed compositionally but holistically, contrary to the general notion of multi-symbolic magnitude processing.

In a subsequent ERP study, however, they found some evidence indicating that the compatibility between digits and the monetary category could play a role in the processing of prices. From this, Cao et al. (2015) assumed a hybrid model in which the overall magnitude and the magnitude of the two constituents of the prices would be processed (Nuerk & Willmes, 2005). In this study, the authors considered both the overall distance between pairs of prices as an index of holistic processing, and the digit/monetary category compatibility as an index of componential analysis. In contrast to the previous study, the authors did not observe a holistic distance effect on behavioural measures in this study, although a compatibility effect was observed with faster responses on compatible trials than on incompatible trials.

Conversely, the ERP data revealed a holistic distance effect over frontal locations. N2 amplitudes were more negative on far-distance prices than on close-distance prices. In addition, compatibility modulated ERP components in parietal regions. In particular, the compatibility effect was marginal in the 350–450 ms time window, with greater negativity for incompatible prices than compatible prices. These frontal N2 modulations associated with the holistic distance were considered evidence that the whole magnitude of the price pairs was computed. Furthermore, the posterior negativity obtained in the incompatible condition relative to the compatible condition was taken as an N400-like effect related to semantic integration between digits and the monetary category. Thus, Cao et al. (2015) concluded that prices were processed in a holistic and componential manner. However, the authors reported some inconsistent findings. In particular, the distance effect as an index of magnitude processing usually modulates the N1-P2p complex in posterior regions (Dehaene, 1996; Libertus et al., 2007; Pinel et al., 2001; Temple & Posner, 1998). However, in Cao et al. (2015), a frontal N2 modulation associated with the distance effect was found instead. In addition, Cao et al. (2015) found negative polarity modulations in the 350–450 period associated with the compatibility of price pairs over posterior regions. However, these N400-like modulations are usually observed over frontal and fronto-central regions in conflict tasks that involve magnitude processing (Schwarz & Heinze, 1998; Szűcs & Soltész, 2007; West et al., 2005). Because of these inconsistencies, these effects would be the subject of some of our studies reported later in this thesis (see Chapters VI and VIII).

CHAPTER III

Processing the magnitude of money

In our previous discussion, prices were considered a type of multi-symbolic magnitude even though some studies have suggested some particularities of their processing in relation to other magnitude representations (Cao et al., 2012, 2015). Although these possible particularities of price processing may be called into question if different methodological aspects of these studies are considered, given the nature of money, it is logical to think that other cognitive processes might bias our representation of money since we use and process monetary quantities in many ways in our day-to-day lives. When discussing money-related tasks, we do it in very broad terms, as both the task (e.g., calculating a price after a discount or estimating how much money you have in your wallet) and the format in which the money is presented (prices, banknotes or coins) vary greatly.

Several biases have been observed in the way people deal with money, both when it comes to price processing and when making cash transactions. Regarding price processing, it has been observed that when people deal with discounts on pairs of prices (e.g., current price: €44; reduced price: €41), those formed by a larger unit (e.g., €49/€47) are perceived as greater discounts than those formed by smaller units (e.g., €43/€41), even if the total discount (2) is the same and it is formed by the same decade (4) (Coulter & Coulter, 2005). Similarly, Coulter and Coulter (2007) observed a congruence effect between size and economic value in a price comparison task, finding that people are more efficient at comparing prices when size is congruent with economic value (e.g., $28-$10) compared to when it is incongruent (e.g., $28-$10).

With regard to biases observed when dealing with cash, they have been shown to differ depending on whether the amount of money is represented by coins or banknotes. Coins are designed to represent amounts of money and to facilitate distinctiveness between them by introducing physical dimensions such as colour and size (Pavlek et al., 2020). Goldman et al. (2012) showed that the number value of coins is processed automatically when comparing the monetary value of coins, even when the number value is not necessary to indicate which coin has a higher value. However, when participants were asked to indicate which coin had a higher numerical value in a coin comparison task, the monetary value had no influence on the task. Furthermore, they found that the physical size of the coins was also automatically activated so that in a coin comparison task, people were more inefficient when the size of the coins was inconsistent with their economic value, compared with situations where a coin was larger in both size and value. Along this line, Peetz and Soliman (2016) observed that individuals can overestimate the value of coins if they are modified and enlarged. In their study, they observed that coin pictures that were enlarged were evaluated as more valuable than those presented in their original size, which could be interpreted as people overestimating the value of coins where greater size is interpreted as greater value. Similarly, Hasegawa

(2020) found that the relationship between the size and monetary value of coins could be bidirectional, observing how the monetary value of coins could modulate the estimation of the size of the coin. In their study, they used coins with different monetary values but equal size and created two conditions by editing their size: a congruent condition in which the size of the coin with the higher value was increased and an incongruent condition in which the size of the coin with the lower value was increased. Individuals displayed worse performance in the incongruent condition than in the congruent condition, indicating that they retrieved the monetary value while estimating the size of the coins.

In the case of banknotes, several studies have also examined their particular processing characteristics, as well as the biases associated with them (Di Muro & Noseworthy, 2013; Giuliani et al., 2018; Macizo & Herrera, 2013b; Macizo & Morales, 2015; Manippa et al., 2019; Mishra et al., 2006; Raghubir & Srivastava, 2009; Ruiz et al., 2017). Like coins, banknotes are representations of money and can be distinguished from each other by the number and monetary category printed on them, as well as by their colour and shape. Regarding how biases and physical magnitudes can influence individuals' access to the value of banknotes, it has been observed that people consider damaged banknotes to be economically less valuable than new banknotes in perfect conditions (Di Muro & Noseworthy, 2013). Another example of biases in accessing the economic value of banknotes is the fact that people are more likely to spend their money when it is presented in many small banknotes than when the same amount is in a single large banknote (Mishra et al., 2006; Raghubir & Srivastava, 2009). Other studies on banknote processing have observed that familiarity also affects banknote processing, finding that participants tend to perceive more familiar banknotes as having greater purchasing power than less familiar ones (Alter & Oppenheimer, 2008). Similar to coin processing, congruency effects have been observed with the size and monetary value of banknotes. Ruiz et al. (2017) used a banknote comparison task where participants were asked to indicate which banknote of a pair presented had a higher economic value. They compared congruent conditions (e.g., €20/€100 banknote pair in which the ratio of the bills' physical sizes was preserved) with conditions in which the size between the two banknotes was equated (e.g., €20/€100 banknote pair presented with the same size) and found better performance in the congruent condition. This pattern of results suggests that physical magnitude, such as the size of the banknote, may influence the way the value of the banknotes is accessed and processed.

Overall, the results of the studies discussed above indicate that differently from other symbolic numerical magnitudes, money might be the subject of additional cognitive processes that induce biases in people when they are accessing the monetary value of coins and banknotes and when calculating prices of goods.

CHAPTER IV

Organization, objectives and hypothesis

The main aim of the studies reported in this thesis is to investigate how prices are processed, whether they are represented holistically, compositionally or in a hybrid manner. With this purpose, we carried out our four studies (Chapters V to VIII) where the compatibility effect was examined in price pair-comparison tasks. We aimed to identify the conditions in which this effect is observed. In these studies, comparisons between one-digit prices (Chapters V and VI) and two-digit prices (Chapters VII and VIII) were explored. In all of them, the compatibility effect was evaluated through behavioural measures, and in two of these studies, the compatibility effect was also examined by recording electrophysiological activity (Chapters VI and VIII). In addition, we report an additional study (Chapter IX) in which we investigated whether physical dimensions, such as size or colour, influence the processing of the monetary value of banknotes.

In the following sections, we discussed the aim of each of the chapters and the design of the empirical studies. Each of the chapters corresponds to a manuscript that has been prepared for publication. The three first chapters (Chapters V, VI and VII) have already been published, whereas the fourth and fifth (Chapters VIII and IV) have been submitted for publication.

Chapter V. The processing of price comparison is not holistic but componential

In the first chapter, three experiments were conducted with the aim of exploring the type of processing carried out when comparing single-digit prices. So far, the only study on price comparison is the one reported by Cao et al. (2012). They studied price processing as a multi-symbolic magnitude, using the Chinese currency, renminbi (RMB). In the present experiments, a price comparison was performed in the euro currency. **The objective of experiments 1a and 1b was to determine whether the results reported by Cao et al. (2012) were replicated and extended to the euro currency by assessing the influence of digit distance and holistic distance during the performance of the price comparison task**. Participants performed two tasks in which they had to indicate whether the prices presented were larger or smaller than a fixed standard price, five euros in experiment 1a and five cents in experiment 1b.

In experiments 2a and 2b, we aimed to explore the compatibility effect in price comparison tasks. Across experiments, we used two different tasks: in the first, the two prices to be compared were presented simultaneously (experiment 2a), and in the second, the prices to be compared were presented sequentially (experiment 2b). These two tasks were introduced to be able to compare the obtained compatibility effect with both the results of our previous studies (experiments 1a and 1b) and those reported by Cao et al. (2012). Simultaneous presentation of the prices is the most common procedure in studies exploring the compatibility effect in multi-symbolic magnitude representations, whereas price comparison is usually performed with the two prices serially presented. Serial presentation is interesting since information about the first price has to be maintained in memory, and this might influence performance.

Finally, **in experiment 3, we aimed to explore contextual factors that could potentially modulate price comparison**. Thus, in experiments 3a and 3b, the ratio of intra/intra-monetary category comparisons was manipulated to assess whether the relevance of digits and monetary category modulated the price processing. In experiment 3a, participants performed a price comparison task in which the ratio of intra/intra-category trials (e.g., intra-category trials: two euro vs. six euro; inter-category trials: two euro vs. seven cents) was 80%, while in experiment 3b, they had an intra/inter-currency category ratio of 20%. Finding a larger compatibility effect when the ratio of intra-category trials is higher would reinforce the view of compositional price processing, as it would indicate that price processing depends on the relevance of each of the magnitude components in the task.

Chapter VI. How Do We Process Prices? Electrophysiological Evidence of Componential Analysis

In this study, we aimed to investigate the neural signatures of price comparison by investigating the compatibility effect in a one-digit price comparison task and recording the electrophysiological activity of the participants during the comparison task. Our objective was to replicate the behavioural results of our previous experiments and to observe **if the compatibility between the prices to be compared modulates the N400 component**, as it is related to conflict resolution. These results would indicate that prices were processed in a compositional manner. Previous studies by Cao et al. (2012, 2015) also reported electrophysiological data while participants performed price comparisons using Chinese currency. However, as we mentioned, their results were not clear-cut, and some features of their design introduced some difficulties in their interpretation. Thus, we wanted to better understand the behavioural and neural factors by introducing some improvement in the procedure to enhance the conclusions.

Chapter VII. The Processing of Prices across Numerical Formats

This study aimed to evaluate the processing of prices composed of a two-digit number and a monetary unit to explore whether these more complex multi-symbolic magnitude representations were processed in a fully compositional way (each component processed separately), in a holistic way (the whole magnitude processed as a whole), or in a hybrid manner (a mixture of holistic and compositional processing). I**n this study, we also aimed to explore whether the format in which prices are presented modulates the processing of prices and in what way**. To do so, participants performed three two-digit price comparison tasks, which differed in the format in which the prices were presented: Arabic numbers, written number words or auditory number words. Since the prices were two-digit prices, both the compatibility effect between the number and the monetary category unit (NMC compatibility effect for short) and the compatibility effect between the decade and the unit composing the number (UD compatibility effect for short) were explored. The predictions regarding compatibility effects were straightforward: if the two types of compatibility effects were observed, the fully compositional view would be reinforced, as it would indicate that each of the price components had been analysed separately. On the other hand, if no compatibility effect was found, the holistic view would be reinforced, as this would suggest that the entire price had been processed as a whole. Finally, if only one of the compatibility effects was found, the hybrid view would be supported. Concerning the manipulation of the presentation format, it was expected first to confirm the pattern regarding the UD compatibility effect that had been observed in previous studies, that is, a UD compatibility effect with Arabic numerals, and the absence of it with numerals in verbal format (Macizo & Herrera, 2008; Macizo et al., 2010, 2011a; Nuerk et al., 2005). Secondly, it was also of interest to explore the effect of presentation format on the NMC compatibility effect, as it has not been previously investigated in this or similar magnitudes. In this case, we expected that as the Spanish language favours the processing of the first price component (in this case, the number), a greater compatibility effect might be observed in the verbal format than in the Arabic format. Overall, this study would further our understanding of how prices are represented by extending previous research to more complex formats.

Chapter VIII. Multi-digit Prices: Electrophysiological Evidence of Fully Compositional Analysis

While in the previous section we evaluated the processing of multi-symbolic magnitudes, such as two-digit prices, by looking at behavioural performance in comparison tasks, in this new experiment, we introduced behavioural and electrophysiological measures. Hence, **the aim of this study was to examine both the NMC and UD-compatibility effects, using electrophysiological measures to try to replicate our behavioural results and to take advantage of the temporal precision of the EEG signal to shed light on the results of the previous study, where an NMC compatibility effect was observed but the UD compatibility effect was not evident**. If both behavioural and electrophysiological data replicate this pattern (evidence of NMC compatibility effect but not of UD compatibility), the hybrid view would be reinforced since it assumes separate processing of the number and the monetary category, but processing of the decade and the unit as a whole. However, if the two compatibility effects were observed, the fully compositional view would be reinforced since it would indicate that each of the price components had been processed separately.

Chapter IX. Analysis of the relevance of physical dimensions for access to the value of banknotes

Chapters V to VIII focused on prices as represented by numerical values. In this Chapter IX, we assess the question of how the format of the monetary value, as represented by the size and colour of banknotes, affect the processing of the monetary value. As we mentioned in the introduction, a few studies have shown biases in the processing of money depending on the physical dimensions of coins and banknotes. Thus, **the objective of this study was to evaluate the relevance of the physical dimensions of size, colour and design when accessing the value of banknotes**. To this end, a banknote comparison task was designed in which participants had to indicate which of the two banknotes presented had the highest monetary value. Participants performed three comparison tasks that varied in the dimension of the banknotes, which was manipulated (size, colour, design). These dimensions were manipulated so that for each, there were congruent trials (the value of the physical dimension corresponded to its actual value), incongruent trials (the value of the physical dimension did not correspond to its actual value) and neutral trials (no information about the physical dimension was provided), and we assessed facilitation and interference to evaluate which of the magnitudes considered was the most relevant when accessing the value of the banknotes.

In sum, the studies composing this doctoral thesis focus on the monetary value of banknotes and how people process prices. Whereas the chapters V to VIII focused on numerical multi-symbolic prices composed of one or two digits by looking at behavioural performance and EEG recording of people during price comparison tasks, the last chapter of the experimental section focused on banknotes. In the following chapter, we describe each of these studies in detail, and in the final chapter, we draw the overall conclusions extracted from these studies.

-PART 2-

Experimental Section

CHAPTER V

The processing of price comparison is not holistic but componential[1]

In three experiments, we evaluate whether the processing of prices is holistic or componential. When participants receive two prices and they select the higher price, distance effects are found when the distances between the two prices are defined holistically but not when they are defined in terms of digits (Experiment 1). This result suggests that prices are processed holistically. However, we show that the holistic distance effect can be explained by the compatibility between the digits and the monetary category of prices (euro and cent). After controlling for the holistic distance, compatible trials (e.g., 8 euro–4 cent, 8 > 4, and euro > cent) are processed faster than incompatible trials (e.g., 8 cent–4 euro, 8 > 4 but cent < euro) with simultaneous and sequential presentation of prices (Experiment 2). Moreover, the compatibility effect is modulated by the ratio of intra monetary category comparisons (8 euro–6 euro) and inter monetary category comparisons (8 euro–4 cents) (Experiment 3). The existence of compatibility effects between the digits and the monetary category of prices suggests that cognitive processing of prices is not holistic but componential.

[1]This study was published as Macizo, P., & Ojedo, F. (2018). The processing of price comparison is not holistic but componential. *Psychological Research*, *82*(6), 1144-1157. https://doi.org/10.1007/s00426-017-0884-4

Introduction

Dealing with money is a common activity in everyday life that involves, to a large extent, numerical processing. However, there are very few studies addressing the processing of currency from a cognitive perspective such as, for instance, the perception of money (Cao et al., 2012; Coulter, & Coulter, 2005, 2007; Dehaene, & Marques, 2002; Fitousi, 2010; Goldman et al., 2012; Marques, & Dehaene, 2004; Thomas, & Morwitz, 2005) or the production of the monetary value of currency (Macizo, & Herrera, 2013b; Macizo, & Morales, 2015).

In a recent study, Cao et al. (2012) evaluated two theories that explain how individuals compare the magnitude of prices. These two theories refer to the processing of multi-digit numbers from the holistic and the componential perspective (Nuerk et al., 2011, for a review; Huberet al., 2016, for a general model framework). From a holistic perspective (e.g., Dehaene et al., 1990), two-digit numbers are unitary entities represented in a single space, where they are linearly ordered. Thus, the magnitude of two-digit numbers is retrieved as a whole and the two constituents of these numbers (the decade digit and the unit digit) are not analyzed separately. On the contrary, from a componential view, the decade digit and the unit digit of two-digit numbers are separately processed and they determine the participants' performance on magnitude comparison tasks (Nuerk et al., 2001).

To evaluate whether individuals process prices in a holistic or componential manner, Cao et al. (2012) used a comparison task with Chinese prices. In China, each price is composed of a number and a Chinese character that represents a monetary category (yuan, jiao and fen). The basic unit of Chinese currency is yuan and the fractional units are jiao (1 yuan = 10 jiao) and fen (1 jiao = 10 fen). In Cao et al.'s study, yuan, jiao, and fen prices were presented and participants had to decide whether they were higher or lower than a standard price (5 jiao). The authors elegantly argued that, from the holistic perspective, individuals would process the prices as unitary elements when they had to compare them. In contrast, the componential view would indicate that individuals would decompose the prices into their constituent components, i.e., the number and the monetary character, and they would make comparisons of numbers and monetary characters separately.

To dissociate between these two accounts, Cao et al. (2012) appealed to a well-established effect in numerical cognition, known as the *distance effect* (the time required to compare two numbers varies inversely with the numerical distance between them, Moyer, & Landauer, 1967). Two types of distances, close and far, were defined, taking into account the whole magnitude of the prices or the digit magnitude (see Table 1). To illustrate, there were close holistic distance prices (1 yuan and 4 yuan) and far holistic distance prices (6 yuan and 9 yuan) compared with the standard price (5 jiao). Similarly, close and far distances were considered according to the digits of prices. Continuing with the example described above, there were close digit distance prices (4 yuan and 6 yuan) and far digit distance prices (1 yuan and 9 yuan) compared with the standard price (5 jiao). The authors predicted that if prices were processed holistically, a distance effect would be observed when it was defined holistically, while no digit distance effect would be observed, because the digits of prices would not be compared separately. In contrast, the componential processing of prices would lead to a digit distance effect, because digits would be processed and compared when individuals accessed the magnitude of the prices. It is important to note that the critical trials to dissociate between the holistic and componential views with a 5 jiao standard price were those involving yuan and fen prices (between-monetary category comparisons). When participants compared prices from the same monetary category (jiao prices), close distance prices (4 jiao, 6 jiao) and far distance prices (1 jiao, 9 jiao) were the same regardless of whether the distance was defined holistically or based only on the value of the digits.

Cao et al. (2012) recorded behavioral and electrophysiological data, and when focusing on the behavioral pattern of results, they found a holistic distance effect. When yuan prices and fen prices were compared with the 5 jiao standard price, the accuracy was higher and the reaction times were faster with far holistic distance prices relative to close holistic distance prices. However, when the distance was defined in terms of digit values, distance effects were not found with yuan prices and fen prices. From these results, the authors concluded unambiguously that the processing of prices was not componential but holistic.

The notion of holistic processing of prices (Cao et al., 2012) contrasts sharply with the evidence from a large number of studies on numerical cognition supporting the componential processing of multi-digit numbers (see Nuerk et al., 2011, for a review). Indeed, while the holistic view of two-digit number processing has received some support in the past (Brysbaert, 1995; Dehaene et al., 1990), many recent studies support the componential view (Macizo, 2017; Macizo, & Herrera, 2010, 2011a, 2013a; Macizo et al., 2010, 2011a, 2012; Moeller et al., 2013; Nuerk et al., 2001, 2004). The major source of evidence in favor of the componential perspective comes from the unit-decade compatibility effect (compatibility effect for short). When individuals decide the larger of a two-digit number pair, while controlling for overall numerical distance, their responses are faster when the decade and unit of one number are larger than those of the other number (compatible trials, i.e., 67–52, 6 > 5, and 7 > 2) relative to number pairs in which the decade of one number is larger, but the unit is smaller than those of the other number (incompatible trials, i.e., 62–47, 6 > 4 but 2 < 7) (Macizo, & Herrera, 2010). Within the componential perspective, the compatibility effect reflects separate but interactive comparisons of the decade magnitude and the unit magnitude. These comparisons are assumed to activate the corresponding response. On compatible trials, the activation of decade and unit comparisons converge to select the correct response, while on incompatible trials, unit comparisons, and decade comparisons lead to a different response, thus increasing the time needed to make the correct selection.

The compatibility effect with two-digit numbers is a robust phenomenon that has been confirmed in numerous studies and laboratories (Macizo, & Herrera, 2010; 2011a, 2013a; Nuerk et al., 2001, 2004). It does not depend on the perceptual configuration of numbers (Nuerk et al., 2004), has been observed with a range of different tasks (e.g., comparison task with an internal standard, Moeller, Nuerk & Willmes, 2009; physical size comparison task, Ganor-Stern et al., 2007), is sensitive to contextual effects such as the relevance of units and decades in the experimental task (e.g., the percentage of intra/inter decade comparison ratio; Macizo, & Herrera, 2011a), and has been extended to the processing of three-digit numbers (Huber et al., 2013).

However, it could be argued that two-digit numbers and prices are distinct entities that might be processed in a different manner. In fact, while multi-digit numbers always involve magnitude processing of symbolic numbers (decades, units), prices entail the processing of numbers (the numerical value) and other symbols (the monetary category, e.g., yuan, jiao and fen in the Chinese currency). However, recent evidence has shown componential processing of other magnitudes with non-numerical symbols such as measurement units (e.g., meters, seconds, kilograms; Huber, Bahnmueller, et al., 2015) or negative numbers (composed of a number and a polarity sign; Huber, Cornelesen, et al., 2015). To illustrate, Huber, Bahnmueller, et al., (2015) evaluated the compatibility effect as an index of componential processing in a measurement comparison task in which there were compatible trials (i.e., 3 mm–6 cm, 3 < 6, and mm < cm) and incompatible trials (i.e., 3 cm–6 mm, 3 < 6 but cm > mm). The authors observed a reliable compatibility effect between the digits and the measurement units with slower latencies on incompatible trials relative to compatible trials. Therefore, evidence in favor of componential processing is found when individuals process quantities regardless of whether they are composed of digits only (i.e., two-digit numbers) or a digit and a non-numerical symbol (i.e., measurement units). In fact, Huber, Cornelesen, et al., (2015) extended the componential model of two-digit number processing to introduce a general framework for multi-symbol number processing in which all digits and characters are processed separately in a componential manner regardless of whether they are composed of digits only or other characters such as polarity sign.

Table 1. *Stimulus material used by Cao et al. (2012)*

Units	Digit distance	Holistic distance
Yuan		
Close	4 yuan (incompatible)	1 yuan (incompatible)
	6 yuan (compatible)	4 yuan (incompatible)
Far	1 yuan (incompatible)	6 yuan (compatible)
	9 yuan (compatible)	9 yuan (compatible)
Jiao		
Close	4 jiao	4 jiao
	6 jiao	6 jiao
Far	1 jiao	1 jiao
	9 jiao	9 jiao
Fen		
Close	4 fen (compatible)	6 fen (incompatible)
	6 fen (incompatible)	9 fen (incompatible)
Far	1 fen (compatible)	1 fen (compatible)
	9 fen (incompatible)	4 fen (compatible)

Stimuli depending on the monetary category (yuan, jiao, and fen) and the digit and holistic distances (close and far) when participants compared prices to 5 jiao standard. The table is adapted from Cao et al. to include the compatibility between the digit and the monetary category (compatible and incompatible). Compatibility applies to between-monetary comparisons. Compatible: the digit and monetary category of one price are larger than those of the other price. Incompatible: the digit of one price is larger, but the monetary category is smaller than those of the other price.

The current study. There is abundant evidence showing that multi-digit numbers are processed in a componential manner (Macizo, & Herrera, 2010, 2011a, 2013a; Nuerk et al., 2001, 2004). However, to our knowledge, there is only one study in which the holistic vs. componential processing of prices is evaluated and its results favor the holistic perspective. Hence, it is critical to investigate in more depth whether prices represent a unique category of magnitude that is processed differently. This was, therefore, the aim of the current study. First, Cao et al.'s (2012) study deserved replication and extension to other monetary categories. This objective was covered in Experiment 1. Furthermore, given that the compatibility effect is considered key for demonstrating the componential processing of multi-digit numbers and multi-digit symbols, it seemed worthwhile to study this effect when individuals process prices. This was the aim of Experiments 2 and 3. If a compatibility effect is observed in price comparison tasks, then this would run counter to the claim that prices are processed holistically.

Experiment 1

In a price comparison task, Cao et al. (2012) reported holistic distance effects but not digit distance effects in between-monetary category price comparisons, which prompted the conclusion that prices are processed holistically. In Experiment 1, we aimed to replicate and extend the pattern of results found in Cao et al.'s study. In our experiment, Spanish individuals who were users of the euro currency performed a price comparison task with euro prices. In the euro currency, prices are composed of a number and a character that represent its monetary category, i.e., euro and cent. The euro is the basic unit and the cent is the fractional unit. Following a similar procedure to that employed by Cao et al. (2012), we evaluated the influence of digit distance and holistic distance when participants performed two separate price comparison tasks. Relative to a fixed standard price in Chinese currency (5 jiao), the authors evaluated the processing of prices with a lower monetary value (fen prices) and a higher monetary value (yuan prices). In Experiment 1a, we used a 5 euro standard and the between-category prices were in cent (lower monetary value), while in Experiment 1b, we used a 5 cent standard and the between-category prices were in euro (higher monetary value).

The critical conditions to dissociate between the holistic and componential processing of prices were those including price comparisons with between-monetary category (e.g., 5 cent vs. 3 euro) in which the digit and holistic distance might differ. In contrast, the digit distance goes hand in hand with the holistic distance in within-monetary category comparisons (see Table 2). The holistic and componential views would predict a completely different pattern of results in between-monetary category comparisons. According to the componential perspective, the reaction times would be slower with close digit distance relative to far digit distance, while the holistic view would predict no such difference, due to the distance between the digits. According to this view, a distance effect would be observed only when it was defined holistically.

Method

Participants

Thirty-six students from the University of Granada (30 women and 6 men) took part in Experiment 1a. Their mean age was 22.75 years (*SD* = 6.90). Twenty-seven students (21 women and 6 men) took part in Experiment 1b. Their mean age was 22.93 years (*SD* = 7.47). All participants were right-handed. They gave informed consent before performing the experiment, and their participation was rewarded with academic credits. All participants used the euro currency on a daily basis, reported no history of numerical disabilities, and they had normal or corrected-to-normal visual acuity.

Table 2. *Stimulus material used in Experiment 1*

Price	Digit distance	Holistic distance
Experiment 1a (5 Euro standard)		
1 cent (compatible)	Far	Far
2 cent (compatible)	Far	Far
3 cent (compatible)	Close	Far
4 cent (compatible)	Close	Far
6 cent (incompatible)	Close	Close
7 cent (incompatible)	Close	Close
8 cent (incompatible)	Far	Close
9 cent (incompatible)	Far	Close
Experiment 1b (5 cent standard)		
1 euro (incompatible)	Far	Close
2 euro (incompatible)	Far	Close
3 euro (incompatible)	Close	Close
4 euro (incompatible)	Close	Close
6 euro (compatible)	Close	Far
7 euro (compatible)	Close	Far
8 euro (compatible)	Far	Far
9 euro (compatible)	Far	Far

Stimuli used in between-monetary category comparisons as a function of the monetary category (euro and cent) and the digit and holistic distances (close and far). The compatibility between the digit and the monetary category is indicated in brackets.

Design and materials

A price comparison task was employed. A one-digit euro price or cent price was presented and participants had to decide whether its monetary value was higher or lower than a standard price (5 euro in Experiment 1a, and 5 cent in Experiment 1b). In Experiment 1a, 16 prices were selected. Eight prices were from the same monetary category as that of the 5-euro standard (within-category comparisons in euro) and eight prices were used from a different monetary category (between-category comparisons in cent). When within-category prices were considered, there were four prices in the close distance condition (3 euro, 4 euro, 6 euro, and 7 euro) and four prices in the far distance condition (1 euro, 2 euro, 8 euro, and 9 euro) regardless of whether the distance was defined in terms of the digit or the holistic price. Regarding between-category prices, two variables were manipulated within-participants: the holistic distance (close, far) and the digit distance (close, far). The crossing of these two variables produced four experimental treatments: (a) close holistic distance–close digit distance; (b) close holistic distance–far digit distance; (c) far holistic distance–close digit distance; and (d) far holistic distance– far digit distance. Two prices were assigned to each treatment in between-category comparisons producing the total number of the eight prices used in the between-cate- gory condition. The stimuli and design were the same in Experiment 1b with the only difference that within-category comparisons were in cent and between-category comparisons were in euro (see Table 2).

Each participant received a list of 72 trials presented randomly. Forty-eight trials were within-category com- parisons (24 in the close distance condition and 24 in the far distance condition) and 24 trials were between-category comparisons (6 trials in each of the 4 treatments). The different proportions of within/between-category comparisons were fixed to have the same number of prices with higher/lower value than the standard (36 trials in each). The within/between-monetary category ratio used here (66.67 and 33.33%, respectively) was the same as that employed by Cao et al. (2012).

Procedure

The stimuli were always presented in the middle of the screen in black color (Courier New, 18 point size) on a white background. Participants were tested individually and they were seated at approximately 60 cm from the computer screen. All prices presented to the participants included one digit denoting the monetary value and the label denoting the monetary category. The labels used were ‘‘euro’’ and ‘‘cent’’ (e.g., 4 euro, 4 cent).

In the price comparison task, each price was presented and participants were instructed to decide whether it was higher or lower than the standard price (5 euro in Experiment 1a and 5 cent in Experiment 1b) by pressing the Z and M keys of the keyboard. Use of the Z and M keys to indicate a ‘higher’ and ‘lower’ selection was counterbalanced across participants. Each trial began with a blank screen for 300 ms followed by the price until the participant’s response. After the participant’s response, the next trial began. The duration of the experiment was approximately 25 min.

Results

Trials on which participants committed an error were eliminated from the analyses (3.07% in Experiment 1a and 3.16% in Experiment 1b). Furthermore, following the same trimming procedure used by Cao et al. (2012), we excluded reaction times (RTs) below and above 2 *SD* for each individual participant's mean (4.51% in Experiment 1a and 4.58% in Experiment 1b). Since we were interested in comparing the data of this study with those reported by Cao et al., we first conducted exactly the same analyses as those described by these authors. Thus, separate analyses are reported for the processing of prices with a lower value than the standard (5 euro standard, Experiment 1a) or a higher value than the standard (5 cent standard, Experiment 1b). Accuracy analyses were not performed due to the reduced variability of error rates within each cell of the design (e.g., in Experiment 1a, there were two cells of the design in which only 1 participant out of 36 committed errors). In all analyses reported here, the interactions between variables are reported first, and then, the main effects are shown. When a disordinal interaction is found, the main effect is not interpreted.

Experiment 1a: 5 euro standard

Similar to Cao et al. (2012), we first evaluated the componential view of price comparison by submitting RTs to an analysis of variance (ANOVA) with digit distance (far vs. close) and monetary category (euro vs. cent) as within-participant factors. The monetary category 9 digit distance interaction was significant, $F(1, 35) = 11.94$, $p < .001$, $\eta_p^2 = .006$. Further exploration of this interaction revealed a monetary category effect in close digit distance prices, $F(1, 35) = 13.23$, $p < .001$, $\eta_p^2 = .033$, but not in far digit distance prices, $F < 1$. Furthermore, the digit distance effect was significant when participants were presented with euro prices, $F(1, 35) = 15.68$, $p < .001$, $\eta_p^2 = .019$, but not when they received cent prices, $F < 1$. Note that the distance effect in within-category comparisons could be explained by the holistic and the componential views, since the distance of prices (close and far) was the same in terms of the digits and the holistic value of prices. The main effect of monetary category was significant, $F(1, 35) = 6.34$, $p = .01$, $\eta_p^2 = .012$. The main effect of digit distance was also significant, $F(1, 35) = 4.78$, $p = .035$, $\eta_p^2 = .005$.

We continued with the analyses reported by Cao et al. (2012) by evaluating the possible holistic processing of prices. We conducted an ANOVA with holistic distance (close vs. far) and the monetary category (euro vs. cent) as within-participant factors. The monetary category 9 holistic distance interaction was not significant, $F < 1$. The main effect of monetary category was significant, $F(1,35) = 6.59$, $p = .01$, $\eta_p^2 = .01$. The main effect of holistic distance was also significant, $F(1, 35) = 16.76$, $p < .001$, $\eta_p^2 = .027$. The participants responded more slowly to close distance prices (M = 712 ms, SE = 26) relative to far distance prices (M = 663 ms, SE = 20). Hence, the holistic distance effect was found regardless of the monetary category of prices (euro prices and cent prices).

We carried out further analyses by focusing on between-monetary category comparisons (cent prices vs. 5 euro standard). An ANOVA was conducted with digit distance and holistic distance as within-participants factors. The holistic distance x digit distance interaction was significant, $F(1, 35) = 9.75$, $p = .003$, $\eta_p^2 = .017$. When the digit distance was close, there were no differences between far holistic distances ($M = 663$ ms, $SE = 24$) and close holistic distances ($M = 679$ ms, $SE = 25$), $F < 1$. However, when the digit distance was far, the holistic distance effect was significant, $F(1, 35) = 13.68$, $p < .001$, $\eta_p^2 = .084$. The reaction times were faster in far holistic distances ($M = 626$ ms, $SE = 19$) than in close holistic distances ($M = 721$ ms, $SE = 32$). The main effect of holistic distance was significant, $F(1, 35) = 7.68$, $p = .008$, $\eta_p^2 = .033$, but the digit distance effect was not, $F < 1$.

Experiment 1b: 5 cent standard

The ANOVA conducted with digit distance (far vs. close) and monetary category (euro vs. cent) as within-participant factors revealed a significant monetary category x digit distance interaction, $F(1, 26) = 4.97$, $p = .03$, $\eta_p^2 = .003$. The analyses of this interaction revealed a monetary category effect in close digit distance prices, $F(1, 26) = 81.46$, $p <.001$, $\eta_p^2 = .154$, and far digit distance prices, $F(1, 26) = 72.97$, $p < .001$, $\eta_p^2 = .113$. In addition, the digit distance effect was significant when participants were presented with cent prices, $F(1, 26) = 5.04$, $p = .03$, $\eta_p^2 = .007$, but not when they received euro prices, $F < 1$. The main effect of monetary category was significant, $F(1, 26) = 116.54$, $p < .001$, $\eta_p^2 = .134$. The main effect of digit distance was not significant, $F(1, 26) = 1.71$, $p = .20$, $\eta_p^2 = .001$.

Furthermore, in the analysis conducted with holistic distance (close vs. far) and monetary category (euro vs. cent) as within-participant factors, the monetary category x holistic distance interaction failed to reach significance, $F(1, 26) = 1.70$, $p = .20$, $\eta_p^2 = .001$. However, the main effect of the holistic distance was significant, $F(1, 26) = 17.78$, $p < .001$, $\eta_p^2 = .016$. The responses were faster with far distance prices (M = 658 ms, SE = 22) relative to close distance prices (M = 690 ms, SE = 25).

Finally, the data obtained on between-monetary category comparisons (euro prices vs. 5 cent standard) were subject to an ANOVA with digit distance and holistic distance as within-participant factors. The holistic distance x digit distance interaction was significant, $F(1, 26) = 6.31$, $p = .02$, $\eta_p^2 = .007$. When the digit distance was close, there were no differences between far holistic distances (M = 611, SE = 24) and close holistic distances (M = 629 ms, SE = 29), $F(1, 26) = 1.47$, $p = .24$, $\eta_p^2 = .004$. In contrast, the holistic distance effect was significant when the digit distance was far, $F(1, 26) = 28.57$, $p < .001$, $\eta_p^2 = .072$. The reaction times were faster with far holistic distances (M = 599 ms, SE = 18) relative to close holistic distances (M = 659 ms, SE = 23) (see Table 3). The main effect of holistic distance was significant, $F(1, 26) = 14.05$, $p < .001$, $\eta_p^2 = .025$. The digit distance effect was not significant, $F(1, 26) = 1.19$, $p = .28$, $\eta_p^2 = .001$.

Table 3. *Results obtained in Experiment 1*

	5 euro standard		5 cent standard	
	RT	*E%*	RT	*E%*
Far digit distance				
Far holistic distance	626 (19)	0.93 (0.93)	599 (18)	3.03 (1.78)
Close holistic distance	721 (32)	5.56 (2.20)	659 (23)	3.78 (1.88)
Close digit distance				
Far holistic distance	663 (24)	0.46 (0.46)	611 (24)	0.00 (0.00)
Close holistic distance	679 (25)	2.78 (1.41)	629 (29)	7.57 (2.84)

Results obtained in between-monetary category comparisons as a function of the digit distance (close, far) and holistic distance (close, far). Standard error is reported in brackets RT reaction times (in ms), E% error percentages.

Discussion

In Experiment 1, we aimed to evaluate digit and holistic distance effects when participants performed a price com- parison task similar to that employed by Cao et al. (2012). The findings of our experiment confirm the pattern of results obtained by Cao et al. Specifically, when between- monetary comparisons were considered, the main effect of holistic distance was found in the absence of a main effect of the digit distance. These results were found when participants compared cent prices relative to a 5 euro standard (Experiment 1a) and when they compared euro prices relative to 5 cent standard (Experiment 1b). However, the interaction between the holistic distance and digit distance found in the current study seems to suggest that digits might play a role in the processing of prices.

The notion of a holistic processing of prices contrasts sharply with the evidence found from a large number of studies showing that multi-digit numbers and other multi-symbol magnitudes are processed in a componential manner (Huber et al., 2016; Huber, Bahnmueller, et al., 2015; Huber, Cornelsen, et al., 2015; Macizo, 2015; Macizo, & Herrera, 2010, 2011; Nuerk et al., 2001, 2004).

At first glance, price might be regarded as a unique category that is holistically processed. However, after close inspection of the stimulus set used by Cao et al. (2012) (see Table 1) and those used in our Experiment 1 (see Table 2), we observed a drawback which was inherent in the design utilized to evaluate digit and holistic distance effects. In particular, there was a confound between the holistic distance of prices and the compatibility between the digits and the monetary categories in the study by Cao et al. When yuan prices were compared to the 5 jiao standard, close holistic distance prices (1 yuan, 4 yuan) were presented on incompatible trials (yuan < jiao but 1 and 4 > 5), while far holistic distance prices (6 yuan and 9, yuan) were presented on compatible trials (yuan < jiao, 6 and 9 < 5). The same confound occurred when fen prices were compared to the 5 jiao standard. This confound was also evident in Experiment 1 with prices in the Euro currency. For example, when cent prices were compared to the 5 euro standard (Experiment 1a), close holistic distance prices (e.g., 9 cent) were presented on incompatible trials (cent < euro but 9 > 5), and far holistic distance prices (e.g., 1 cent) were presented on compatible trials (cent < euro and 1 < 5). Therefore, slower reaction times in the close holistic distance condition (incompatible trials) relative to the far holistic distance condition (compatible trials) could be due to a compatibility effect.

The compatibility between digits and monetary categories could also explain the absence of digit distance effects reported by Cao et al. (2012). In between-monetary category comparisons, the compatibility was equated in the far/close digit distance conditions. Thus, when the yuan prices were compared to the 5 jiao standard, there were compatible and incompatible trials in both cases, close digit distance prices (incompatible trial: 4 yuan, 4 < 5 but yuan > jiao; compatible trial: 6 yuan, 6 > 5 and yuan > jiao) and far digit distance prices (incompatible trial: 1 yuan, 1 < 5 but yuan > jiao; compatible trial: 9 yuan, 9 > 5 and yuan > jiao). The same happened when fen prices were compared to 5 jiao standard. Compatibility was also equated when the digit distance was considered in Experiment 1. For instance, with the 5 euro standard (Experiment 1a), close digit distance prices involved compatible trials (e.g., 4 cent, cent < euro and 4 < 5) and incompatible trials (e.g., 6 cent, cent < euro but 6 > 5), and far digit distance prices included compatible trials (e.g., 1 cent, cent < euro and 1 < 5), as well as incompatible trials (9 cent, cent < euro but 9 > 5).

In short, although compatibility was equated in far/close digit distances (and no digit distance effects were found), it varies with far/close holistic distances (and holistic distance effects were observed). Thus, the compatibility between the digit and monetary category of prices would be sufficient to explain the results found by Cao et al. (2012) and these reported in Experiment 1.

Moreover, in Experiment 1, we also observed a digit distance 9 holistic distance interaction. The holistic distance effect was found on far digit distance trials, while it was not observed on close digit distance trials. Digits are irrelevant to perform the task with between-monetary category prices that can be compared by the processing of the monetary category only (5 euro–8 cent, euro < cent). Hence, this interaction suggests that holistic distance effects were found when the irrelevant dimension (digit distance) was easily processed (far distance). This finding can also be accommodated within the componential account of price processing. In fact, for the first time, the compatibility effect was described when participants processed two-digit numbers (Nuerk et al., 2001), and a similar pattern of results was reported2. To be more specific, for close decade distance trials, when the unit distance was far (the irrelevant dimension in two-digit number com- parison), and thus, more easily processed, the compatibility effect was larger (59 ms) relative to the compatibility effect when the unit distance was close (6 ms). Since the compatibility effect is the major source of evidence to dissociate between the holistic and componential processing of multi-symbol quantities, a systematic

[2] We are indebted to an anonymous reviewer of a previous (unpublished) version of this paper (in which only Experiment 1 was included). The author provided this argumentation and also inspired the experiments reported here manipulating the compatibility between the digit and the monetary category of prices.

analysis of this effect during the processing of prices was required. This was directly examined in Experiments 2 and 3.

Experiment 2

The goal of Experiment 2 was to evaluate the compatibility between the magnitude of digits and the monetary category of prices. There were compatible trials in which the digit and the monetary category of one price were larger than those of the other price (e.g., 8 euro–4 cent) and incompatible trials, where the digit of one price was larger, but the monetary category was smaller than those of the other price (e.g., 8 cent–4 euro). The majority of studies exploring the compatibility effect have used a comparison task with simultaneous presentation of stimuli (Macizo, 2015; Macizo, & Herrera, 2010, 2011a; Nuerk et al., 2001, 2004; although see Moeller et al., 2009). Hence, in Experiment 2a, participants performed a price comparison task with prices presented simultaneously. However, the task used in Experiment 1 involved the comparison of prices with a price that had to be maintained in memory (the standard price). Thus, to enable cross-experiment comparisons, a sequential presentation of prices was also implemented (Experiment 2b) in which participants had to decide whether one price was higher than another price presented previously.

Since the digit and holistic distance of prices was con- trolled in Experiment 2, the prediction regarding the processing of prices was clear. If participants process prices in a componential manner, a compatibility effect should be found in

Experiment 2 with faster performance on compatible trials relative to trials with incompatible price pairs.

Method

Participants

Thirty-three students took part in Experiment 2a (simultaneous presentation of prices) and 31 students took part in Experiment 2b (sequential presentation of prices). All students were from the University of Granada, they participated in exchange for course credits, and they provided informed consent before taking part in the experiment. In Experiment 2a and Experiment 2b, the mean age of the participants was 21.76 (SD = 3.57) and 21.64 (SD = 3.66) respectively; the number of female/male participants was 23/10 and 22/9, respectively, and the number of left/right-handed participants was 2/31 and 1/30, respectively. All participants used the Euro currency on a daily basis. They reported no history of numerical disabilities and they had normal or corrected-to-normal visual acuity.

Design and materials

Compatibility (compatible trials vs. incompatible trials) was manipulated within-participants. In addition, the presentation mode was considered to be a between-participant variable with two levels: simultaneous presentation (Experiment 2a) and sequential presentation (Experiment 2b). Thus, a 2 x 2 mixed design was used.

The experimental trials consisted of two prices. The prices contained one-digit number from 1 to 9 and a monetary category (euro-cent). Experimental prices were always between-monetary category comparisons (euro-cent) with different digits (e.g., 2 euro–2 cent was not used). The compatible condition was composed of pairs of prices in which the digit and the monetary category of one price were larger than those of the other price (e.g., 8 euro–4 cent). The incompatible condition was composed of two prices in which the digit of one price was larger, but the monetary category was smaller than those of the other price (e.g., 8 cent–4 euro).

The experimental trials were composed of 80 between-monetary category comparisons (40 compatible prices and 40 incompatible prices). The stimulus group on compatible and incompatible trials was equated both absolutely and logarithmically in terms of their absolute distance (in cents), digit distance, and problem size (mean value in cent of the two prices) (see Table 4 for further details).

In addition to 80 experimental trials, a set of 40 filler trials was included in Experiment 2. These trials were added to maintain the same percentage of within/between-monetary category comparisons used by Cao et al. (2012), and our Experiment 1 (66.67 and 33.33%, respectively). These trials were comparisons within the same monetary category (20 prices in euro and 20 prices in cent). The digits of filler prices were randomly selected from 1 to 9.

In studies with multi-symbol quantities (Huber, Bahnmuller, et al., 2015), slower reaction times are observed when there is incompatibility between the magnitude of digits and the length of the symbol (e.g., 2 m–1 mm, where 2 > 1 but 2 < 3 characters) relative to a length compatible condition (e.g., 1 m–2 km, where 1 < 2 and 2 < 3 characters). This possible string length effect did not apply in Experiment 2, since all prices used in compatible and incompatible trials had the same number of characters (e.g., 5 characters; e.g., 4 euro–5 cent, etc.).

Table 4. *Characteristics of experimental prices used in Experiments 2 and 3*

	Compatible prices	Incompatible prices
Abs. diff. (in cent)	522.25 (148.89)	467.75 (148.89)
Log. diff.	2.70 (0.15)	2.65 (0.14)
Digit diff.	2.50 (1.34)	2.50 (1.34)
Digit diff. log.	0.33 (0.25)	0.33 (0.25)
Problem size (in cent)	263.88 (75.34)	241.13 (75.34)
Problem size log.	2.40 (0.15)	2.36 (0.13)

Standard deviations are in brackets

Abs. absolute, Diff. difference, Log. logarithmic values

Procedure

The experiment was designed and controlled by the E-prime experimental software. The stimuli were presented in lower case black letters (Courier New font, 48 point size) on a white background. Participants were tested individually and were seated approximately 60 cm from the computer screen. The participants received 120 prices (80 experimental trials and 40 filler trials) randomly presented. All prices presented to the participants included one digit denoting the monetary value and the label denoting the monetary category. The labels used were ‘‘euro’’ and ‘‘cent’’ (e.g., 4 euro, 4 cent). A simultaneous (Experiment 2a) or sequential (Experiment 2b) presentation was used.

Experiment 2a: simultaneous presentation

Each trial began with a blank screen for 300 ms, after which two prices were presented in the middle of the screen above each other. The two prices were presented until the subject elicited a response. The participants were instructed to indicate as quickly and accurately as possible the higher of two prices by pressing the top key if the top price was higher and the bottom key if the bottom price was higher. On half of the trials, the top price was the higher and on the rest of trials the bottom price was the higher. The spatial presentation of the two prices (top/ bottom) and the response hand (right/left) was counter-balanced across participants. Half of the participants received the instructions to respond to the higher price with the right hand when it was presented at the top of the screen (U key) and with the left hand when it was presented at the bottom of the screen (B key). The remaining participants were instructed to respond to the higher price with the left hand when it was presented at the top of the screen (Y key) and with the right hand when it was presented at the bottom of the screen (N key).

Experiment 2b: Sequential presentation

When sequential number comparison tasks are used, several low-level perceptual features must be controlled, since they determine the compatibility effect with two-digit numbers (Moeller et al., 2009). Thus, the sequential presentation of prices in Experiment 2 followed the same procedure as that used by Moeller et al. for two-digit number pairs.

On each trial, two prices were presented sequentially in a central position, and the participants were instructed to indicate which of the two prices was higher. Half of the participants had to press the A button when the first price was higher and the L button when the second price was the higher one of the pair. The remaining participants pressed the L button when the first price was higher and the A button when the second price was the higher one of the pair. Each trial started with a blank screen for 300 ms followed by the first price which was presented for 800 ms. Afterwards, a backward mask (a row of Xs) was presented for 50 ms, followed by a blank screen for 150 ms. The second price was then presented until the participant made a response.

The backward mask was used to control for low-level perceptual influences of the rapid change of digits and monetary category positions due to the short interval between the two prices to be compared. Moreover, the first and second price did not appear in exactly the same location at the center of the screen, but their positions were jittered randomly by one character position to the left or to the right (see Moeller et al., 2009).

Results

Trials on which participants committed an error were eliminated (4.75%). As in Experiment 1, trials with RTs below and higher than 2 *SD* for each individual participant's mean were excluded from the analyses (3.90% in Experiment 2a and 3.71% in Experiment 2b).

RTs associated with correct responses were entered into an ANOVA with compatibility (compatible vs. incompatible) as a within-participant variable and presentation mode (simultaneous in Experiment 2a, and sequential in Experiment 2b) as a between-participant factor. The compatibility x presentation mode interaction was not significant, $F < 1$ (see Table 5). The main effect of compatibility was significant, $F(1, 62) = 22.32$, $p = .001$, $\eta_p^2 = .007$. Participants were faster on compatible trials ($M = 930$ ms, $SE = 35$) relative to incompatible trials ($M = 981$, $SE = 39$). The main effect of presentation mode was not significant, $F < 1$. Participants took a similar amount of time to respond to prices presented simultaneously ($M = 973$ ms, $SE = 51$) and those presented in sequential mode ($M = 938$ ms, $SE = 53$).

Table 5. *Results obtained in Experiment 2*

	Simultaneous presentation		Sequential presentation	
	RT	*E%*	RT	*E%*
Compatible trials	944 (49)	0.76 (0.70)	916 (50)	6.13 (0.72)
Incompatible trials	1001 (55)	4.55 (0.95)	960 (56)	7.58 (0.98)
Compatibility Effect	56*		44*	

*Results obtained on the price comparison task as a function of presentation mode (simultaneous, sequential). Standard error is reported in brackets. * p \ .05*

RT reaction times (in ms), E% error percentages, Compatibility effect incompatible minus compatible

Discussion

In Experiment 2, we evaluated the possible compatibility effect when participants performed price comparison tasks. The results we observed were clear-cut. Performance was better on compatible trials relative to incompatible trials. The compatibility effect was found when the task involved the simultaneous comparison of prices (Experiment 2a) and when prices were presented sequentially (Experiment 2b). The compatibility effect obtained in the simultaneous processing of prices extends the results of previous studies in which compatibility effects are found with simultaneous presentation of two-digit numbers (Macizo, 2015, Nuerk et al., 2001) and multi-symbol quantities (e.g., measurement units, Huber et al., 2015).

There are very few studies in which the quantities to be compared follow a sequential presentation. For instance, Ganor-Stern et al. (2009) failed to find compatibility effects with two-digit numbers suggesting that when the task involves the maintenance of one number in memory (the first number which serves as the standard price), participants judge the magnitude of the second number in a holistic manner. However, other studies have found the compatibility effect with two-digit numbers presented in a sequential mode when some methodological flaws were addressed (Moeller et al., 2009). For example, Ganor-Stern et al. (2009) employed a sequential arrangement in which the first and second numbers were presented in the same location. The rapid change of decades and units between the first and second number might modulate the comparison process. Moeller et al. (2009) controlled for this factor by the inclusion of a mask after the presentation of the first number and by jittering the position of the second number. In this situation, compatibility effects were also found during the sequential processing of two-digit numbers. When these perceptual variables were controlled for in Experiment 2, the compatibility effect also emerged when participants compared the magnitude of prices.

In Experiment 2, the digit distance and holistic distance of prices were equated in compatible and incompatible comparisons. Moreover, in Experiments 1 and 2b, participants had to indicate whether a price was higher than another price maintained in memory (internal standard in Experiment 1, the first price presented in the sequential presentation mode of Experiment 2b). The difference between experiments was that compatibility was not considered in Experiment 1, while it was directly manipulated in Experiment 2. In this scenario, the observation of a compatibility effect agrees strongly with the componential account of price processing. Thus, prices would be processed in the same way as other multi-symbol quantities (Huber et al., 2016; Huber, Bahnmueller, et al., 2015; Huber, Cornelsen, et al., 2015; Macizo, 2015; Nuerk et al., 2001).

Experiment 3

In Experiment 2, we observed compatibility effects between the digits and the monetary category of prices: the price comparison tasks were performed faster on compatible trials (e.g., 8 euro–4 cent) relative to incompatible trials (e.g., 4 euro–8 cent). This finding cannot be explained by a holistic account of price processing. In contrast, it strongly suggests that prices are processed in a componential manner similar to the way in which two-digit numbers are analyzed. Experiment 3 aimed to reinforce this conclusion by exploring contextual factors that might be expected to modulate the magnitude of the compatibility effect in the price comparison task.

In two-digit number processing, it has been shown that the compatibility effect depends on the amount of intra/inter decade comparisons. Zhang and Wang (2005) used a comparison task with a standard procedure in which participants received a two-digit number and they were required to decide whether it was larger than a standard number presented previously (55 or 65). The experiment included 13% within-decade comparisons. The authors observed that the units did not play an independent role, which led them to suggest that two-digit numbers were processed holistically. However, Moeller et al. (2009), observed unit-based effects with the same task when the percentage of within-decade comparisons was increased to 50% to preclude any attentional bias towards the decades. Similarly, Macizo and Herrera (2011b) evaluated the compatibility effect with number words while varying the relevance of the unit digit by manipulating the intra/inter decade comparison ratio (20, 50, and 70%). The authors found regular compatibility effects with slower responses on incompatible trials relative to compatible trials only when the intra/inter decade comparison ratio was high (70%). Therefore, these studies indicate that participants exert cognitive control so they adjust the weight given to the processing of decades or units based on their relevance for performing the comparison task. When the intra/inter decade comparison ratio is high, the relevance of units increases relative to the condition with a low intra/inter decade comparison ratio. The increased processing of units would reinforce the compatibility effect, since units are irrelevant for performing the comparison task with between-decade comparisons.

In Experiment 3, we evaluated whether the relevance of the digits and the monetary category also modulated the processing of prices. To this end, participants performed the comparison task with between-monetary category prices under two conditions: high intra/inter monetary category ratio (80%) and low intra/inter monetary category ratio (20%). With a large number of intra monetary category comparisons (e.g., 2 euro–6 euro), the importance of the digits increases, since their processing is necessary for selecting the higher price. If prices are analyzed in a componential manner and the processing of the digit and the monetary category depends on their relevance for performing the price comparison task, the compatibility effect should be larger in the high vs. low intra/inter monetary category ratio.

Method

Participants

Thirty-five students took part in Experiment 3a (20% intra/inter monetary category ratio) and 35 students in Experiment 3b (80% intra/inter monetary category ratio). The students were from the University of Granada and had not participated in any of the previous experiments. In Experiment 3a and Experiment 3b, the mean age of the participants was 23.23 (*SD* = 3.68) and 22.43 (*SD* = 3.19), respectively; the number of female/male participants was 20/15 and 25/10, respectively; and the number of left/right- handed participants was 3/32 and 4/31, respectively. All participants used the Euro currency on a daily basis. They reported no history of numerical disabilities and they had normal or corrected-to-normal visual acuity.

Design and materials

Compatibility (compatible trials vs. incompatible trials) was manipulated within-participants. In addition, the intra/inter monetary category ratio was considered a between- participant variable with two levels: 20% intra/inter monetary category ratio (Experiment 3a) and 80% intra/inter monetary category ratio (Experiment 3b). Thus, a 2 x 2 mixed design was used.

The experimental trials were the same 80 between-monetary category comparisons (40 compatible prices and 40 incompatible prices) as those employed in Experiment 2. However, the number of filler trials varied across Experiment 3a and 3b. In Experiment 3a, 20 filler trials with within-monetary comparisons were added (10 comparisons with euro prices and 10 comparisons with cent prices). In Experiment 3b, 320 filler trials with within-monetary comparisons were included (160 comparisons with euro prices and 160 comparisons with cent prices).

Procedure

The procedure used in Experiment 3 was the same as that described in the simultaneous presentation of prices in Experiment 2a. The only difference was the amount of trials participants received. In Experiment 3a, participants received 80 between-monetary category trials (40 compatible trials, 40 incompatible trials), and 20 within-monetary category comparisons; therefore, the intra/inter monetary category ratio was 20%. In Experiment 3b, participants received 80 between-monetary category trials and 320 within-monetary category comparisons; thus, the intra/ inter monetary category ratio was 80%.

Results

Trials on which participants committed an error were eliminated (6.09%). After this, trials with RTs below and higher than 2 *SD* for each individual participant's mean were excluded from the analyses (3.82% in Experiment 3a and 4.82% in Experiment 3b).

The RTs associated with correct responses were entered into an ANOVA with compatibility (compatible vs. incompatible) as a within-participant factor and the intra/inter monetary category ratio (20% in Experiment 3a and 80% in Experiment 3b) as a between-participant factor. The compatibility x intra/inter monetary category ratio was significant, $F(1, 68) = 15.34$, $p < .001$, $\eta_p^2 = .005$ (see Table 6). The compatibility effect was significant in the 20% intra/inter monetary category ratio, $F(1, 34) = 34.02$, $p < .001$, $\eta_p^2 = .021$, and the 80% intra/inter monetary category ratio, $F(1, 34) = 81.06$, $p < .001$, $\eta_p^2 = .058$; however, the magnitude of the compatibility effect was larger in the 80 vs. 20% intra/inter monetary category ratio (101 and 47 ms, respectively). The main effect of compatibility was significant, $F(1, 68) = 114.82$, $p < .001$, $\eta_p^2 = .039$. Participants were faster on compatible trials (*M* = 914 ms, *SE* = 22) relative to incompatible trials (*M* = 987, *SE* = 23). The main effect of intra/inter monetary category ratio was also significant, $F(1, 68) = 15.94$, $p < .001$, $\eta_p^2 = .186$. Participants took more time to respond on the 80% intra/inter monetary category ratio trials (*M* = 1038 ms, *SE* = 31) relative to the 20% intra/inter monetary category ratio trials (*M* = 863 ms, *SE* = 31).

Table 6. *Results obtained in Experiment 3*

	20% intra/inter monetary category ratio		80% intra/inter monetary category ratio	
	RT	*E%*	RT	*E%*
Compatible trials	839 (31)	0.64 (0.29)	987 (31)	1.50 (0.29)
Incompatible trials	886 (32)	2.29 (1.39)	1088 (32)	19.93 (1.39)
Compatibility effect	47*		101*	

*Results obtained on the price comparison task as a function of the intra/inter monetary category ratio (20, 80%). Standard error is reported in brackets. * p < .05*

RT reaction times (in ms), E% error percentages, Compatibility effect incompatible minus compatible

Discussion

The results obtained in this experiment reveal a compatibility effect when participants performed a price comparison task. The observation of this effect supports the componential account of price processing. When participants compared prices, they processed the digits and the monetary category separately. In between-monetary comparisons (e.g., 2 euro–8 cent), the processing of the monetary category was sufficient to produce the correct answer (e.g., 2 euro > 8 cent); however, even when the digit was irrelevant, it was processed and influenced the comparison process. Moreover, the results found in Experiment 3 indicate that the degree of interference depends on the need to process the irrelevant dimension of the price in the experiment (e.g., the digit in between-decade comparisons). Thus, when the percentage of intra/inter monetary comparisons was high (80%), the compatibility effect increased relative to the condition with 20% intra/inter monetary comparisons. Previous studies have shown this contextual modulation when individuals process two-digit numbers (Macizo, & Herrera, 2011a). The current experiment extends this finding to the processing of prices.

General discussion

To our knowledge, the study conducted by Cao et al. (2012) is the only one in which the holistic vs. componential processing of prices has been evaluated. The authors found a holistic distance effect in the absence of a digit distance effect when participants compared the magnitude of prices relative to an internal standard price. It was concluded that price constitutes a unique category that is processed holistically. The current study aimed to evaluate this conclusion in more depth, because it runs counter to theories of multi-symbol processing in which a componential type of processing is assumed (Huber et al., 2016). Evidence supporting the componential processing of quantities has been shown for two-digit numbers (Macizo, 2017; Nuerk et al., 2001), three-digit numbers (Huber et al., 2013), the symbol and digit of negative numbers (Huber, Cornelsen, et al., 2015), and measurement units (Huber, Bahnmueller, et al., 2015). Therefore, additional empirical evidence was required to determine the way in which prices are processed.

In Experiment 1, we employed the same markers utilized by Cao et al. (2012) to index the holistic vs. componential processing of prices: the holistic distance and digit distance, respectively, when participants compared the magnitude of prices relative to an internal standard (5 euro in Experiment 1a and 5 cent in Experiment 1b). The pattern of results found in Experiment 1 confirmed those reported previously. In between-monetary category comparisons (e.g., cent vs. euro prices), participants were faster when judging far holistic distances (5 euro–2 cent) than close holistic distances (5 euro–9 cent). This was evident regardless of the standard price (5 euro and 5 cent). However, the digits might still play a role in the processing of prices, since the digit distance interacted with the holistic distance in Experiment 1.

Furthermore, even when the experiment reported by Cao et al. (2012) and our Experiment 1 were correctly designed and performed, there was a methodological flaw inherent in the selection of prices in comparison tasks with a fixed standard. In particular, and as we have already explained in previous sections of this report, all trials in the close holistic distance condition (5 euro–9 cent) are also incompatible stimuli (5 < 9 but euro > cent) while all trials in the far holistic distance condition (5 euro–2 cent) are compatible (5 > 2 and euro > cent). Hence, the slower responses in close vs. far holistic distance trials might be due to a compatibility effect; this effect has been well established in number cognition, where poorer performance is observed on incompatible trials relative to compatible trials (Macizo, & Herrera, 2010, 2011a, 2011b, 2013b; Nuerk et al., 2001, 2004).

In Experiments 2 and 3, we directly evaluated the compatibility effect during the processing of prices while controlling for other factors that might determine the performance of participants (digit distance, holistic distance, and low-level perceptual factors). Across several experiments in which we examined various factors (the mode of presentation in Experiment 2 and the intra/inter monetary category ratio in Experiment 3), we obtained a clear-cut pattern of results. The participants performed better on compatible trials relative to incompatible trials.

In Experiment 2, we explored the compatibility effect in the classic task used to evaluate the componential processing of two-digit numbers (simultaneous presentation). Moreover, we also examined the processing of prices when presented sequentially, which was similar to the task used in Experiment 1. The critical difference between the sequential and simultaneous presentation of prices is that the former involves the maintenance of information in memory (the standard price in this case) to perform the task. In contrast, memory requirements would be reduced when the prices are presented simultaneously. Individuals appear to cluster information in working memory, a chunking process by which pieces of information are bound together in a meaningful whole for later recall (Miller, 1956). This observation would favor the holistic processing of prices, where the digit and the monetary category are grouped and maintained in memory as an integrated whole. Nevertheless, compatibility effects were observed in the simultaneous and sequential processing of prices, suggesting that separate comparisons of digits and monetary categories took place in both cases, regardless of the memory demands imposed by the comparison task.

Moreover, the compatibility effect found with prices in the current study seems to be subject to the same principles that govern the processing of two-digit numbers. In particular, the processing of between-monetary category comparisons is influenced by contextual information (Macizo, & Herrera, 2011b, for this observation in two-digit number processing). Even when between-monetary category comparisons can be made by processing only the monetary category, digits are processed. Importantly, the degree to which the processing of digits affects the comparison process depends on their relevance during the experimental task. In Experiment 3, we found that the compatibility effect was modulated by the intra/inter monetary category ratio. When it was high (80%), the compatibility effect increased relative to the low intra/inter monetary category condition (20%). To perform within-monetary category comparisons, the processing of the digits is mandatory. Thus, a higher percentage of intra monetary category comparisons would foster the processing of the digits and would determine the analyses of between-monetary category prices. Figure 1 shows the compatibility effect across three conditions that use a similar mode of presentation (simultaneous) but different intra/inter monetary category ratios (bars in grey color). The magnitude of the compatibility effect linearly increased as a function of the percentage of within-monetary category comparisons.

If we return to previous results supporting the holistic account of price processing (Cao et al., 2012) and those reported here (Experiment 1), we have argued that the compatibility between the digit and monetary category might be the underlying factor explaining the holistic distance effect. This conclusion is strengthened in Experiments 2 and 3. To be more specific, the magnitude of the holistic distance effect found in Experiment 1 (43.92 ms) was practically the same as that of the compatibility effect observed in the experiment with similar methodological conditions (43.93 ms, Experiment 2a with sequential presentation mode, and 33% intra/inter monetary category ratio; see Figure 2, bars in black color).

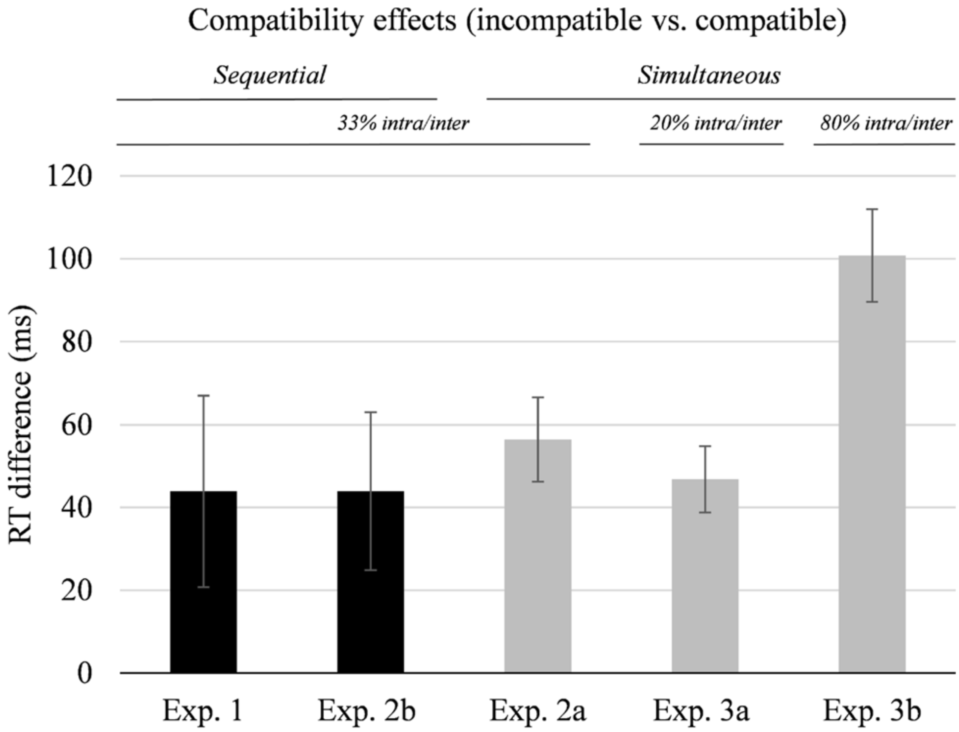

Figure 2. Compatibility effects (incompatible minus compatible) obtained in the study across experiments. Note that the compatibility effect in Experiment 1 is also the holistic distance effect (compatible = far holistic distance, incompatible = close holistic distance). Sequential and simultaneous refer to the presentation mode of prices; % intra/inter indicates the percentage of intra/inter monetary category comparisons. Bars in black color show the experiments with the same methodological conditions (sequential presentation and 33% intra/ inter monetary category comparisons). Error bars represent standard error.

Taken together, the findings reported in this study are generally in line with a componential model of multi-symbol processing (Huber et al., 2016). In this model, it is proposed that multi-symbol numbers consisting of digits only (e.g., the decade and the unit in 42), digits and other characters (e.g., negative symbol and number in -4), and physical quantities (e.g., the digit and the measurement unit in 4 cm) are processed and compared to each other separately in a componential manner. The results found in our study appear to indicate that prices composed of a digit and a monetary category (e.g., 4 euro) should also be understood as multi-symbol numbers. Thus, an adapted version of the multi-symbol processing model would include separate pathways for the processing of the digit and the monetary category constituents of prices. Hence, we suggest that magnitude would be accessed separately for the case of digits and monetary category. The activated magnitude representations within each pathway would be compared and the result of these independent comparisons could lead to the same response (which is, for example, observed when comparing a compatible pair of prices) or diverge (e.g., on incompatible trials). This would determine whether or not conflict arises in price comparison tasks.

In sum, this study suggests that prices are not a unique category of quantity representation. Similar to multi-digit numbers and measurement units, prices appear to be processed in a componential manner.

CHAPTER VI

How do we process prices? Electrophysiological evidence of componential analysis[3]

The aim of this study was to evaluate if the processing of prices (e.g., 8 euro) involves separate analysis of the digit (8) and the monetary category (euro). Event-related potentials (ERPs) were recorded when participants performed a price comparison task in which a pair of prices was presented and they selected the one with higher monetary value. There were compatible comparisons where the digit and the monetary category of one price were higher than those of the other price (e.g., 7 euro – 4 cent, 7 > 4 and euro > cent), and incompatible comparisons where the number of one price was larger but the monetary category smaller than those of the other price (e.g., 4 euro – 7 cent, 4 < 7 but euro > cent). Compatibility effect modulated ERPs in the 350–450 ms time window, with more negative amplitudes in incompatible trials relative to compatible trials. This pattern of results suggests that prices were processed in a componential manner, challenging the evidences of the holistic model. The results of this study agree with the general model framework for multi-symbol number comparison: The constituents of a multi-symbol magnitude are processed and compared to each other separately in a componential manner.

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Introduction

In spite of being a common activity in everyday life, the way people process money has not been considered too much from a cognitive perspective. There is very little research evaluating how people orally produce the monetary value printed on coins and banknotes (Macizo & Herrera, 2013b; Macizo & Morales, 2015, Ruiz et al., 2017) and how they understand their monetary value (Cao et al., 2012, 2015; Dehaene & Marques, 2002; Goldman etl., 2012; Thomas & Morwitz, 2005).

Cao et al. (2012) was one of the few studies that aimed to investigate the processing of prices, to be more precise, how people compared the magnitude of prices. The objective of Cao et al. was to dissociate between two accounts of price processing, the holistic view and the componential view, based on the study of multi-symbol number processing (Huber et al., 2016). On the one hand, from the holistic perspective it is assumed that the magnitude of two-digit numbers is computed as a whole, being understood as unitary entities represented in a linearly ordered single space. This means that the decade and the unit of multidigit numbers do not have an independent contribution when individuals decide the larger of a two-digit number pair in a comparison task (Dehaene et al., 1990; Hinrichs et al., 1981). On the other hand, the componential view defends that the constituents of two-digit numbers are separately processed and, differently from the holistic view, both the decade digit and the unit digit contribute to the decision about the magnitude of the numbers (Nuerk et al., 2001, 2004). Recently, this componential perspective has been reflected in a general model framework for multi-symbol number processing in which it is suggested that multi-symbol number strings that consist of digits only (e.g., two-digit numbers) or digits and other characters (e.g., the polarity sign in negative numbers, measurement units) have common processing characteristics. To be more specific, regardless of whether a multi-symbol number consists of digits only (e.g., 28) or of digits and other characters (e.g., -28, 28 cm) the constituents of the respective multi-symbol number are processed and compared to each other separately in a componential manner (Huber et al., 2016).

Cao et al. (2012) used a comparison task with Chinese prices in which prices were presented (e.g., 2 yuan) and participants had to decide whether they were higher or lower than a standard price (5 jiao) (Chinese prices are composed of a number and a monetary category; 1 yuan = 10 jiao). To dissociate between the holistic and componential accounts, the authors considered the distance effect (the time required to compare two magnitudes varies inversely with the numerical distance between them, Moyer & Landauer, 1967). Two types of distances were defined, close and far, taking into consideration the whole magnitude of the prices or the digit magnitude. To illustrate, compared to the standard price (5 jiao), there were close (1 yuan) and far (9 yuan) holistic distance prices as well as close (4 yuan) and far (1 yuan) digit distance prices.

Cao et al. (2012) found a holistic distance effect with behavioural and electrophysiological measures. Regarding the behavioural analyses, when yuan prices were compared with the 5 jiao standard price, the accuracy was higher and the reaction times (RTs) were faster with far holistic distance prices relative to close holistic distance prices. Furthermore, when focusing on the electrophysiological pattern of results, the authors observed greater positivity for far holistic distances than for close distances in the 350-450 ms period. This event-related potential (ERP) modulation located on posterior scalp distributions (i.e., occipito-parietal regions) when participants compared the magnitude of prices was interpreted as a P3 potential (Cao et al., 2015). This component is sensitive to several cognitive processes and thus, its interpretation is not straightforward; however, in the context of magnitude comparison tasks, the P3 component seems to reflect magnitude processing (e.g., Dehaene, 1996; Turconi, et al., 2004). Nevertheless, behavioural and electrophysiological analyses did not reveal distance effects when they were defined in terms of the digits of prices. From these results, the authors concluded unambiguously that the processing of prices was not componential but holistic.

The notion of holistic processing of prices (Cao et al., 2012) contrasts sharply with the evidence from a large number of studies supporting the componential processing of multi-digit numbers (Macizo, 2017; Macizo et al., 2010; Macizo et al., 2011a; Macizo & Herrera, 2008, 2010, 2011a, 2011b; Macizo & Herrera, 2013a; Moeller et al., 2013; Nuerk et al., 2001). The major source of evidence in favor of the componential perspective comes from the unit-decade compatibility effect (compatibility effect for short, see Nuerk et al., 2011, for a review); an instance of conflict situation in magnitude processing (Macizo, 2017). When individuals decide the larger of a two-digit number pair, while controlling for overall numerical distance, their responses are slower when the decade of one number is larger but the unit is smaller than those of the other number (incompatible trials, i.e., 62-47, 6 > 4 but 2 < 7) relative to number pairs in which the decade and the unit of one number are larger than those of the other number (compatible trials, i.e., 67-52, 6 > 5 and 7 > 2). Within the componential perspective, this conflict effect reflects separate but interactive comparisons of the decade magnitude and the unit magnitude. These comparisons are assumed to activate the corresponding response. On compatible trials, the activation of decade and unit comparisons converge to select the correct response, while on incompatible trials, unit comparisons and decade comparisons lead to a different response, thus increasing the time needed to make the correct selection.

The compatibility effect has been shown for two-digit numbers (Macizo, 2017; Nuerk et al., 2001), three-digit numbers (Huber, et al., 2013), the symbol and digit of negative numbers (Huber, Cornelesen, et al., 2015), and measurement units (Huber, Bahnmuelleret al., 2015). Moreover, neuroimaging studies have found neural correlates of the compatibility effect through different methods such as ERPs (Szűcs & Soltész, 2010), and fMRI (Wood, et al., 2006). Thus, the conclusion that prices are processed holistically runs counter to general theories of multi-symbol processing in which a componential type of processing is assumed (Huber et al., 2016).

Following the general framework for multi-symbol number comparison (Huber et al., 2016), prices should be understood as multi-symbol numbers. Accordingly, the constituents of prices (the digit and the monetary category) should be processed separately in a componential manner. Therefore, a compatibility effect such as that found for digits, polarity sign and measurement units should be observed when comparing the magnitude of prices as well. According to this hypothesis, Macizo and Ojedo (2017) showed that the holistic distance effect found by Cao et al. (2012) could be explained by the compatibility between the digits and the monetary category of prices. In fact, there was a drawback which was inherent in the design utilized to evaluate digit and holistic distance effects. To be more specific, there was a confound between the holistic distance of prices and the compatibility between the digits and the monetary categories. When yuan prices were compared to the 5 jiao standard, close holistic distance prices (1 yuan) were always incompatible comparisons (yuan > jiao but 1 < 5), while far holistic distance prices (9 yuan) were always compatible comparisons (yuan > jiao and 9 > 5). Therefore, slower reaction times in the close holistic distance condition (incompatible trials) relative to the far holistic distance condition (compatible trials) could be due to a compatibility effect. In contrast, the compatibility was equated in the far/close digit distance conditions. To illustrate, compared to the 5 jiao standard, there were compatible and incompatible trials in both cases, close digit distance prices (incompatible trial: 4 yuan, 4 < 5 but yuan > jiao; compatible trial: 6 yuan, 6 > 5 and yuan > jiao) and far digit distance prices (incompatible trial: 1 yuan, 1 < 5 but yuan > jiao; compatible trial: 9 yuan, 9 > 5 and yuan > jiao). In short, although compatibility was equated in far/close digit distances (and no digit distance effects were found), it varied with far/close holistic distances (and holistic distance effects were observed). Thus, the compatibility between the digit and monetary category of prices would be sufficient to explain the results found by Cao et al. (2012).

Macizo and Ojedo (2018, Experiments 2 and 3) evaluated directly the compatibility between the magnitude of digits and the monetary category after controlling for the digit and holistic distance of prices in the euro currency (Euro prices are composed of a number and a monetary category; 1 euro = 100 cents). There were compatible trials in which the digit and the monetary category of one price were larger than those of the other price (e.g., 8 euro - 4 cent, 8 > 4 and euro > cent); and incompatible trials where the digit of one price was larger but the monetary category was smaller than those of the other price (e.g., 8 cent - 4 euro, 8 > 4 but cent < euro). The results were clear-cut: performance was better (the RTs were faster and the accuracy was higher) on compatible trials relative to trials with incompatible price pairs. The compatibility effect was found when the task involved the simultaneous comparison of prices (Experiment 2a and 3), and when prices were presented sequentially (Experiment 2b). The existence of compatibility effects between the digits and the monetary category of prices suggests that cognitive processing of prices was not holistic but componential.

A recent ERP study also left open the possibility that the compatibility between the digits and the monetary category could play a role in the processing of prices. Cao et al. (2015) assumed a hybrid model in which the overall magnitude and the magnitude of the two constituents of the prices would be processed (see Nuerk & Willmes, 2005, for a hybrid model of two-digit number processing). In the study, the authors considered the overall distance between pairs of Chinese prices as an index of holistic processing, and the digit/monetary category compatibility as an index of componential analysis. The authors observed compatibility effect on behavioral measures with faster responses on compatible trials than on incompatible trials; however, the holistic distance effect was not significant. The ERP data revealed holistic distance effects over frontal locations. N2 amplitudes were more negative on far distance prices than on close distance prices. In addition, the compatibility modulated ERP components in parietal regions. In particular, the compatibility effect was marginal in the 350-450 ms time-window with greater negativity for incompatible prices than compatible prices.

The frontal N2 modulations associated to the holistic distance were considered evidence that the whole magnitude of the price pairs was computed. Furthermore, the posterior negativity obtained in the incompatible condition relative to the compatible condition was taken as an N400-like effect related to semantic integration between digits and monetary category. Thus, Cao et al. (2015) concluded that prices were processed in a holistic and componential manner. However, the authors acknowledged some inconsistent findings. In particular, the distance effect as an index of magnitude processing usually modulates the N1-P2p complex in posterior regions (Dehaene, 1996; Libertus et al., 2007; Pinel et al., 2001; Temple & Posner, 1998); in Cao et al.'s study, frontal N2 modulations associated to the distance effect were found instead. In addition, Cao et al. (2015) found negative polarity modulations in the 350-450 period associated to the compatibility of price pairs over posterior regions. However, these N400-like modulations are usually observed over frontal and fronto-central regions in conflict tasks that involve magnitude processing (Schwarz & Heinze, 1998; Szűcs & Soltész, 2007; West et al., 2005), and they are interpreted either as reflecting the conflict-monitoring activity of the anterior cingulate cortex (Liotti et al., 2000; West & Alain, 1999), or as an N400 component (Rebai et al., 1997), that indexes semantic analysis (Kutas & Hillyard, 1980).

Moreover, Cao et al. (2015) manipulated the holistic distance and the compatibility between the digits and the monetary category within the same design. However, when one-digit price pairs are considered, there is a close relationship between the compatibility and the holistic distance where compatible trials usually exhibit far holistic distance and incompatible trials close holistic distance[4]. Therefore,

[4]Cao et al.'s (2015) study was a short report that did not provide detailed information about stimulus selection and levels of the holistic distance factor. Importantly, to explore the compatibility between digits and monetary categories, the holistic and digit distance should be equated in compatible and incompatible comparisons. In text, the authors reported the use of 18 Chinese prices ranging from 1 jiao to 9 yuan. These prices were composed of nine Arabic digits (1-9) combined with two monetary units (yuan and jiao) (Cao et al., 2015, p. 839). According to this description, the total number of between-monetary price comparisons (e.g., 1 jiao - 2 yuan) with the 18 Chinese prices was 72 price pairs (excluding price pairs with the same digit, e.g., 1 jiao - 1 yuan, that cannot be used when the compatibility factor is manipulated). Thirty-six of these price pairs are compatible comparisons and 36 are incompatible comparisons. However, in this situation, there is an intrinsic association between the compatibility and the holistic distance: When all these prices are transformed to jiao prices (1 yuan = 10 jiao), the holistic distance of compatible prices and incompatible prices is 63.33 and 26.67, respectively. Thus, compatible comparisons exhibit far distances and incompatible comparisons close distances. Finally, it is unknown the way digit distance was controlled for between compatible trials and incompatible trials.

given all these aspects, the conclusions drawn by Cao et al.'s study should be interpreted with caution.

Experiment 4

Electrophysiological evidence suggests that price processing is performed holistically (Cao et al., 2012). However, previous studies may suffer from confusion between holistic distance and price compatibility. The goal of this work was to explore whether the processing of prices is holistic or componential (as suggested in the general model framework for multi-symbol number comparison, Huber et al., 2016) when this potential confound between factors was controlled. To this end, an electrophysiological experiment was conducted to evaluate the compatibility between the magnitude of digits and the monetary category of prices. A comparison task with sequential presentation of prices was used (Macizo & Ojedo, 2018, Experiment 2b) in which participants had to decide whether one price was higher than another price presented previously. There were compatible trials in which the digit and the monetary category of one price were larger than those of the other price (e.g., 8 euro - 4 cent); and incompatible trials where the digit of one price was larger but the monetary category was smaller than those of the other price (e.g., 8 cent - 4 euro). In the experiment, we took care to control for the holistic distance of prices in the compatible/incompatible conditions.

In our study, we expected to find a digit/monetary category compatibility effect. This effect would support the generalized model framework account which defends the componential processing of the constituents of multi-symbol numbers

(Huber et al., 2016). Our study cannot distinguish between a purely componential view and a hybrid model of price comparison because we did not explicitly test whether holistic magnitude influenced the processing of prices. Instead, we compared a purely holistic perspective to a compositional view. According to the compositional view, at the behavioural level, we expected to corroborate the pattern of results found in previous studies (Cao et al., 2015; Macizo & Ojedo, 2018) with faster RTs and higher accuracy on compatible trials relative to incompatible trials. To perform the task, the participants had to necessarily process the magnitude of the prices, however, at the neural level, no effects were expected between compatible and incompatible trials in ERP components associated to magnitude processing (i.e., N1-P2p modulations, Dehaene, 1996; Libertus et al., 2007; Pinel et al., 2001; Temple & Posner, 1998; Turconi et al., 2004) since we controlled for the holistic distance and the digit distance between these two conditions. However, the compatibility would modulate an ERP component (i.e., N400-like component) related to conflict resolution in magnitude processing. In particular, more negative amplitudes were expected over frontal electrodes on incompatible price comparisons relative to compatible comparisons. These predictions were based on previous studies in which it is observed that this N400-like component is sensitive to the processing of conflict in magnitude processing (e.g., Schwarz & Heinze, 1998; Szűcs & Soltész, 2007; West et al., 2005).

Method

Participants

Twenty-six students (19 women and 7 men) took part in this experiment. The participants' mean age was 21.27 (*SD* = 2.08). All of them used the Euro currency on a daily basis, and they had normal or corrected-to-normal visual acuity. Participants signed an informed consent form before performing the experiment and they were rewarded with academic credits.

Task

A price comparison task was used, where participants received a sequence of two prices and they had to indicate the price with higher monetary value as quickly and accurately as possible. Participants used the keyboard to give their answers by pressing "A" or "L" keys. The assignment of the first/second price to the A/L keys was counterbalanced across participants.

Stimuli

The stimuli used in the comparison task were prices formed by one-digit number (from 1 to 9) and a monetary category (euros or cents). We used the word "euro" instead of the frequent symbol € to make the length of the prices in euros ("euros", five characters) and cents ("cents", five characters) comparable. This avoids the possible string length congruity effect (responses are longer and error rates higher when a number, e.g., a decimal fraction such as 7.14, has less magnitude but more characters than another number, e.g., 7.6) (Huber et al., 2014). The experimental prices were between-monetary category comparisons that included a price in euros and another price in cents. All price pairs included different digits (e.g., 4 euro - 4 cent was not used). The digit/monetary category compatibility was manipulated within-participants. There were 40 compatible price comparisons and 40 incompatible price comparisons. The compatible and incompatible conditions were equated both absolutely and logarithmically in terms of their absolute distance (in cents), digit distance, and problem size (mean value of the two prices in cents) (see Table 7 for further details).

Table 7. *Characteristics of Experimental Prices Used in the Study*

	Compatible	Incompatible	*t*(78)	*p*
Abs. diff. (in cent)	522.25 (148.89)	467.75 (148.89)	1.64	.11
Log. diff.	2.70 (0.15)	2.65 (0.14)	1.49	.14
Digit diff.	2.50 (1.34)	2.50 (1.34)	0	1
Digit diff. log.	0.33 (0.25)	0.33 (0.25)	0	1
Problem size (in cent)	263.88 (75.34)	241.13 (75.34)	1.35	.18
Problem size log.	2.40 (0.15)	2.36 (0.13)	1.20	.23

Note. Abs. = Absolute, Diff. = Difference, Log. = logarithmic values. Standard deviations are in brackets. Compatible and Incompatible refer to the compatibility between the digits and the monetary categories of price pairs.

In addition to the 80 experimental comparisons (between monetary category comparisons), we used a set of 40 filler trials (within monetary category comparisons). These trials were included in order to maintain the same percentage of within/between monetary category comparisons employed by Cao et al. (2012; 66.67% and 33.33%, respectively). In order to obtain more observations in each experimental condition, the experimental and filler trials were presented twice. So that each participant received 80 compatible prices, 80 incompatible prices, and 80 filler trials. The participants received these prices in random order.

Procedure

The participants were seated approximately 60-70 cm from the computer screen (Captativa E1903D, LCD, 1280 x 1024, 60 Hz, 19 ’’) and each stimulus was presented in Arial 30-point font. All prices were presented in black font on a white background. We used a sequential presentation of prices since this is the usual way of presenting the stimuli in electrophysiological studies on magnitude processing (Temple & Posner, 1998; Turconi et al., 2004). In behavioural studies with sequential presentation of prices, the second price is presented until the participant's response (e.g., Macizo & Ojedo, 2018). However, because our task was adapted for the recording of the EEG associated with the second price, we decided to follow the same procedure used in electrophysiological studies on price processing (short presentation of the second stimulus followed by a blank screen, Cao et al., 2012, 2015). Thus, in each trial, a blank screen was presented for 500 ms. Then, the first price appeared at the centre of the screen during 800 ms, followed by a mask (row of Xs) which was presented for 50 ms. Afterwards, the second price was presented during 500 ms and, finally, a blank screen appeared until the response of the participant (see Figure 3).

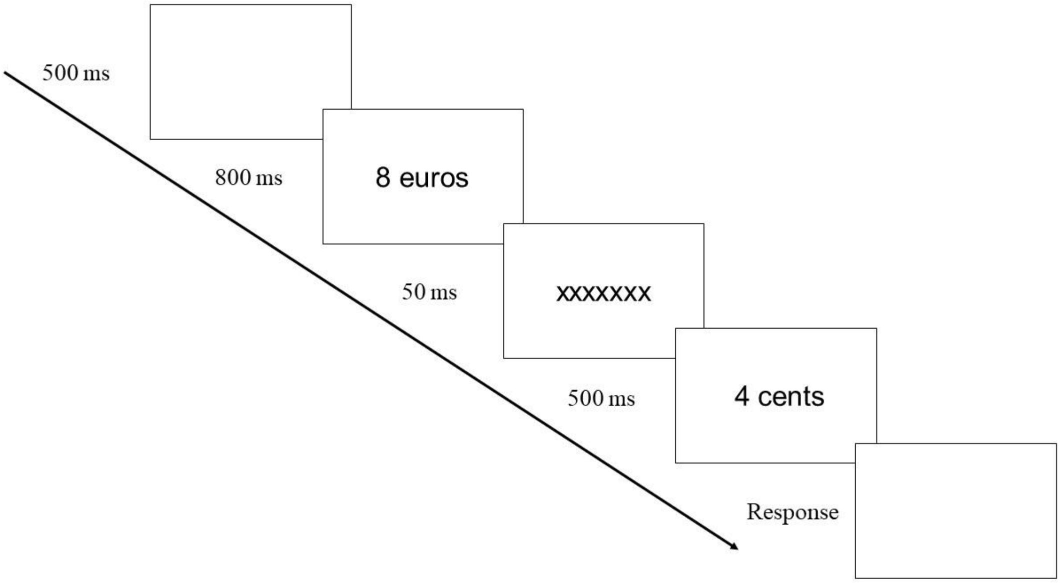

Figure 3. Procedure used in the study to implement the price comparison task. A sequence of two prices was presented and participants had to indicate the price with higher monetary value.

The reason for using a backward mask was to avoid the low-level perceptual influences of the rapid change at digits and monetary category positions as a result of the short interval of time between the two stimuli to be compared. In addition, to control for this factor, the position of the two prices at the centre of the screen was not exactly the same. In each trial, the position of the second price was moved randomly by one character position to the left or to the right (see Macizo & Ojedo, 2018; Moeller et al., 2013, for the same procedure in a two-digit number comparison task).

Electrophysiological recording

The Electroencephalogram (EEG) was recorded from 28 scalp electrodes mounted on an elastic cap (see Figure 4). In order to perform the statistical analysis we grouped the electrodes taken into account the anterior-posterior axis (four different regions: frontal, F5, F3, F1, FZ, F2, F4, F6; fronto-central, FC5, FC3, FC1 FCZ, FC2, FC4, FC6; parietal, P5, P3, P1, PZ, P2, P4, P6; parieto-occipital, PO7, PO5, PO3, POZ, PO4, PO6, PO8) and the lateral-medial axis (seven locations from left to right). Thus, in the ERP analysis, a 2 x 4 x 7 within-participants factorial design was considered with Compatibility (two levels: compatible, incompatible), Anterior-posterior axis (four levels: frontal, fronto-central, parietal and occipito-parietal) and Lateral-medial axis (seven levels) as within-participant factors. If the Compatibility and Lateral-medial axis interaction was significant (it was only in the 100-150 ms time-window, see results section), the compatibility effect was analyzed separately in the left hemisphere (i.e., mean amplitude of electrodes: F5, F3, F1, FC5, FC3, FC1, P5, P3, P1, PO5, PO3, PO1), in the midline (i.e., mean amplitude of electrodes: FZ, FCZ, PZ, POZ), and the right hemisphere (i.e., mean amplitude of electrodes: F2, F4, F6, FC2, FC4, FC6, P2, P4, P6, PO2, PO4, PO6).

There is controversy about the location of conflict effects in magnitude processing on ERPs, posterior localization (Cao et al., 2015), as opposed to anterior localization (Schwarz & Heinze, 1998; Szűcs & Soltész, 2007; West et al., 2005). Hence, the regions selected in the current study were established according to these previous studies to determine the anterior/posterior location of conflict effects.

The continuous electrical activity was recorded with Neuroscan Synamps2 amplifiers (El Paso, TX). The EEG was initially recorded against an electrode placed in the midline of the cap (between Cz and CPz) and re-referenced off-line against a common average reference. In order to control for blinks artefacts, a pair of electrodes placed above and below the left eye were used. In the case of the horizontal and vertical eye movements artefacts, another pair of electrodes placed on the external canthi, one on the left eye and the other on the right eye. We amplified each EEG channel with a band pass of 0.01 – 100 Hz and digitized at sampling rate of 500 Hz. During recording, impedances were kept below 5 kΩ. The recording was filtered to delete trials in which participants gave an incorrect response, and trials in which the EEG was contaminated by eye movements or amplifier saturations. In addition, the blinks were corrected as follows: Visual inspection of the activity in the electrodes placed above and below the left eye was carried out for each participant separately in order to determine the voltage range associated with blinks. A voltage threshold was then individualized for each participant to capture as blink artefacts those epochs exceeding the voltage criterion (the mean voltage threshold across participants was 100 µV). The blinks were then averaged for each participant separately using a minimum of 46 blinks for each participant and later corrected with linear regression in the time domain (Neuroscan Scan 4.5 software, El Paso, TX). Once artefacts were removed and blinks were corrected, individual epochs were conducted for each participant in each experimental condition beginning with a 100 ms pre-stimulus baseline. The averages in each experimental condition of the study (compatible prices, incompatible prices) were comprised of a mean of 71.40 trials out of 80 trials (with a minimum of 43 trials per condition and participant).

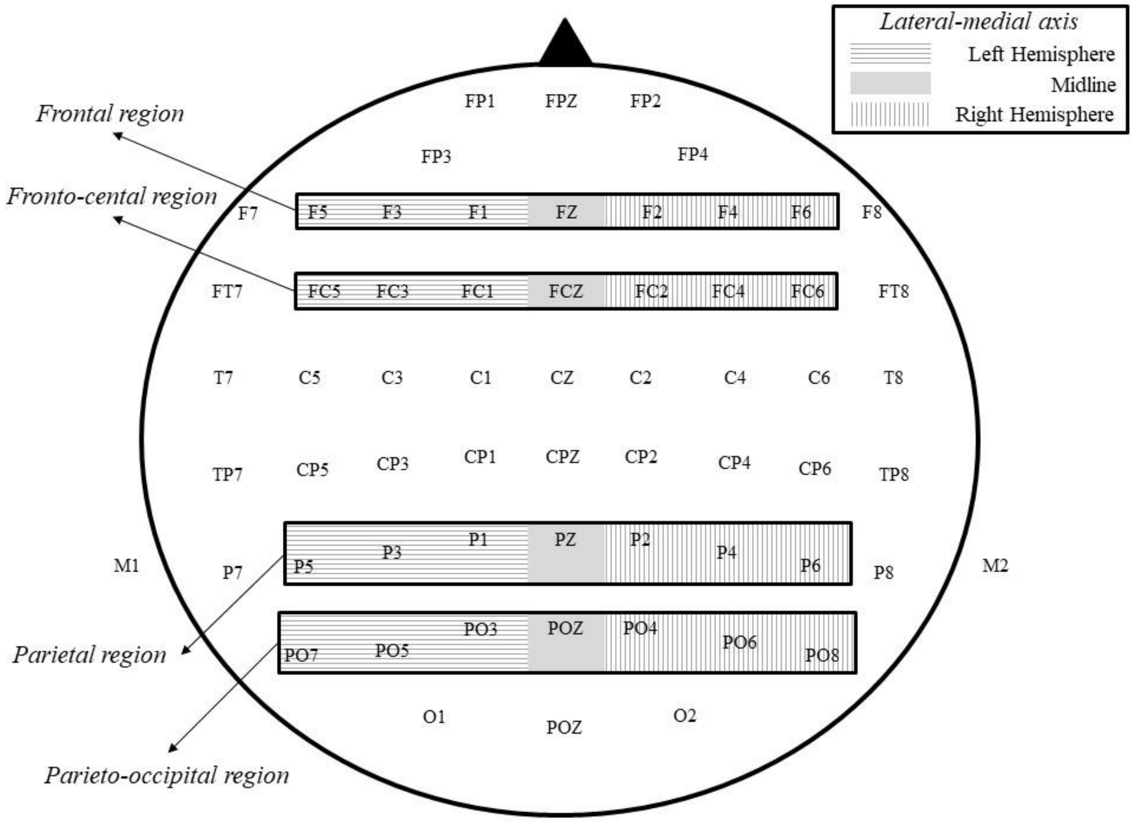

Figure 4. Map of the regions considered in the study, from the anterior-posterior locations (frontal, fronto-central, parietal and occipito-parietal) to the lateral-medial locations (left hemisphere, midline, right hemisphere).

Results

Data are fully and freely accessible at

https://osf.io/rx8u5/?view_only=48470ebc44bd47e191a6c92b5a831d87

Behavioural Results

Trials on which participants committed an error were eliminated from the latency analysis and submitted to the accuracy analysis (6.97%). After this, the reaction times (RTs) associated with correct responses were trimmed following the procedure described by Tabachnick and Fidell (2001) to eliminate univariate outliers. Raw scores were converted to standard scores (*z*-scores). Data points which, after standardization, were 3 *SD* outside the normal distribution were considered outliers. After removing outliers from the distribution, z-scores were calculated again. The filter was applied in recursive cycles until no observations were outside 3 *SD*. The percentage of outliers was 10.17%. This percentage was high compared to other studies using the same experimental paradigm (price comparison with sequential presentation, 3.71%, Macizo & Ojedo, 2018, Experiment 2b). One possible explanation for this high percentage of outliers could be due to participants' fatigue (in the current study, the total number of trials was 240 vs. 120 in Macizo & Ojedo, 2018). However, this does not seem to be the case. To evaluate if the percentage of outliers was due to the fatigue of the participants when performing the experiment (*N* trials = 240), we computed the percentage of outliers depending on the order of presentation (4 blocks, each of them with *N* = 60 trials). The percentage of outliers at the beginning and the end of the experiment was similar (block 1 = 13.65%, block 2 = 8.56%, block 3 = 7.98%, block 4 = 10.48%). Thus, fatigue does not seem to be the cause of the percentage of trials eliminated in this study (see Appendix 1).

Similar to what was done in Macizo and Ojedo (2018), RTs and error rates were submitted to repeated-measures analysis of variance (ANOVA) with compatibility between the two components of the prices, digits and monetary category, as the within-participant factor (two levels: compatible trials, incompatible trials). In the latency analyses, the compatibility effect was significant, $F(1,25) = 6.75$, $p = .015$, $\eta^2 = .21$. Participants were faster in compatible trials (M = 822 ms, SE = 21) than in incompatible trials (M = 838 ms, SE = 22). In the accuracy analysis, the compatibility effect was significant also, $F(1,25) = 6.34$, $p = .018$, $\eta^2 = .20$. Participants committed fewer errors in compatible trials (M = 5.67%, SE = 1.11) than in incompatible trials (M = 8.26%, SE = 1.64) (Figure 5).

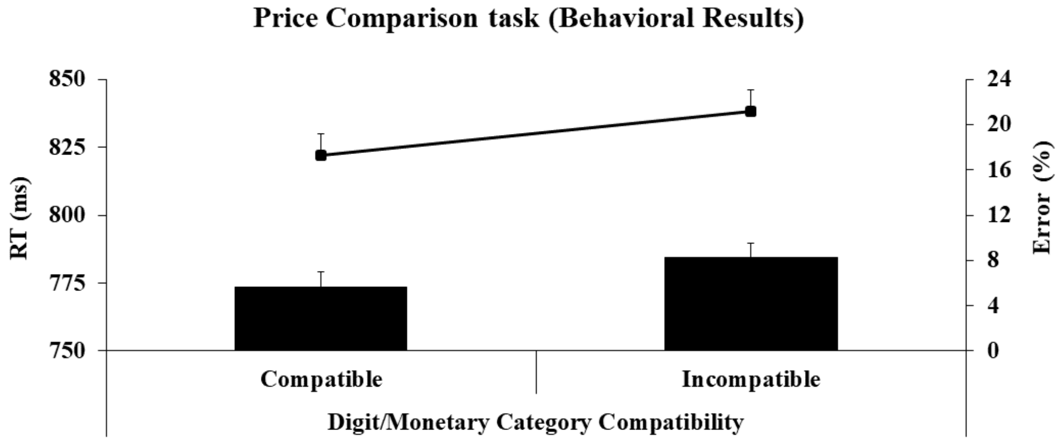

Figure 5. Reaction times (RT in milliseconds, ms) (lines) and error percentages (bars) obtained in the price comparison task as a function of the Digit/Monetary category compatibility (compatible price pairs, incompatible price pairs). Standard error of the mean (within-participant difference) is plotted in vertical lines.

Electrophysiological Results

Statistical analyses were carried out on the mean amplitude in four temporal windows, which were time-locked to the onset of the second prices. The selection of each temporal windows was done according to previous electrophysiological studies on Arabic digit processing (Dehaene, 1996; Temple & Posner, 1998; West et al., 2005): In the 100-150 ms time-window, a P1 component in parieto-occipital electrodes is usually accompanied by a fronto-central (N1) negativity (Dehaene, 1996). In the 250-350 ms time-window a N2 component in anterior regions is found with a positive P2 counterpart in posterior regions (Turconi et al., 2004). Finally, in the 350-450 ms, a N400 component associated with conflict tasks is usually observed in frontal regions (Szűcs & Soltész, 2007) while a P300 is found in parietal regions during the performance of numerical comparison tasks (Cao et al., 2015).

ANOVAs for the ERP analyses were conducted with compatibility (two levels: compatible, incompatible), anterior–posterior axis (four levels: frontal, fronto-central, parietal and occipito-parietal), and lateral–medial axis (seven levels) as within-subject factors. This last factor was included in the analysis in an exploratory manner as we had no predictions about interhemispheric differences regarding the compatibility effect. In the EEG analyses, we considered all correct responses (regardless of whether they were excluded in the data filtering process conducted for the response latency analyses). For the repeated-measure analyses of variance (ANOVAs), the Greenhouse-Geisser correction (Greenhouse & Geisser, 1959) for nonsphericity of variance was used for all *F*-ratios with more than one degree of freedom in the denominator; reported here are the original *df*, the corrected probability level, and the ε correction factor. In all analyses reported in text, the critical *p* level for significance was α =.05. When the compatibility variable interacted with other factors, the compatibility effect was further analysed by orthogonal contrast with no alpha adjustment. When FDR correction for multiple comparisons were applied (i.e., false discovery rate analyses, Benjamini & Hochberg, 1995), the pattern of results was the same as that reported in text (see Appendix 2). The ERPs analysis are reported in temporal order. Compatibility effects and interactions are reported in Table 8.

An additional approach to evaluate the componential view is to investigate the effect of the digit distance of prices. If prices are processed in a componential manner, a digit distance effect should be observed. These analyses were not planned a priori and for brevity are reported in Appendix 3. The ERP results revealed a digit distance effect.

Table 8. *Statistical Analyses Performed on ERP Data. Compatibility Effects and Interactions.*

Time-window	Effects	*F*	*p*	η_p^2
100–150 ms	Compatibility	2.22	.15	.08
	Compatibility x AP axis	1.70	.20	.11
	Compatibility x LM axis	3.02	.05*	.06
	Compatibility x AP axis x LM axis	1.06	.33	.00
150–250 ms	Compatibility	0.89	.35	.03
	Compatibility x AP axis	1.65	.20	.06
	Compatibility x LM axis	0.64	.33	.02
	Compatibility x AP axis x LM axis	0.91	.37	.03
250–350 ms	Compatibility	1.46	.24	.05
	Compatibility x AP axis	3.69	.04*	.13
	Compatibility x LM axis	0.75	.47	.03
	Compatibility x AP axis x LM axis	0.84	.41	.03
350–450 ms	Compatibility	5.35	.03*	.18
	Compatibility x AP axis	4.05	.05*	.14
	Compatibility x LM axis	1.43	.25	.05
	Compatibility x AP axis x LM axis	0.82	47	.03

Note. AP: Anterior-Posterior, LM: Lateral-Medial. $^*p \leq .05$

100-150 ms time-window. The ANOVA conducted in this time-window did not reveal a significant main effect of Compatibility. Conversely, the main effect of Lateral-medial axis, $F(6, 150) = 4.20$, $p = .017$, $\varepsilon = .37$, $\eta_p^2 = .14$, the main effect of Anterior-posterior axis, $F(3, 75) = 26.45$, $p < .001$, $\varepsilon = .39$, $\eta_p^2 = .51$, and the Compatibility x Lateral-medial axis interaction were significant. The compatibility effect was significant on the right hemisphere, $F(1, 25) = 4.30$, $p = .048$, $\eta_p^2 = .15$, where the mean amplitude was larger for incompatible trials (0.004 µV) than for compatible trials (-0.10 µV); and also on the left hemisphere, $F(1, 25) = 5.43$, $p = .028$, $\eta_p^2 = .18$, in this case, the mean amplitude was larger for compatible trials (0.09 µV) than for incompatible trials (-0.05 µV). However, the compatibility effect was not significant on midline electrodes, $F(1, 25) = 0.88$, $p = .36$, $\eta_p^2 = .03$. Finally, the Compatibility x Anterior-posterior axis interaction, the Anterior-posterior axis x Lateral-medial axis interaction, $F(18, 450) = 1.86$, $p = .154$, $\varepsilon = .14$, $\eta_p^2 = .19$, and the three-way interaction were not significant.

150-250 ms time-window. The results in this time-window revealed a non-significant main effect of Compatibility, but the two other main effects were significant; Lateral-medial axis, $F(6, 150) = 17.67$, $p < .001$, $\varepsilon = .35$, $\eta_p^2 = .41$, and Anterior-posterior axis, $F(3, 75) = 12.03$, $p < .001$, $\varepsilon = .51$, $\eta_p^2 = .32$. The Lateral-medial axis x Anterior-posterior axis interaction was significant also, $F(18, 450) = 8.28$ $p < .001$, $\varepsilon = .23$, $\eta_p^2 = .25$. The Compatibility factor did not interact with any other variable (*p*s > .05), nor was the three-way interaction significant.

250-350 ms time-window. The analysis of the third time-window revealed that the main effect of Compatibility was not significant. However, the main effect of Lateral-medial axis was significant, $F(6, 150) = 3.67$, $p = .015$, $\varepsilon = .51$, $\eta_p^2 = .13$; the Compatibility x Anterior-posterior axis interaction was significant, and the Lateral-medial axis x Anterior-posterior axis interaction was significant, $F(18, 450) = 4.08$, $p = .003$, $\varepsilon = .23$, $\eta_p^2 = .14$. Furthermore, the compatibility factor did not interact with Lateral-medial axis, nor was the three-way interaction significant.

Regarding the Compatibility x Anterior-posterior axis interaction, the compatibility effect was examined in each ROI separately. The compatibility effect was significant in frontal regions, $F(1, 25) = 4.47$, $p = .044$, $\eta_p^2 = .15$. The mean amplitude was more negative for compatible trials (-0.15 µV) than for incompatible trials (0.04 µV). The compatibility effect was not significant in any other regions (all *p*s > .05).

350-450 ms time-window. The ANOVA revealed significant main effects of Compatibility; Lateral-medial axis, $F(6, 150) = 3.37$, $p = .027$, $\varepsilon = .44$, $\eta_p^2 = .12$; and Anterior-posterior axis, $F(3, 75) = 55.08$, $p < .001$, $\varepsilon = .45$, $\eta_p^2 = .68$. The Compatibility x Anterior-posterior axis interaction was significant. Additional analyses revealed a significant effect of Compatibility in two regions: frontal region, $F(1, 25) = 5.33$, $p = .029$, $\eta_p^2 = .17$, where the mean amplitude of incompatible trials was more negative (-0.75 µV) than that of compatible trials (-0.67 µV); and fronto-central region, $F(1, 25) = 7{,}28$, $p =.012$, $\eta_p^2 = .22$, brain-waves were more negative in incompatible trials (-0.75 µV) relative to compatible trials (-0.57 µV). The compatibility effect was not significant in the parietal region, $F(1, 25) = 4.85$, $p = 0.252$, $\eta_p^2 = .05$, nor in the occipital-parietal region, $F(1, 25) = 2.50$, $p = .126$, $\eta_p^2 = .09$ (see Figure 6, see Appendix 4 for the complete pattern of electrophysiological results).

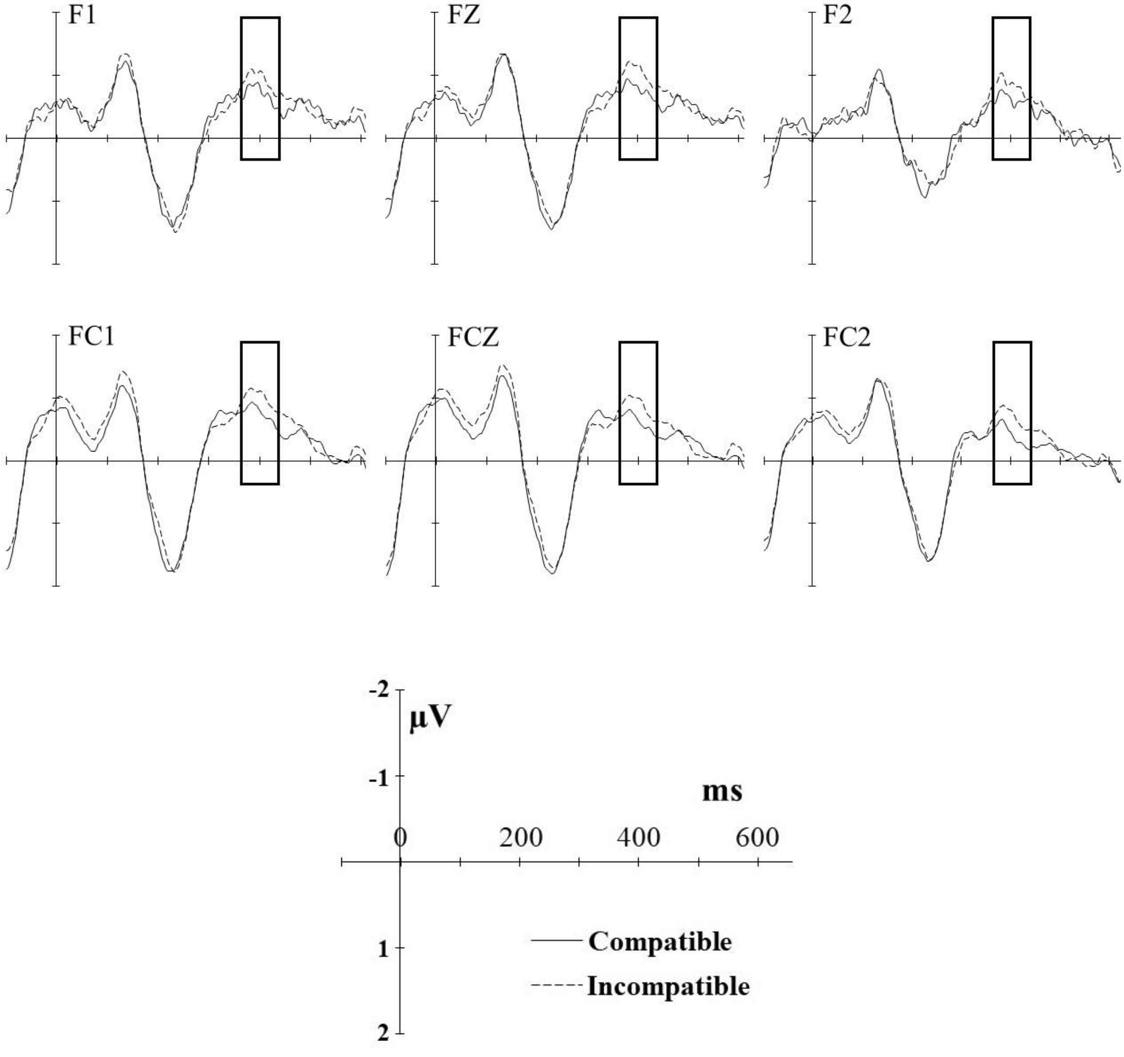

Figure 6. Compatibility effect. Grand average ERPs for compatible trials and incompatible trials found in the 350-450 ms time-window (boxes) (see Appendix 4 for the complete pattern of electrophysiological results).

The Compatibility factor did not interact with Lateral-medial axis, the Anterior-posterior axis x Lateral-medial axis interaction was not significant, $F(18, 450) = 1.66$, $p = .178$, $\varepsilon = .18$, $\eta_p^2 = .06$, and the three-way interaction was not significant.

Discussion

To our knowledge, there are only three previous studies conducted to evaluate whether prices are processed holistically or in a componential manner (Cao et al., 2012; Cao et al., 2015; Macizo & Ojedo, 2018). Two behavioural experiments suggest that the digit and the monetary category of prices are separately analysed in price comparison tasks (Macizo & Ojedo, 2018; Experiments 2 and 3). On the contrary, two electrophysiological experiments appear to demonstrate that prices are processed as unitary entities only (Cao et al., 2012) or as a combination of holistic and componential processing (Cao et al., 2015). However, as commented in the introduction section, these EEG studies had some disadvantages. Therefore, an electrophysiological experiment systematically conducted to control for several confounding variables was needed to discern the way prices are processed.

In the current study, we gathered behavioural and electrophysiological evidence in favour of the componential processing of prices. In particular, we considered the compatibility between the digit and the monetary category of prices as an index of componential processing while controlling for the influence of numerical variables (e.g., the holistic distance, the digit distance). Concerning behavioural results, we corroborated the compatibility effect previous reported by

Macizo and Ojedo (2018; Experiment 2b). The data revealed slower and less accurate responses in incompatible trials relative to compatible trials. This effect indicated that participants compared the digits and the monetary category of the prices. In incompatible trials, the comparison of the digits and monetary categories guided to different responses. Thus, interference emerged and more time was needed to resolve conflict between opposing responses. This interference effect agrees with that found during the processing of multidigit numbers (the unit-decade compatibility effect; Macizo, 2017; Macizo & Herrera, 2010; 2011; 2013; Macizo et al., 2010; Macizo et al., 2011a; 2013a; Moeller et al., 2013; Nuerk et al., 2001; 2004). Thus, the behavioural pattern of data obtained in this experiment seems to support the general model framework for multi-symbol number comparison (Huber, Bahnmueller, et al., 2016) by showing that prices can be understood as an example of multi-digit numbers whose constituents are processed separately and in a componential manner similar to the way two-digit numbers, metrics (km/m/cm), and weights (kg/g/mg) are processed. In fact, the magnitude of the compatibility effect found in this study (difference between incompatible vs. compatible trials, 16 ms) was similar to that found in other studies with two-digit numbers (12 ms, Moeller et al., 2013) presented with the same paradigm used here (sequential presentation of quantities).

The ERP results showed that in the 100-150 ms time-window associated with the P1 component, the compatibility effect interacted with Lateral-medial axis, while in the 250-350 ms time-window associated with the N2 component, the compatibility effect interacted with Anterior-posterior axis. These ERP modulations have been found in other studies on price processing (e. g., Cao et al., 2012) and do not seem to be related to the conflict between digit magnitude and monetary category. In particular, previous studies with numerical comparison tasks have shown a right-lateralized P1 that is independent of numerical notation (Arabic numbers, verbal numbers) and is not modulated by numerical distance. The authors have interpreted this component as an indicator of early processing of visual features (Dehaene, 1996). In line with this interpretation, the electrophysiological recording obtained in our study showed that the early effect of compatibility (100-150 ms time-window) was lateralized in the right hemisphere. In this location, the P1 amplitude was more positive in incompatible trials suggesting greater visual processing in these trials compared to compatible trials. At the same time, in the left hemisphere, a greater negativity was observed in incompatible trials compared to compatible trials. Previous studies have shown that magnitudes presented with number words elicit a more negative N1 component over the left hemisphere than Arabic digits (Pinel et al., 2001). Therefore, although as a tentative interpretation, the modulation of the N1 component in the left hemisphere could reflect an increased processing of words associated with the magnitude of the monetary category of prices (euros and cents) in incompatible trials relative to compatible trials.

On the other hand, compatibility modulated the mean amplitude of the N2 component (250-350 time-window) in frontal regions. In particular, greater amplitudes were observed in compatible trials than in incompatible trials. Turconi et al. (2004) observed a greater amplitude of the N2 component in front-central regions when judging order on numbers compared to letters which was interpreted as evidence of differences depending on the stimuli (Arabic numbers vs. letters) in the activation of quantity and order information. Thus, the modulation observed in our study in the N2 component suggests that access to the numerical magnitude depends on the compatibility of the prices that are compared.

Importantly, as we indicated in the introduction, the critical electrophysiological component for evaluating the compatibility effect was the N400-like component in the 350-450 ms time-window. The electrophysiological pattern of data obtained in this time-window supports the componential view of price comparison. We observed a main effect of compatibility effect in the 350-450 ms time-window where incompatible trials exhibited more negative amplitudes than compatible trials in anterior locations. This ERP modulation and topographic distribution (i.e., anterior regions) resembles N400-like effects obtained in previous studies about conflict detection (Szűcs & Soltész, 2007). In particular, the amplitude of the N400-like component increases in comparison tasks that involve incongruence between the physical size and the magnitude of two numbers (e.g., the incongruent pair 2 - 4 in a numerical Stroop task, Schwarz & Heinze, 1998; Szűcs & Soltész, 2007; West et al., 2005).

Cao et al. (2012) observed that the holistic distance between price pairs modulated the mean amplitude in the 350-450 time-window. In particular, there was greater negativity for close distance prices than for far distance prices. The authors interpreted this ERP modulation as evidence that the holistic magnitude was processed. However, this interpretation contrasts with previous studies in which the distance effect is found in earlier time-windows (P2p time-window, Dehaene, 1996; Temple & Posner, 1998). The authors argued that this delayed distance effect could be due to the difficulty of visual identification of the stimuli and the difficulty of the price comparison task. However, the results found in our study suggest that the effect of the holistic distance found in the study by Cao et al. (2012) actually reflected a compatibility effect with greater negativity in incompatible prices than in compatible prices (close and far holistic distance prices, respectively, in the study by Cao et al., 2012).

It is important to note that in order to perform the price comparison task, the magnitude of the prices had to be necessarily processed. However, behavioural and electrophysiological compatibility effects found in the current study cannot be explained only by differences in the holistic distance of prices because it was equated in compatible and incompatible trials. The observation of digit/monetary category compatibility after controlling for the influence of several numerical variables, strongly reinforces the componential view of price processing.

It is important to highlight the methodological differences between the study of Cao et al. (2012) and the current work. Specifically, Cao et al. used a comparison task with a standard price while in our study we used a comparison task between two prices that varied from trial to trial. However, it is unlikely that these methodological differences can explain the pattern of results found in our study. For example, Macizo and Ojedo (2018) observed the same digit/monetary category compatibility with behavioural measures when the task was a comparison with a standard price (Experiment 1) and when the comparison task was between prices varying from trial to trial (Experiments 2 & 3).

The occurrence of a compatibility effect with behavioural and electrophysiological measures supports the componential view of price processing. However, this effect could also be explained from a hybrid perspective in which both the overall magnitude of prices and the magnitude of their constituents (digits and monetary category) are processed. In fact, from the hybrid perspective it is suggested that during the performance of numerical tasks, there is a parallel comparison of the overall magnitude of quantities (i.e., two-digit numbers) and the magnitude of their constituents (decades and units) (Moeller et al., 2011). According to this view, the relevance of one comparison or another would depend on the task requirements (e. g., holistic representation for an approximation task, componential representation for an exact comparison task). Since the task used in our study was an exact comparison of prices, the magnitude of price constituents would have a greater influence than the overall magnitude. Nevertheless, the presence of a compatibility effect seems to clearly suggest that the digits and monetary category of prices were processed and both contributed to the comparison of price magnitude. Therefore, the current study provides electrophysiological evidence in favour of a general model of multi-symbol number processing (Huber et al., 2016) in which the constituents of multi-digit numbers, in our case, composed of digits and other characters (the monetary category) are separately processed in a componential manner.

Conclusion

To wrap up, the behavioural and electrophysiological data obtained in the current work demonstrate that prices are not a special category of quantity representation. Similar to other types of magnitudes, they appear to be processed in a componential manner.

CHAPTER VII

The Processing of Prices across Numerical Formats[5]

We evaluated whether the format in which prices are presented determine the processing of their magnitude. A price comparison task was used in which two-digit prices with Arabic digits, written numbers and auditory number words were presented in the euro currency. Prices were number-monetary category (NMC) compatible (49 euros vs. 36 cents) when the numbers and monetary category of one price were larger than those of the other (49 > 36, euros > cents); or NMC incompatible (49 cents vs. 36 euros) when the number of one price was larger but the monetary category smaller than those of the other (49 > 36, cents < euros). In addition, there were unit-decade (UD) compatible prices when the decade and unit of one price were larger than those of the other (49 euros, 36 cents, 4 > 3, 9 > 6) and UD incompatible prices when the decade of one price was larger but the unit smaller than those of the other (46 euros, 39 cents, 4 > 3, 6 < 9). The results showed NMC compatibility effects in all numerical formats. However, the DU compatibility effect was not found in any numerical format. The results are discussed within models of multisymbolic magnitude processing.

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Introduction

Handling money (coins, banknotes, price processing) is an everyday activity in our daily lives that involves numerical processing. Previous studies have investigated numerical processing in the context of price cognition (Dehaene & Marques, 2002; Goldman et al., 2012; Macizo & Herrera, 2013a; Macizo & Morales, 2015; Ruiz, et al.,2017; Thomas & Morwitz, 2005), however, there is no a priori reason to believe that the cognitive mechanisms associated to the processing of prices are different from those responsible for the processing of other kinds of magnitude representation. In fact, price processing from a cognitive perspective could easily be integrated within a general framework of multi-symbolic magnitude processing (Huber et al., 2016). Specifically, in this framework, it is proposed that all symbols representing a magnitude (e.g., numbers, units of measurement, etc.) are processed separately (Nuerk & Willmes, 2005). Thus, with respect to natural numbers (e.g., 38), people would independently process the ten (3) and the unit (8) to reach the magnitude of two-digit numbers. In the case of negative numbers (e.g., -7), people would process both the negative sign (-) and the digit (7) separately, etc.

Empirical evidence in favor of this componential processing of prices has been obtained in several studies that evaluate the possible conflict derived from the independent processing of multi-symbol magnitudes (Huber, Bahnmueller, et al., 2015; Huber, Cornelsen, et al., 2015; Macizo, 2017; Macizo et al., 2010; Macizo et al., 2011a; Macizo & Herrera, 2008, 2010, 2011a, 2011b; Macizo & Herrera, 2013a; Moeller et al., 2013; Nuerk et al., 2001). These studies have used the magnitude comparison task in which pairs of magnitudes are presented (e.g., pairs of numbers, pairs of units of length) and people have to select the one with the larger magnitude. In order to evaluate the possible conflict caused by the independent comparison of each symbol composing a magnitude, the compatibility between the results of these comparisons is considered. Thus, compatible trials are established in which the two symbols of one magnitude are larger than the symbols of the other magnitude (67-52, 6 > 5 and 7 > 2 in the case of a two-digit number, 5 cm - 4 mm 5 > 4 and cm > mm in the case of units of measurement); and incompatible trials in which one magnitude contains a larger symbol and another smaller symbol compared to these symbols in the other magnitude (62-47, 6 > 4 but 2 < 7; 5 mm - 4 cm, 5 > 4 but mm < cm). The results of different studies have shown compatibility effects with poorer performance (slower and less accurate magnitude comparisons) in the incompatible condition relative to the compatible condition. This compatibility effect (e.g., for the case of two-digit numbers, the unit-decade compatibility effect, UD compatibility for short) suggests that people process the constituents of multi-symbol magnitudes separately. In addition, the interference produced by the processing of incompatible vs. compatible magnitudes is easily interpreted within a theoretical perspective of conflict resolution in numerical cognition (Macizo, 2017). In particular, the processing of the units in incompatible trials would interfere with the processing of the decades so that participants would have to inhibit the irrelevant information (the magnitude of the units) in order to correctly solve the comparison task.

With regard to the processing of prices, the first studies suggested that prices composed of a number and a monetary category were not processed in a componential manner (Cao et al., 2012, 2015). Specifically, different studies conducted by Cao and colleagues suggested that the comparison of price pairs (2 juan - 5 jiao) in the Chinese currency (1 yuan = 10 jiao) was performed holistically. From the holistic view, it would be defended that multi-symbol magnitudes would be analyzed as a whole and that the constituent elements would not affect the processing of prices independently. In different studies, Cao and colleagues observed a distance effect between prices (worse performance with close vs. far distance price pairs). However, subsequent research conducted by Ojedo and Macizo (Macizo & Ojedo, 2018; Ojedo & Macizo, 2020) revealed that the pattern of results obtained by Cao et al. could be interpreted in terms of the compatibility between the symbols representing the digits and the monetary units of the prices.

In particular, Macizo and Ojedo (2018) evaluated the possible Number-Monetary Category (NMC) compatibility effect with a price comparison task in the Euro currency (Euro prices are composed of a number and a monetary category; 1 euro = 100 cents). The authors selected one-digit price pairs that produced compatible or incompatible comparisons when the number and the monetary category were independently considered. In compatible comparisons, the digit and the monetary category of one price were larger than those of the other price (e.g., 7 euro - 5 cent, 7 > 5 and euro > cent) while in incompatible comparisons, the digit of one price was larger but the monetary category was smaller than those of the other price (e.g., 5 cent - 7 euro, 7 > 5 but cent < euro). The results revealed a Number-monetary category compatibility effect (NMC compatibility effect for short) with behavioural and electrophysiological measures (Macizo & Ojedo, 2018; Ojedo & Macizo, 2020, respectively). The results obtained with behavioural measures revealed that participants were faster and more accurate on compatible price pairs relative to incompatible trials. The electrophysiological results showed that the NMC compatibility modulated event-related components (ERPs) in the 350-450 ms time-window, with more negative amplitudes on incompatible trials relative to compatible trials which was interpreted as a N400-like component (an ERP component that has been related to conflict resolution). Thus, the results obtained by Ojedo and Macizo suggest that price processing is carried out in a componential manner, similar to the way in which people process other multi-symbol magnitudes (e.g., two-digit numbers).

However, although the pattern of results found in previous studies suggests that all multi-symbol magnitudes (e.g., prices, two-digit numbers) are processed in a componential manner, several studies show that the comparison of magnitudes is modulated by the format in which they are coded. For example, with two-digit numbers, the UD compatibility effect depends on whether the tens and the units are presented with Arabic digits or in verbal format (numbers written with words or numbers in auditory format). Specifically, with Arabic numerals, the UD compatibility effect is observed with worse performance in incompatible vs. compatible trials (Huber et al., 2013; Macizo, 2017; Macizo & Herrera, 2008, 2010, 2011a, 2011b;

Macizo et al., 2011a; Moeller et al., 2011, 2013; Nuerk et al., 2001, 2005, for a review). However, when numbers are coded in verbal format (e.g., Spanish number words presented in written or auditory format) the results show no compatibility effect (Macizo & Herrera, 2008) or even a reverse compatibility effect with worse performance in compatible trials than in incompatible trials (Macizo & Herrera, 2010) (see Appendix 5).

The lack of compatibility effect or the observation of a reverse compatibility effect with number words has been confirmed in languages such as Spanish (Macizo & Herrera, 2008), Italian (Macizo et al., 2010), or English (Macizo et al., 2011a, 2011b; Nuerk et al., 2005), where the two-digit numbers in verbal notation follow the decade-unit order (e.g., 37 = thirty-seven). In contrast, in languages where written numbers follow the unit-decade order (e.g., German, 34 = vierunddreißig, literally, four and thirty), a regular compatibility effect is observed with verbal numbers. This pattern of results suggests that people codify number words according to the internal structure of the language they speak. Thus, speakers of languages as Spanish, English and Italian, for example, might have learnt to pay more attention to decades because they are presented first when numbers are coded in verbal notation (e.g., auditory number words). On the contrary, speakers of languages such as German, would pay more attention to the unit digit since it is processed first.

This pattern of processing based on a greater relevance of the first numerical symbol in two-digit numbers (the ten, which is the leftmost symbol in written numbers and the first digit heard in auditory numbers) would have direct implications for price processing. These implications are directly evaluated in the current study. Particularly, prices in euros follow the number - monetary category order (e.g., 37 euros, number = 37, monetary category = euro), which would imply an accentuated processing of the number when people read or heard a price presented with written or auditory number words.

However, the most relevant symbol for performing a price comparison task (e.g., 37 euros - 26 cents) would be the second constituent of a prices, the monetary category, because its processing is enough to perform the task (i.e., the magnitude of euros is always greater than that of cents). Therefore, in the context of the NMC compatibility effect described above, an analysis where more attention is paid to the first constituent of the price (the number) would imply greater processing of the less relevant dimension of the price (the magnitude of the numbers) which would increase the NMC compatibility effect with prices in verbal format compared to prices presented with Arabic numbers.

In our study, participants performed a comparison task with prices composed of two-digit numbers. To evaluate the NMC compatibility effect across formats, price pairs could be NMC compatible when the number and monetary category of one price were higher than those of the other price (49 euros, 36 cents, 49 > 36 and euros > cents) or NMC incompatible when the number of one price was higher but the monetary category smaller than those of the other price (46 cents, 39 euros, 46 > 39 but cents < euros).

Furthermore, in our study, we used prices with two-digit numbers for two reasons. First, as far as we know, there are no previous studies evaluating the possible componential processing in prices with more than one digit. Second, this type of stimuli would allow us to examine the possible conflict associated to the processing of two-digit numbers in the context of price cognition. For this reason, in the study, price pairs could be UD compatible, when the ten and the unit of one price were higher than those of the other price (e.g., 49 euros - 36 cents, where $4 > 3$ and $9 > 6$) or UD incompatible when the ten of one price was higher, but the unit lower than those of the other price (46 euros - 39 cents, where $4 > 3$ but $6 < 9$).

In addition, NMC compatibility and the UD compatibility were evaluated in three price formats: Arabic numbers, written number words and auditory number words. These three formats were used, on the one hand, to confirm the pattern of UD compatibility effects observed in previous studies across notations (e.g., Macizo & Herrera, 2008): UD compatibility effect with Arabic numbers and lack of compatibility effect (or reverse compatibility effect) with numbers in verbal format. On the other hand, we wanted to examine the NMC compatibility effect in the verbal format because, to our knowledge, it has been never considered in previous research. The study of prices in verbal format is relevant. Although the processing of written numbers is unusual (e.g., reading numbers written with words), to hear and compare price pairs is a frequent and daily activity in people's lives. Regarding the NMC compatibility effect through price formats our hypothesis was as follows: If the linguistic structure of the Spanish language favors the processing of the first symbol (the number) of a price, the NMC compatibility effect would be greater in verbal format compared to the Arabic format because it would stress the processing of the irrelevant dimension of the price (the magnitude of the numbers) in the comparison task (price comparison can be done attending only to the second symbol, that is, the monetary category of the prices).

Experiment 5

Method

Participants

Students from the University of Granada served as participants. Three groups of participants were established: Arabic digit group (*N* = 29, mean age = 22.8, 8 men); Written number word group (*N* = 28, mean age = 24.2, 7 men) and Auditory number word group (*N* = 27, mean age = 24.0, 6 men). Participants were randomly assigned to one of the three groups. All participants used the Euro currency on a daily basis and had normal or corrected-to-normal visual acuity. An informed consent form was signed by the participants before performing the experiment, and their participation was rewarded with academic credits. The sample size was determined using G*Power, version 3.1.9.4 (Faul, Erdfelder, Lang, & Buchner, 2007). It was calculated that for a 3 x 2 x 2 multivariate analysis of variance (MANOVA) to achieve 80% statistical power with α =.05 and an effect size of .25, the total sample size needed was N = 30.

Task

The present experiment was designed and controlled by the experimental software E-Prime 2.0 (Schneider, Eschman, & Zuccolotto, 2002). A price comparison task was used where, in each trial, a pair of two-digits prices in the euro currency were presented sequentially and participants had to decide which one has the higher monetary value. Participants used the keyboard to give their answers by pressing "A" or "L" keys. The assignment of the first/second price to the A/L keys was counterbalanced across participants. Depending of the group, prices were presented in three different formats: Arabic digits, written number words or auditory number words. The experimental task used in the current study is freely available at . https://osf.io/h6fqm/?view_only=4d197ebbc27e4299aeaf83e2aa990123

The simultaneous presentation of price pairs would have been preferable to the sequential presentation since the magnitude of the compatibility effects is greater with the simultaneous vs. sequential procedure in number comparison tasks (Moeller et al., 2013) and price comparison tasks (Macizo & Ojedo, 2018). However, in the current study, we selected the sequential presentation of prices due to the introduction of auditory number words in one experimental condition. Nevertheless, with the sequential procedure, compatibility effects are also observed with two-digit numbers (Macizo & Herrera, 2008) and prices (Macizo & Ojedo, 2018; Ojedo & Macizo, 2020).

Stimuli and Design

All prices used in the task were formed by a two-digit number (between 21 and 98) and a monetary category (euro or cent). The experimental trials were always comparisons between monetary categories. Pair of prices formed by the same digits were not included in the task (e.g., 39 euros - 39 cents, or 93 euros – 39 cents were not used). The price comparisons used in the study were the same in the three groups; the only difference between the groups was the format in which the prices were presented.

Three independent variables were considered in the study. The format of prices was manipulated across participants (Arabic digits, written number words, and auditory number words), while the NMC compatibility and the UD compatibility were manipulated within-participants. Thus, a mixed 3 x 2 x 2 design was employed in the study. Prices were number-monetary category (NMC) compatible (49 euros, 36 cents) when the numbers and monetary category of one price were larger than those of the other (49 > 36, euros > cents); and they were NMC incompatible (49 cents, 36 euros) when the number of one price was larger but the monetary category smaller than those of the other (49 > 36, cents < euros). In addition, prices were UD compatible when the decade and unit of one price were larger than those of the other (49 euros, 36 cents, 4 > 3, 9 > 6) while they were UD incompatible when the decade of one price was larger but the unit smaller than those of the other (46 euros, 39 cents, 4 > 3, 6 < 9) (see Table 9).

Table 9. *Examples of Compatibility Conditions Used in the Study*

	Unit-Decade Compatible	Unit-Decade Incompatible
Number-Monetary Category Compatible	**38 euros** > 26 cents	**3**6 **euros** > 2**8** cents
Number-Monetary Category Incompatible	47 **euros** > **59** cents	4**9 euros** > **5**7 cents

Note. The stimuli were presented in black font. In the table, the tens, units and the largest monetary category in each of the price pairs are highlighted.

The experimental stimuli were composed of two-digit number pairs. These stimuli were previously used in number comparison tasks conduced in our laboratory (Macizo & Herrera, 2008; 2010). One-hundred twenty number pairs were UD compatible number pairs and 120 were UD incompatible number pairs. The compatible and incompatible number pairs were equated in their absolute distance, unit distance and problem size (mean value of the two numbers) (see Table 10). A series of *t*-tests revealed that all these measures were similar in compatible and incompatible number pairs (all *p*s > .05). The only difference between them was observed in the decade distance which is due to the necessity of equating the overall distance. Decade numbers (i.e., numbers that refer to decades; e.g., 30, 40, 50, etc.) and tie numbers (i.e., two-digit numbers in which the decade and the unit refer to the same digit; e.g., 33, 44, 55, etc.) were not included. The 240 experimental price pairs (120 UD compatible and 120 UD incompatible) were presented in both the

NMC compatible condition and the NMC incompatible condition. Thus, each participant received 480 experimental stimuli presented randomly throughout the experiment: 120 UD compatible – NMC compatible prices, 120 UD compatible – NMC incompatible prices, 120 UD incompatible – NMC compatible prices.

Table 10. *Characteristics of Two-Digit Numbers that Composed the Prices Used in the Study*

	Compatible numbers	Incompatible numbers
s diff.	36.83 (18.40)	34.93 (18.11)
g. diff.	1.50 (0.25)	1.47 (0.27)
s. diff. log.	0.31 (0.16)	0.28 (0.15)
cade diff.	3.30 (1.86)	3.88 (1.83)*
cade diff. log.	0.43 (0.29)	0.53 (0.24)*
it diff.	3.83 (2.14)	3.83 (2.14)
it diff. log.	0.50 (0.29)	0.50 (0.29)
oblem size	57.27 (15.04)	59.65 (13.10)
oblem size log.	1.74 (0.12)	1.76 (0.10)
ord length	24.48 (1.75)	24.46 (1.78)
llable number	10.28 (1.15)	10.46 (1.05)
cade length	14.36 (1.19)	14.28 (1.04)
it length	8.47 (1.35)	8.53 (1.26)
ration	2008.14 (95.14)	2007.26 (85.28)

Note. Abs. = Absolute, Diff. = Difference of the numbers, Log. = logarithmic values. Word length and syllable number correspond to the number of letters and syllables of each two-digit numbers in Spanish. Decade and unit lengths refer to the number of letters of decades and units of each two-digit numbers in Spanish, respectively. Standard deviations are in brackets. Duration refers to the length (in milliseconds) of the numbers in auditory format (sum of the two numbers presented in each pair of prices). $^{*}p < .05$ (compatible numbers vs. incompatible numbers).

In addition to the 480 experimental price pairs (between monetary category comparisons), a set of 240 filler trials were used. These trials were introduced with the aim of ensuring that the participants did not carry out the comparison task on the basis of the monetary category or the decade of prices only. Thus, 120 filler trials with the same monetary category were included. Sixty of these trials were prices in euro (30 UD compatible and 30 UD incompatible trials) and another 60 trials were prices in cents (30 UD compatible and 30 UD incompatible trials). Furthermore, 120 additional filler trials comprised within-decade numbers: 40 trials with euro-cent price pairs, 40 trials with euro prices, and 40 trials with cent prices. Thus, each subject received 720 trials (480 experimental comparisons and 240 filler comparisons). The price pairs were presented randomly in 6 blocks of 120 trials each so that participants could rest between blocks. Stimuli used in the study are fully and freely accessible at https://osf.io/h6fqm/?view_only=4d197ebbc27e4299aeaf83e2aa990123

Procedure

Participants were tested individually, seated 60-70 cm approximately from the computer screen (Captativa E1903D, LCD, 1280 x 1024, 60 Hz, 19''). Each stimulus was presented in Arial 30-point font, in black font on a white background. Since auditory stimuli (auditory number words) are necessarily presented in a sequential manner, prices with Arabic numbers and written number words were also presented sequentially. In each trial, a fixation point (a row of asterisks) was presented in the middle of the screen for 500 ms. Then, the first price appeared during 1000 ms, followed by a mask (row of Xs) which was presented for 50 ms. Then, after a delay of 250 ms, the second price was presented until the response of the participant (see Figure 7).

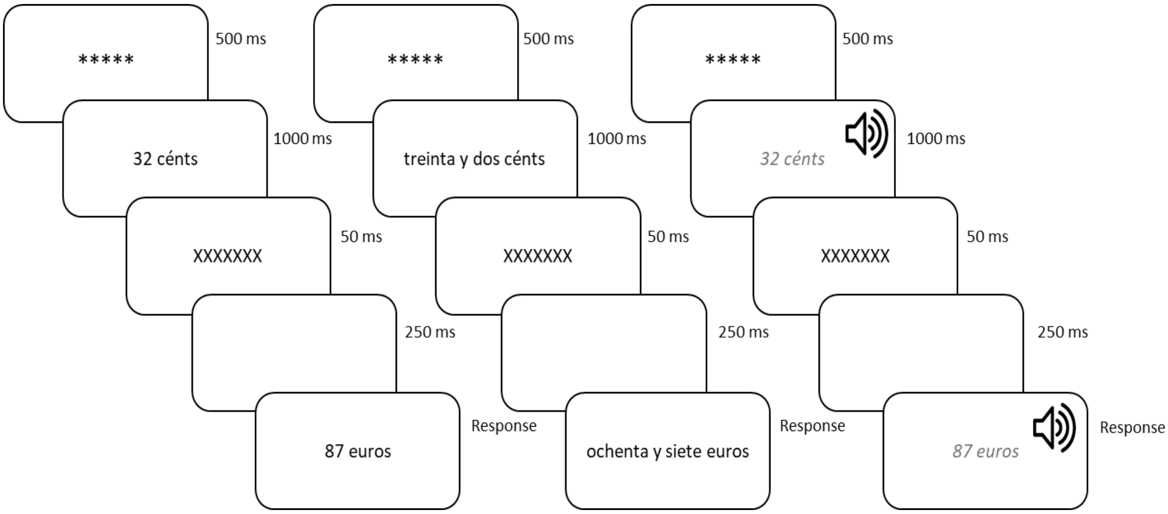

Figure 7. Procedure used in the study.

The reason for using a backward mask was to avoid the low-level perceptual influences of the rapid change at digits and monetary category positions as a result of the short interval of time between the two stimuli to be compared. In addition, to control for this factor, the position of the two prices at the centre of the screen was not exactly the same. In each trial, the position of the second price was moved randomly by one character position to the left or to the right (see Macizo & Ojedo, 2018; Moeller et al., 2013, for the same procedure).

Results

Data are fully and freely accessible at https://osf.io/h6fqm/?view_only=4d197ebbc27e4299aeaf83e2aa990123

Trials in which participants committed an error were excluded from the latency analysis and submitted to the accuracy analysis (Arabic digits: 4.69%; written numbers 4.28%; auditory numbers: 4.69%). Afterwards, the reaction times (RTs) associated with correct responses were trimmed following the procedure described by (Tabachnick & Fidell, 2007) in order to eliminate univariate outliers. Raw scores were converted to standard scores (*z*-scores). Data points which, after standardization were 3 *SD* outside the normal distribution, were considered outliers. After removing outliers from the distribution, z-scores were calculated again. The filter was applied in recursive cycles until no observations were outside 3 *SD*. The percentage of outliers was 7.78% for price pairs presented with Arabic digits, 6.62% for price pairs presented with written numbers and 3.58% for price pairs presented in the auditory format.

Firstly, RTs and accuracy were submitted to an analysis of variance (ANOVA) with NMC Compatibility (two levels: NMC compatible trials, NMC incompatible trials) and UD Compatibility (two levels: UD compatible trials, UD incompatible trials) and Format of the price pairs (three levels: Arabic digits, written numbers, auditory numbers) as within-participant factors.

In the latency analysis, the Format effect was significant, $F(1, 81) = 154.84$, $p < .001$, $\eta^2 = .79$. The difference between the processing of prices in Arabic format ($M = 683$ ms, $SE = 42$) and prices written with number words ($M = 780$ ms, $SE = 43$) was marginal, $t(55) = -1.80$, $p = .07$. Furthermore, price pairs with written numbers were responded to faster than price pairs in the auditory format ($M = 1664$ ms, $SE = 44$), *t*(53) = -13.19, $p < .001$. The NMC compatibility effect was significant, $F(1, 81) = 43.21$, $p < .001$. $\eta^2 = .35$. Participants were faster in NMC compatible trials (*M* = 1005 ms, *SE* = 28) than in NMC incompatible trials (*M* = 1080 ms, *SE* = 22). The UD Compatibility effect was not significant, $F(1, 81) = 0.15$, $p = .69$, $\eta^2 = .01$. There were no differences between the UD compatible condition (*M* = 1043 ms, *SE* = 25) and the UD incompatible condition (*M* = 1042 ms, *SE* = 25). The interaction between Format x NMC Compatibility factors was significant, $F(2, 81) = 20.93$, $p < .001$. $\eta^2 = .34$. No other interactions were significant (all *p*s > .05). The NMC compatibility effect was significant when prices were processed in Arabic format, $t(29) = 6.11$, $p < .001$ and in oral format, $t(27) = 5.24$, $p < .001$. The NMC compatibility effect was marginal with prices written with number words, $t(28) = 1.87$, $p = .07$. Thus, the interaction was due to differences in the magnitude of the NMC compatibility effect across the format of the prices (see Table 11).

Table 11. *Number-Monetary Compatibility and Unit-Decade Compatibility Effects across Formats.*

	UD Comp.		UD Incomp.		NMC Effect	
	RT	E%	RT	E%		
			Price Pairs with Arabic Digits			
NMC Comp.	668 (33)	2.84 (0.59)	666 (35)	3.42 (0.66)	667	
NMC Incomp.	700 (35)	6.35 (0.85)	699 (35)	6.15 (0.70)	699	
UD Effect	684		682			-2
					32***	
			Price Pairs with Written Numbers			
NMC Comp.	773 (41)	3.93 (0.75)	774 (42)	3.04 (0.67)	774	
NMC Incomp.	781 (42)	5.06 (0.87)	792 (44)	5.09 (0.98)	787	
UD Effect	777		783			6
					13˜	
			Price Pairs with Auditory Numbers			
NMC Comp.	1582 (66)	3.80 (1.05)	1565 (70)	4.07 (1.04)	1574	
NMC Incomp.	1755 (40)	5.25 (1.09)	1755 (38)	5.68 (1.22)	1755	
UD Effect	1668		1660			-8
					181***	

Note. Reaction times (RT) (in milliseconds), error percentage (E%) and standard error (in parentheses) according to the Number-Monetary Category (NMC) compatibility and the Unit-Decade (UD) compatibility, obtained with price pairs presented with Arabic digits, written numbers and auditory numbers. Comp. = Compatible, Incomp. = Incompatible. NMC Effect = NMC Incompatible minus NMC Compatible (RT). UD Effect = UD Incompatible minus UD Compatible (RT). ****p* < .001, ˜*p* = .07

Regarding the accuracy analysis, the Format effect was not significant, $F(2, 81) = 0.09$, $p = .92$, $\eta^2 = .01$. Mean percentage of errors was $M = 4.69\%$ ($SE = 0.80$) in the Arabic digit format, $M = 4.28\%$ ($SE = 0.82$) in the written number format, and *M*

= 4.70% (*SE* = 0.83) in the auditory format. The NMC compatibility was significant, $F(1, 81) = 49.39$, $p < .001$. $\eta^2 = .38$, participants committed fewer errors in NMC compatible trials (*M* = 5.60 %, *SE* = 0.53) than in NMC incompatible trials (*M* = 3.52 %, *SE* = 0.45). The UD Compatibility effect was not significant $F(1, 81) = 0.04$, $p = .83$, $\eta^2 = .01$. The interaction between Format x NMC Compatibility factors was significant, $F(2, 81) = 3.14$, $p = .05$. $\eta^2 = .07$. No other interactions were significant. The NMC compatibility effect was significant when participants processed prices in Arabic format, $t(29) = 5.04$, $p < .001$, written format, $t(28) = 3.25$, $p = .003$, and oral format, $t(27) = 3.99$, $p < .001$. Thus, as in the latency analyses, the interaction was due to differences in the magnitude of the NMC compatibility effect across price format.

The three-way interaction was not significant in either the latency analyses or the accuracy analyses. Therefore, it is not statistically justified to decompose this interaction. However, in order to have a complete profile of the pattern of results, further analyses were conducted. For each numerical format, three separate analysis of variance (ANOVA) were conducted with NMC Compatibility (two levels: NMC compatible trials, NMC incompatible trials) and UD Compatibility (two levels: UD compatible trials, UD incompatible trials) as within-participant factors. The results found in these analyses confirmed the pattern of data reported here (see Appendix 6)

Discussion

To our knowledge, there are no previous studies that have evaluated the possible differences in the way people process prices through different formats (prices with Arabic numbers, prices with written number words, and prices in oral format). This comparison is particularly relevant: the vast majority of studies on price processing have been conducted in Arabic format (Cao et al., 2012, Macizo & Ojedo, 2018); however, price in verbal format (e.g., oral price processing) is a common activity in everyday life (e.g., listen to the cashier of a supermarket for the amount of money you have to pay, listening to financial news, etc.). The objective of this study was twofold, on the one hand, to evaluate the possible differences in price processing depending on the format in which prices were coded and, on the other hand, to investigate the possible componential analysis of two-digit numbers embedded within prices. To investigate these two goals, we considered the NMC compatibility effect and the UD compatibility effect in price comparison tasks with Arabic digits and verbal numbers (number words and oral numbers).

The results of the current study revealed NMC compatibility effects across numerical formats. The presence of this effect with Arabic numbers has been confirmed in previous studies (Macizo & Ojedo, 2018; Ojedo & Macizo, 2020), and suggests that prices are processed in a componential manner with separate processing of the two constituent symbols (the number and the monetary category). Thus, although early studies with the comparison task suggested that prices were processed holistically (Cao et al., 2012; 2015). The data from this study confirm the componential perspective. In addition, the NMC compatibility effect was found with prices presented with both Arabic numbers and verbal words (written and auditory number words). The occurrence of NMC compatibility effects across different notations indicates that prices are analyzed componentially irrespective of their initial encoding (visual, auditory) and the format in which the magnitudes are presented (Arabic numbers, orthographic and auditory number words). This pattern of results is in favor of a general framework of multi-symbol unit processing according to which all quantities are processed componentially (multi-symbol numbers, units of measurement, etc.) (Huber et al., 2016).

However, although NMC was consistently found through price notations, the magnitude of the effect varied depending on the format. In particular, the magnitude of the NMC compatibility effect with Arabic numbers (32 ms difference between NMC incompatible trials vs. NMC compatible trials was close to that obtained in previous studies (approximately 43 ms in Macizo & Ojedo, 2018). In contrast, the magnitude of the NMC compatibility effect was greater in the auditory format than in the rest of notations (181 ms). The increased NMC compatibility effect in the verbal format vs. Arabic format was predicted in the introductory section. The processing of the first symbol of a multi-digit magnitude is emphasized in languages such as Spanish (i.e., the ten, in two-digit numbers). In the context of the processing of prices, this would involve a greater processing of the number vs. the monetary category in the verbal format, which would increase the interference because the number of a price is irrelevant for comparing price pairs with a different monetary category. Thus, in NMC incompatible comparisons such as 36 euros - 49 cents, the euros > cents comparison would be sufficient to answer and the analysis of the numbers would interfere with the processing by leading to a different answer (36 < 49). Nevertheless, we did not have specific hypotheses about possible differences in price processing across the two verbal formats (written and oral presentation of prices). However, in our study, the magnitude of the NMC compatibility effect was greater with auditory words (181 ms) than with number words (13 ms). The difference between the two verbal formats (prices with written number words and prices with oral numbers) was not predicted before conducting and analyzing the data of the current study. However, this difference between verbal formats resembles that observed in other areas of cognition concerning semantic processing. For example, in classical semantic priming studies, the effect of the semantic relationship between pairs of words (processing semantically unrelated vs. related word pairs, car-pen vs. dog-cat, respectively) is greater with auditory words (109 ms) than with written words (33 ms) (Holcomb & Neville, 1990). These differences between formats are interpreted as evidence of the greater and faster semantic processing of the stimuli in the oral vs. written format. In the case of price processing, this would imply an increased processing of the price magnitude (i.e., the semantic content of numbers) in the oral vs. written format which would enhance the NMC compatibility effect when the comparison between the constituents of the prices (the number and the monetary category) guided to different responses.

Concerning the second objective of our study, the results did not reveal UD compatibility effects in any of the price formats we examined (prices with Arabic numbers, written number words and auditory words). The absence of UD compatibility effect in the verbal format confirms the results obtained when participants process two-digit number pairs presented in isolation (Macizo & Herrera, 2008) which seem to indicate the influence of languages such as Spanish in which more relevance is given to the processing of the ten than the unit of two-digit numbers. However, the UD compatibility effect with Arabic numbers appears to be language-independent and it is found in all the languages in which it has been examined such as English (Nuerk et al., 2005), Spanish (Macizo & Herrera, 2008, 2010, 2011b; Macizo et al., 2011a), German (Macizo et al., 2011a, 2011b; Moeller et al., 2011, 2013; Nuerk et al., 2001), Italian (Macizo et al., 2010). This pattern of results could be interpreted in terms of a hybrid view in which the processing of the magnitude is both holistic and componential. For example, in different theoretical proposals, it is assumed that in comparison tasks, an analysis of both the holistic magnitude and the magnitude of each of the constituent symbols is produced (Moeller, Huber, Nuerk, & Willmes, 2011). From this perspective, the weight of holistic vs. componential processing would depend on different factors. For example, holistic vs. componential processing would be more relevant in case of an approximate vs. exact comparison task. In addition, it would also depend on the type of symbols with which the magnitude is represented. For instance, while componential analysis seems to predominate in multidigit number processing, in the case of fractions, both componential and holistic processing would be relevant (e.g., models indicating a componential processing followed by the accessing to the overall magnitude of the fraction (Meert et al., 2009, 2010). Regarding the processing of prices composed of a two-digit number and a monetary category, this hybrid perspective would imply a componential analysis of the number and the monetary category but a greater weight of holistic processing for the analysis of the tens and the units that comprise the two-digit number.

Conclusions

To our knowledge, this is the first study to evaluate whether the processing of prices composed of two-digit numbers is holistic vs. componential and whether the coding of the price format influences price comparison. The results of this study appear to favor a hybrid model with a greater weight of componential processing for the analysis of the number and the monetary category and a greater relevance of the holistic processing for the analyses of the constituents of two-digit number (tens and units). In addition, the format of the prices does not seem to modulate the type of analysis (componential vs. holistic) but it emphasizes the processing of the number vs. the monetary category when people listen to prices compared to the reading of prices written with Arabic numbers or number words.

CHAPTER VIII

Multidigit Prices: Electrophysiological Evidence of Fully Compositional Analysis[6]

In the current study, we evaluate if the processing of multi-symbolic magnitude (i.e., two-digit prices) involves fully compositional analysis or a mixture of compositional and holistic analysis. Behavioural and electrophysiological measures were recorded when participants performed a price comparison task while the number-monetary (NMC) compatibility and the unit-decade (UD) compatibility were examined. Prices were NMC compatible when the number and the monetary category of one price were larger than those of the other price (49 euros - 25 cents, 49 > 25 and euros > cents), and NMC incompatible when the number of one price was larger but the monetary category smaller than those of the other price (38 euros - 56 cents, 38 < 56 but euros > cents). Additionally, prices were UD compatible when the decade and unit of one price were larger than those of the other (47 euros - 59 cents, 4 < 5 and 7 < 9), and UD incompatible when the decade of one price was larger but the unit smaller than those of the other (36 euros - 28 cents, 3 > 2 but 6 < 8). Behavioural data revealed NMC compatibility effect but not UD compatibility effect. However, electrophysiological data revealed an interaction between these two compatibilities which suggest a fully componential and parallel processing of the symbols (decade, unit and monetary category) of multi-digit prices.

[6]This study has been submitted as. Ojedo, F., & Macizo, P. (2022a). Multidigit Prices: Electrophysiological Evidence of Fully Compositional Analysis [Manuscript submitted for publication]. Department of Experimental Psychology, University of Granada.

Introduction

Magnitude or quantity information can be represented in a non-symbolic manner (e.g., number of elements in a set) or by using labels to denote magnitudes (symbolic magnitude representations) as in the case of Arabic numbers (1, 2), verbal numbers (one, two), units of measurement (1 meter, 2 liters), or prices (1 euro, 2 cents) (Gallistel & Gelman, 2005). It is widely accepted in the scientific literature that symbolic magnitudes composed of a single symbol (e.g., one-digit numbers) are represented as unitary entities in a mental number line (e.g., Buckley & Gillman, 1974; Dehaene et al., 1990). Several empirical data seem to confirm this form of representation for one-digit numbers. For instance, when people compare the magnitude of two numbers, their performance is more efficient when the numerical distance between them increases (e.g., Moyer & Landauer, 1967). This distance effect is explained by the fact that pairs of numbers with close distance would be more overlapped in the mental number line than far numbers, which would increase the difficulty of the comparison process (Buckley & Gillman, 1974).

However, several theoretical proposals are possible if we consider the representation of multi-symbolic magnitudes (e.g., two-digit numbers, length measurements, prices) composed of two or more constituent symbols such as tens and units (e.g., 97), numbers and units of length (e.g., 9 meters), numbers and monetary categories (e.g., 9 euros), respectively. From a holistic perspective, it would be assumed that the comparison of two-digit numbers (e.g., 97 vs. 82) will be made by retrieving and comparing the whole magnitude of each number.

Conversely, from a compositional view, it would be argued that people would compare the tens (9 > 8) and the units (7 > 2) separately to arrive at the comparison result (97 > 82). Finally, from a hybrid perspective, it would be accepted that both forms of processing (holistic and compositional) would be possible (see Nuerk et al., 2011, for a review).

To dissociate between these theoretical perspectives, the multi-symbolic magnitudes that have received more attention have been numbers composed of two digits (Dehaene et al., 1990; Hinrichs et al., 1981; Macizo & Herrera, 2008; Nuerk et al., 2001). Hinrichs et al. (1981) observed a numerical distance effect when participants compared the magnitude of a number (between 11 and 99) relative to a fixed standard (i.e., 55). Furthermore, the distance of the units also influenced the performance of the task when the numbers were from the same decade (e.g., 52 vs. 55). The authors interpreted this pattern of results in favor of the hybrid perspective according to which people would process the holistic magnitude of the numbers and, in some situations, the magnitude of the units (e.g., when the pairs of numbers contain the same decade digit). However, Dehaene et al. (1990) found that the influence of the unit when comparing two-digit numbers with the same decade was not primarily due to the processing of the unit itself but to the difficulty associated to the processing of a standard with repeated numbers (e.g., 55). Thus, the authors concluded that the processing of multi-symbolic quantities could be explained exclusively from a holistic view.

Nevertheless, an empirical effect described by Nuerk et al. (2001) challenged the holistic model, the unit-decade compatibility effect (UD compatibility effect for short) (Nuerk, et al., 2011, for a review). People compare more efficiently the magnitude of compatible number pairs (e.g., 97 vs. 82) in which the decade and unit of one number are larger than those of the other number (9 > 8 and 7 > 2), relative to incompatible pairs (e.g., 63 vs. 48) in which the decade of one number is larger but the unit smaller than those of the other number (6 > 4 but 3 < 8). This compatibility effect cannot be explained from the holistic position since the absolute distance between number pairs is equated in compatible and incompatible trials (15 in the example). On the contrary, the compatibility effect could be explained from the compositional model. People would compare separately the magnitude of the tens and the units which would lead to a conflict situation with incompatible number pairs (63 vs. 48) because the result of this comparison would point to opposite responses (6 > 4 but 3 < 8) (see Macizo, 2017; for an explanation of the compatibility effect in terms of conflict resolution). Furthermore, this compatibility effect suggests that participants processed the decade and the unit in a componential process that occurred in parallel rather than sequentially. In fact, if participants had compared first the decade and then the unit, no compatibility effect should have been observed since in both compatible trials (97 vs. 82) and incompatible trials (63 vs. 48), the comparison of the decade suffices to perform the comparison task (9 > 8 so 97 > 82, and 6 > 4 so 63 > 48, respectively).

The UD compatibility effect has been a key piece to explain multi-symbol magnitude processing beyond two-digit numbers (see, Huber et al., 2016 for a generalized model of multi-symbol magnitude processing). For instance, Huber, Bahnmueller et al. (2015) reported more efficient processing in selecting the larger magnitude between pairs of physical magnitudes (lengths, e.g., 6 cm vs. 3 mm) when the digit (6 > 3) and the unit of measurement (cm > mm) pointed to the same response (compatible trials) compared to incompatible trials (e.g., 6 mm vs. 3 cm) where the digit and the unit of measurement pointed to different responses (6 > 3 but mm < cm). Similarly, in a price comparison task, Macizo and Ojedo (2018) showed better performance when participants selected the larger price with compatible price pairs (e.g., 8 euros vs. 4 cents) in which the number and monetary category of one price were larger than those of the other (8 > 4 and euros > cents) compared to incompatible trials (e.g., 8 cents vs. 4 euros) in which the comparison of the numbers and the monetary category led to different responses (8 > 4 but cents < euros) (number-monetary category compatibility effect, NMC compatibility effect for short). Furthermore, in an electrophysiological study, Ojedo and Macizo (2021) found that the compatibility effect with prices modulated event-related potentials (ERPs) related to conflict resolution in magnitude processing (N400-like component) with more negative amplitudes when participants processed incompatible price pairs relative to compatible prices, a pattern of results congruent with the componential processing of prices. Thus, regardless of the type of symbols that constitute the multi-symbolic magnitudes (ten and unit, digit and measurement unit, digit and monetary category), individuals seem to process these two symbols in a compositional process that occurs in parallel.

However, empirical evidence in favor of componential processing would not preclude the possibility that people also processed multi-symbolic magnitudes in a holistic manner. In fact, different data seem to support the hybrid approach. First, since the first paper describing the UD compatibility effect (i.e., Nuerk et al., 2001), it has been consistently shown that the overall distance between two-digit numbers influences the performance of participants in magnitude comparison tasks (logarithmic of the absolute distance Moeller, Nuerk & Willmes, 2009; Nuerk et al., 2001, 2005; overall absolute distance, Moeller, Nuerk & Willmes, 2009; Nuerk et al., 2004; distance of the logarithmic magnitudes, Moeller, Nuerk & Willmes, 2009). Second, in computational modeling studies (e.g., Moeller et al., 2011) it has been observed that the UD compatibility effect can be correctly explained by artificial neural network architectures that implement both fully compositional and hybrid approaches. Third, different studies seem to demonstrate the coexistence of these types of processing (holistic and componential) and these studies suggest that the relevance of one type of processing over the other depends on different factors. For example, while componential processing would be observed when people process magnitudes both automatically and intentionally, evidence in favor of holistic processing would be more easily observed when people process magnitudes in an intentional manner compared to the automatic processing of quantities (Ganor-Stern et al., 2007). In addition, the compatibility effect would be modulated by the sex of the individuals (Harris et al., 2018; larger compatibility effect on women than men), sex hormones (Pletzer, Jäger, & Hawelka, 2019), spatial navigation strategies (Pletzer, Harris, & Scheuringer, 2019) and individual differences in visual hierarchical analysis (global-local processing, Pletzer et al., 2021). Thus, compositional and holistic processing seem to coexist and the relevance of one over the other form of processing would depend on the characteristics of the participants, the task at hand and the multi-symbolic magnitudes that are processed.

However, the processing of multi-symbolic magnitudes is not restricted to quantities formed by two symbols. Studies concerning the processing of magnitudes represented by more than two symbols are rather scarce. To our knowledge, only eight papers have been published investigating the processing of numbers composed of three or more digits by analyzing the compatibility between the digits that constitute the magnitude (Bahnmueller et al., 2015, 2016, 2021; Huber et al., 2013; Klein et al, 2013; Korvorst & Damian, 2008; Man et al., 2012; Meyerhoff et al., 2012). In the first study on this subject with three-digit numbers, Korvorst and Damian (2008) manipulated the compatibility between hundreds and decades and the compatibility between hundreds and units. For example, the pair 872 vs. 345 was hundred-decade compatible (8 > 3 and 7 > 4) but hundred-unit incompatible (8 > 3 but 2 < 5), while the pair 372 vs. 845 was hundred-decade incompatible (3 < 8 but 7 > 4) and hundred-unit compatible (3 < 8 and 2 < 5). The authors found both compatibility effects (hundred-decade and hundred-unit) with more efficient performance in compatible trials than in incompatible trials. This pattern of results suggested that participants conducted full compositional processing by analyzing and comparing all symbols of the three-digit numbers. Moreover, Huber et al. (2013) demonstrated that hundred-decade and hundred-unit compatibility effects could be correctly simulated using a fully compositional computational model. In addition, developmental studies revealed that these compatibility effects with three-digit numbers were more pronounced when the age of the children increased (Mann et al., 2012).

The study by Korvorst and Damian (2008) also revealed that the hundred-decade compatibility effect was greater (30 ms) than the hundred-unit compatibility effect (10 ms) suggesting a parallel processing which was graded from left to right on the relevance of hundreds, tens and units comparisons. However, although parallel compositional processing has been confirmed for three-digit numbers, sequential and parallel compositional processing seem to coexist for numbers with more digits.

To our knowledge, only one study has examined the possible holistic vs. compositional processing with multi-symbolic magnitudes composed of more than three symbols. Meyerhoff et al. (2012) evaluated the comparison of four- and six-digit number pairs. These numbers included compatible and incompatible differing digits pairs at all possible digit positions. For example, the incompatible digit pair could appear at the beginning (e.g., **67**4583 vs. **91**4583, 6 < 9 but 7 > 1) or at the end (e.g., 8712**36** vs. 8712**54**, 3 < 6 but 6 > 4) of the six-digit number pair. The authors observed compatibility effects at the first position of the six-digit numbers but no effects at any other position. The presence of the compatibility effect at the beginning of the number indicated that, in part, the six-digit numbers were processed in parallel. The first two digits were processed in parallel because, if they were analyzed sequentially, the comparison of the first digit (6 < 9) would be sufficient to perform the task (674583 > 914583) and no compatibility effects would be observed. However, the absence of compatibility effects at intermediate and final positions of the number suggested that the processing was also sequential. Specifically, the authors proposed that, at least in initial positions of six-digit numbers, the digits would be grouped together and processed in parallel (chunking hypothesis) which would produce the compatibility effect. Further, according to Meyerhoff et al. (2012, p. 88) this chunking process of grouping digits and comparing then within the cluster would be applicable to the processing of magnitudes composed of 3 to 4 symbols (i.e., three-digit numbers) which would explain the hundred-decade and hundred-unit compatibility effects described by Korvorst and Damian (2008).

Moreover, the clustering of parallel processing proposed by Meyerhoff et al. (2012) seems to extend to the analyses of three-symbols magnitudes composed of numerical and non-numerical symbols. Huber, Cornelsen, et al. (2015) evaluated the possible compositional processing of multi-symbolic quantities (e.g., –97 vs. +53) formed by three symbols: a polarity sign (negative, positive) a decade and a unit. Among other effects, the authors evaluated the compatibility between the sign and the decade (compatible trials: –53 vs. +97, – < + and 53 < 97; incompatible trials –97 vs. +53, – < + but 97 > 53) and the compatibility between the sign and the unit (compatible trials: +38 vs. –14, + > – and 8 > 4; incompatible trials +51 vs. –26, + > – but 1 < 6). The results revealed a sign-decade compatibility effect with faster reaction times in compatible trials compared to incompatible trials. In addition, this effect interacted with the sign-unit compatibility. The authors interpreted this interaction between compatibilities in favor of a compositional approach where the three symbols of the multi-symbolic quantities were compared in parallel.

However, a recent study seems to suggest that not all multi-symbolic quantities composed of three symbols are processed componentially in parallel. Ojedo and Macizo (2021) evaluated the processing of prices formed by two-digit numbers and a monetary category (euros and cents) in a price comparison task with Arabic numbers, written number words and auditory number words. The authors manipulated the compatibility between the monetary category and the number by including compatible trials (e.g., 49 euros vs. 36 cents, 49 > 36 and euros > cents) and incompatible trials (49 cents vs. 36 euros, 49 > 36 but cents < euros). Furthermore, the two-digit numbers were either UD compatible (e.g., 49 euros vs. 36 cents, 4 > 3 and 9 > 6) or UD incompatible (e.g., 46 euros vs. 39 cents, 4 > 3 but 6 < 9). According to the chunking hypothesis proposed for multi-symbolic magnitudes (e.g., Meyerhoff et al., 2012), participants would process and compare the three price symbols in parallel (the decade, the unit and the monetary category) so that the two compatibility effects (NMC compatibility and UD compatibility) would be observed (as in the case of the compatibility effect with three-digit numbers, Korvorst &

Damian, 2008). The results reported by Ojedo and Macizo (2021) revealed a compatibility effect between the monetary category and the two-digit number with better performance when participants compared compatible prices relative to incompatible prices. However, in none of the three price formats, the UD compatibility effect was found.

In Ojedo and Macizo (2021), the existence of a compatibility effect between the monetary category and the two-digit number clearly indicates that the prices were processed in a componential manner. However, the three price symbols were not processed fully in parallel since the UD compatibility was not observed. Two alternative explanations could account for this pattern of results. First, participants may have grouped the monetary category and the decade and processed them in parallel which would explain the compatibility effect between the monetary category and the number. This explanation would be in line with the proposal by Meyerhoff et al. (2012) for the processing of six-digit numbers and would imply that the prices were processed componentially both in parallel (the decade of the number and the monetary category) and sequentially (the unit of the number). While the chunking hypothesis was initially proposed for adjacent symbols (Meyerhoff et al., 2012), the idea of a cluster with non-adjacent symbols (i.e., a decade-monetary category grouping) is reasonable for several reasons. On the one hand, the order of relevance of the symbols to compare the magnitude of two prices is: monetary category > decade > unit, so it makes sense to cluster the two most relevant symbols when performing the comparison task. On the other hand, the processing of the monetary category is not enough to perform the price comparison task because filler trials containing prices with the same monetary category are included (e.g., 49 euros vs. 36 euros) so, apart from the monetary category, the number has to be processed necessarily. However, in all price pairs (compatible and incompatible number-monetary category trials), the comparison of the whole number (e.g., 49 euros > 36 cents) and the decade (4 > 3) lead to the same response, so the joint analysis of the decade and the monetary category would be enough to perform the price comparison task and observe the NMC compatibility effect.

Nevertheless, a second alternative explanation to the pattern of results found by Ojedo and Macizo (2021) would imply that participants processed the decade and the unit of prices in a hybrid manner. Thus, the processing of prices would involve a componential and parallel processing of the monetary category and the two-digit number while the two constituents of the number (the decade and the unit) would be processed as a whole. The holistic processing of the decade and the unit when they are part of a price could be theoretically defended. As indicated earlier, different factors seem to modulate whether participants process two-digit numbers more holistically than componentially (Harris et al., 2018, Pletzer, Harris, Scheuringer, 2019; Pletzer, Jäger, Hawelka, 2019). In this sense, the visual arrangement of two-number prices with a space between the number and the monetary category (e.g., 49 euros) would favor the joint processing of the decade and the unit. Furthermore, of the three symbols that comprise multi-digit prices (e.g., ten, unit, monetary category), the decade and the unit are of the same type (Arabic numbers), which would facilitate their holistic processing.

However, before giving further consideration to these accounts, a first step would be to evaluate whether or not the price comparison with two-digit numbers is subject to NMC and UD compatibility effects. Ojedo and Macizo (2021) used behavioral measures (latency and response accuracy) to index the two compatibility effects. In our study, besides these measures, we considered an electrophysiological component (N400-like component) that is sensitive to conflict processing between linguistic (Rebai et al., 1997), arithmetic (Megías & Macizo, 2016) and magnitude representations (Schwarz & Heinze, 1998; Szucs & Soltész, 2007; West et al., 2005). Furthermore, as described above, the N400-like component is sensitive to NMC compatibility effects when participants compare prices composed of one-digit numbers (Ojedo & Macizo, 2020). In our study, we manipulated the NMC compatibility and the UD compatibility. In case two-digit prices were processed in a fully parallel compositional manner, as suggested for the processing of three-digit numbers (Korvorst & Damian, 2008) and the processing of other multi-symbolic magnitudes (Huber, Bahnmueller, et al., 2015), we expect to find that both the NMC compatibility and the UD compatibility would modulate the N400-like component associated to conflict in magnitude processing. On the contrary, if the processing of prices with two-digit numbers implies a componential processing of the monetary category and the number, and a holistic processing of the digits of the number (the decade and the unit), the NMC compatibility effect would be observed but not the UD compatibility effect.

Experiment 6

Method

Participants

Twenty-six students from the University of Granada (19 women and 7 men), whose mean age was 22.07 (*SD* = 3.08), took part in this experiment. All of them used the Euro currency on a daily basis, and they had normal or corrected-to-normal visual acuity. An informed consent was signed by the participants before performing the experiment and they were rewarded with academic credits. The required sample size was determined using the G*Power program 3.1.9.4 (Faul et al., 2007). It was calculated that for the main design of the study, a 2 x 2 within-participants design with NMC compatibility (NMC compatible trials, NMC incompatible trials) and UD compatibility (UD compatible trials, UD incompatible trials) as factors, to achieve 95% statistical power with α =.05 and an effect size of .50, assuming a zero correlation among repeated measurements, the total sample size needed was N = 22. Thus, the sample used in this study was sufficient to capture the effects evaluate in the experiment.

Task

In the present experiment, a price comparison task was used. In each trial, participants received sequentially a pair of two-digit prices, and they had to indicate after presenting the second price which one had the higher monetary value as quickly and accurately as possible. The responses were given through the keyboard, by pressing the "A" and "L" keys. The assignment of the first/second price to the A/L keys was counterbalanced across participants.

Stimuli

The stimuli used in the comparison task were prices formed by two-digit numbers (between 21 and 98) and a monetary category (euro or cent). Only between-monetary category comparisons were considered as experimental trials. Thus, price pairs whose numbers were formed by the same digits were not used (e.g., 26 euros - 26 cents).

Regarding the UD compatibility factor, prices were UD compatible when the decade and unit of one price were larger than those of the other price (75 euros - 43 cents, 7 > 4 and 5 > 3) while they were UD incompatible prices when the decade of one price was larger but the unit smaller than those of the other price (73 euros - 54 cents, 7 > 5 but 3 < 4). On the other hand, prices were NMC compatible (69 euros - 32 cents) when the numbers and monetary category of one price were larger than those of the other price (69 > 32 and euros > cents); and they were NMC incompatible (69 cents - 32 euros) where the number of one price was larger but the monetary category smaller than those of the other price (69 > 32 but cents < euros) (see Table 12 for examples).

Table 12. *Examples of Compatibility Conditions*

	UD Compatibility	
NMC Compatibility	UD Compatible	UD Incompatible
NMC Compatible	75 euros > 24 cents	83 euros > 75 cents
NMC Incompatible	21 euros > 38 cents	38 euros > 75 cents

Note. NMC: Number-Monetary Category. UD: Unit-Decade compatibility.

The experimental prices use in the study were composed by two-digit numbers taken from the database previously developed in our lab (Macizo & Herrera, 2008, 2010). This database consisted of a total of 240 two-digit number pairs, 120 UD compatible pairs and 120 UD incompatible pairs. These UD compatible and UD incompatible number pairs were equated in their absolute distance, unit distance and problem size (mean value of the two numbers). A series of *t*-tests revealed that all these measures were similar in compatible and incompatible number pairs (all *p*s > .05). Decade numbers (i.e., numbers that refer to decades; e.g., 30, 40, 50, etc.) and tie numbers (i.e., two-digit numbers in which the decade and the unit refer to the same digit; e.g., 33, 44, 55, etc.) were not included (see Macizo & Herrera, 2008; 2010, for details). The set of 240 pairs of two-digit numbers were embedded in NMC compatible prices and NMC incompatible trials. Thus, the total set of stimuli consisted of 120 UD compatible – NMC compatible prices, 120 UD compatible – NMC incompatible prices, 120 UD incompatible – NMC compatible prices and 120 UD incompatible – NMC incompatible prices. In order to ensure that participants did not carry out the comparison task on the basis of the monetary unit only, nor on the basis of the decade digit, a total of 240 filler trials were created. A set of 120 filler trials were within the same monetary category: Sixty trials were prices in euros (30 UD compatible and 30 UD incompatible trials) and another 60 trials were prices in cents (30 UD compatible and 30 UD incompatible trials). Furthermore, 120 additional filler trials comprised within-decade numbers: 40 trials with euro-cent price pairs, 40 trials with euro prices, and 40 trials with cent prices. The stimuli used in the study are fully and freely accessible at https://osf.io/yhnjf/?view_only=45c55b39f1d041bc8eb11e32677a62d3

Procedure

Participants were tested individually, seated 60-70 cm approximately from the computer screen (Captativa E1903D, LCD, 1280 x 1024, 60 Hz, 19''). Each stimulus was presented in Arial 30-point font, in black colour on a white background. In each trial, a blank screen was presented for 500 ms. Then, the first price appeared at the centre of the screen during 800 ms, followed by a backward mask (row of Xs) which was presented for 50 ms. Then, after a delay of 250 ms, the second price appeared on the screen for 500 ms. Finally, a blank screen was shown until the response of the participant. As in previous studies (Macizo & Ojedo, 2017; Moeller et al., 2013; Ojedo & Macizo, 2020), the backward mask was used in order to avoid possible low-level perceptual influences caused by the rapid change between the two stimuli to be compared. In addition, to control for this factor, the position of the two prices at the centre of the screen was not exactly the same. The position of the second price was moved randomly by one character position to the left or to the right in each trial. Each participant received 360 trials randomly selected and presented. These trials were grouped in 6 blocks of 60 trials each, in order to allow the participants to rest between blocks.

Electrophysiological recording and statistical analyses

The continuous electrical activity was recorded with Neuroscan Synamps2 amplifiers (El Paso, TX). The EEG was initially recorded against an electrode placed in the midline of the cap (between Cz and CPz) and re-referenced off-line against a common average reference. Two additional pairs of electrodes were used to control vertical and horizontal movements: A pair of electrodes placed above and below the left eye was used to control blinks artefacts, and another pair of electrodes placed on the external canthi, one on the left eye and the other on the right eye, was used to control eye movements. The EEG signal was amplified with a band pass of 0.01 – 100 Hz and digitized at sampling rate of 500 Hz. The impedances were kept below 5 kΩ during data recording. Trials in which the EEG signal was contaminated by eye movements or amplifier saturations, were rejected. Eye blinks were detected and corrected in the following way: Visual inspection of the activity in the electrodes placed above and below the left eye was carried out for each participant separately in order to determine the voltage range associated with blinks. A voltage threshold was then individualized for each participant to capture as blink artefacts those epochs exceeding the voltage criterion (the mean voltage threshold across participants was 100 µV). Then, blinks were averaged for each participant separately using a minimum of 46 blinks for each participant, and later corrected with linear regression in the time domain (Neuroscan Scan 4.5 software, El Paso, TX). After obtaining the clean EEG data, individual epochs were computed for each experimental condition beginning with a 100 ms pre-stimulus baseline. Finally, mean brain-wave amplitudes were obtained for each participant and condition. The mean number of observations that entered each average was 71.40 trials out of 80 trials (with a minimum of 43 trials per condition and participant).

According to previous studies on the processing of prices (Ojedo & Macizo, 2020) and Arabic numbers (Dehaene, 1996; Temple & Posner, 1998; West et al., 2005) , statistical analyses were conducted on the mean brain-wave amplitudes obtained in five temporal windows, time-locked to the onset of the second price. Our main focus was the analysis of the N400-like component in the 350-500 ms time-window, located over frontal regions, which is associated to the resolution of conflict when participants process prices and Arabic numbers (Ojedo & Macizo, 2020; Szűcs & Soltész, 2007). However, in order to provide a detailed electrophysiological analysis, we set five time-windows from 100 ms to 600 ms post-stimulus onset (100-150 ms, 150-250 ms, 250-350 ms, 350-500 ms, and 500-600 ms). In the 100-150 ms time-window, a P1 component over parieto-occipital electrodes is usually accompanied by a fronto-central N1 negativity (Dehaene, 1996). In the 250-350 time-window, a N2 component in anterior regions and a P2 in posterior regions are frequently observed. In the 350-500 time-window, in addition to the N400-like component related to conflict in magnitude processing (Ojedo & Macizo, 2020; Szűcs & Soltész, 2007) a P300 over parietal region has been found when participants perform numerical comparison tasks (Cao et al., 2015). Finally, in the 500-600 ms time-window, a P600 component is observed in relation to the processing of syntactic incongruences with numerical stimuli (Szucs & Soltész, 2007).

The mean amplitude obtained in the four experimental treatments (UD compatible – NMC compatible prices, UD compatible – NMC incompatible prices, UD incompatible – NMC compatible prices, and UD incompatible – NMC incompatible prices) were sorted in four different regions taking into account the anterior-posterior axis (frontal, fronto-central, parietal, parieto-occipital) and seven different locations according to the lateral-medial axis (Frontal: F5, F3, F1, FZ, F2, F4, F6; Fronto-Central: FC5, FC3, FC1 FCZ, FC2, FC4, FC6; Parietal, P5, P3, P1, PZ, P2, P4, P6; Parieto-Occipital, PO7, PO5, PO3, POZ, PO4, PO6, PO8). The selection of the regions was established according to Ojedo and Macizo (2020), where single-digit price processing was studied. Although it was expected to find conflict effects in the anterior localization (Schwarz & Heinze, 1998; Szucs & Soltész, 2007; West et al., 2005), posterior localizations were also included due to previous studies where conflict effects were observed in these locations during price processing tasks (Cao et al., 2015). As a result, the ERP analysis was conducted for a 2 x 2 x 4 x 7 within-participants design, with NMC compatibility (two levels: NMC compatible trials, NMC incompatible trials) and UD compatibility (two levels: UD compatible trials, UD incompatible trials), Anterior-posterior axis (four levels: frontal, fronto-central, parietal and parieto-occipital) and Lateral-medial axis (seven levels) as within-participant factors.

In all the analyses reported in text, the Greenhouse-Geisser correction (Greenhouse & Geisser, 1959) for nonsphericity of variance was used for all *F*-ratios with more than one degree of freedom in the denominator; reported here are the original *df*, the corrected probability level, and the ε correction factor. The critical *p* level for significance was α =.05. Bonferroni corrections for multiple comparisons were applied when needed.

Results

All data and analyses of the present study, as well as the graphs of the Grand average ERPs for all different conditions, are fully and freely available at the following link: https://osf.io/yhnjf/?view_only=45c55b39f1d041bc8eb11e32677a62d3

Behavioural Results

Trials on which participants committed an error were removed from the latency analysis and submitted to the accuracy analysis (4.39%). Afterwards, the reaction times (RTs) associated with correct responses were trimmed following the procedure described by Tabachnick and Fidell (2007) to eliminate univariate outliers. Raw scores were converted to standard scores (*z*-scores). Data points which, after standardization, were 3 *SD* outside the normal distribution, were considered outliers. After removing outliers from the distribution, *z*-scores were calculated again. The filter was applied in recursive cycles until no observations were outside 3 *SD*. The percentage of outliers was 9.48%.

In order to carry out the behavioural analysis, RTs and error rates were submitted to repeated-measures analysis of variance (MANOVA) with NMC compatibility (NMC compatible trials, NMC incompatible trials) and UD compatibility (UD compatible trials, UD incompatible trials). In the latency analyses, the NMC compatibility effect was significant, $F(1,25) = 14.48$, $p < .001$, $\eta_p^2 = .37$. Participants were faster in NMC compatible trials (M = 796.60 ms, SE = 20) than in NMC incompatible trials (M = 817.67 ms, SE = 20). On the other hand, the UD compatibility effect was not significant, $F(1,25) = 0.54$ $p = .468$, $\eta_p^2 = .02$. There were no differences between UD compatible trials (M = 808.86 ms, SE = 19) and UD incompatible trials (M = 805.41 ms, SE = 20). The interaction between NMC compatibility x UD compatibility was not significant either, $F(1,25) = 1.61$, $p = .215$. $\eta^2 = .06$.

In the accuracy analysis, the same pattern of results observed with RTs was found. The NMC compatibility effect was significant, $F(1,25) = 45.96$, $p < .001$, $\eta_p^2 = .65$. Participants committed fewer errors in NMC compatible trials (M = 2.63%, SE = 0.51) than in NMC incompatible trials (M = 6.92%, SE = 0.90). On the other hand, the UD compatibility effect was not significant, $F(1,25) = 0.04$ $p = .841$, $\eta_p^2 = .01$. There were no differences between UD compatible trials (M =4.85 %, SE = 0.96) and UD incompatible trials (M = 4.70%, SE = 0.54). The interaction between NMC compatibility x UD compatibility was not significant either, $F(1,25) = 0.31$, $p = .584$. $\eta^2 = .01$ (see Table 13).

Table 13. *Behavioural Results*

	UD Compatible		UD Incompatible		NMC Effect
	RT	E%	RT	E%	
NMC Compatible	801 (20)	2.51 (0.59)	792 (20)	2.74 (0.59)	797
NMC Incompatible	817 (21)	7.19 (0.85)	818 (21)	6.65 (0.69)	818
UD Effect	809		805		-4^{ns}
					21^{*}

Note. Reaction times (RT) (in milliseconds), error percentage (E%) and standard error (in parentheses) according to the Number-Monetary Category (NMC) compatibility and the Unit-Decade (UD) compatibility. NMC Effect = NMC Incompatible minus NMC Compatible (RT). UD Effect = UD incompatible minus UD compatible (RT). $^{ns}p > .05$, $^{*}p < .001$

Electrophysiological Results

The results are shown in separate sections depending on the specific time-window. We report in text the results for the NMC compatibility factor, the UD compatibility factor and the interactions between these factors and other variables. The complete set of analyses conducted in each time-window are reported in Table 14.

Table 14. *Statistical Analyses Conducted on ERP Data across Time Windows. Main effects of NMC Compatibility, UD Compatibility and the interactions of these effects with the Anterior-Posterior Axis and the Lateral-Medial Axis*

	Time window									
	100-150 ms		150-250 ms		250-350 ms		350-500 ms		500-600 ms	
Effects	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
NMC	0.02	.89	0.00	.99	0.00	.99	2.73	.11	0.14	.70
UD	0.19	.66	0.00	.96	0.00	.97	2.48	.13	0.54	.47
NMC x UD	1.56	.22	0.11	.74	0.17	.68	0.05	.82	3.18	.09
NMC x AP axis	1.36	.26	0.46	.59	0.23	.70	3.51	.07	1.79	.19
UD x AP axis	0.54	.49	0.46	.53	.17	.68	0.27	.66	1.03	.34
NMC x LM axis	2.28	.11	0.15	.90	0.35	.72	0.76	.47	0.16	.88
UD x LM axis	1.31	.28	0.57	.59	0.55	.58	0.42	.69	1.63	.20
NMC x UD x AP axis	0.20	.70	0.39	.57	1.05	.33	6.93	.00*	0.28	.65
NMC x UD x LM axis	0.25	.79	1.40	.25	1.88	.16	0.27	.73	0.71	.51
NMC x AP axis x LM axis	0.67	.61	1.35	.23	1.04	.39	0.67	.63	1.65	.13
UD x AP axis x LM axis	1.27	.28	0.66	.62	0.85	.50	0.54	.76	1.36	.25
NMC x UD x AP axis x LM axis	0.64	.70	0.56	.66	0.93	.48	0.50	.61	2.12	.06

Note. NMC: Number-Monetary Category Compatibility, UD: Unit-Decade Compatibility, AP: Anterior-Posterior, LM: Lateral-Medial.

*$p \leq .001$

100-150 ms time-window. In this time-window, the NMC compatibility and the UD compatibility were not significant (*F*s < 1). These factors did not interact with each other or with any other variable (*p*s > .05).

150-250 ms time-window. As in the previous time-window, the NMC compatibility and the UD compatibility were not significant (*F*s < 1). These factors did not interact with each other or with any other variable (*p*s > .05).

250-350 ms time-window. The NMC compatibility was not significant, nor was the UD compatibility (*F*s < 1). The NMC compatibility and the UD compatibility did not interact with each other or with any other factor (*p*s > .05).

350-500 ms time-window. In this time-window, the three-way interactions between NMC compatibility x UD compatibility x Anterior-posterior axis was significant, $F(3, 75) = 6.93$, $p = .006$, $\varepsilon = .47$, $\eta_p^2 = .22$. None other interaction including the NMC compatibility and the UD compatibility was significant (*p*s > .05). Additional analyses were conducted to examine the NMC compatibility and the UD compatibility in each level of the anterior-posterior factor[7].

In the frontal region, the NMC compatibility x UD compatibility interaction was significant, $F(1, 25) = 7.32$, $p = .012$, $\eta_p^2 = .23$. When UD trials were compatible, the NMC compatibility effect was not significant, $t(25) = 0.40$, $p = .694$. However, in

[7]In order to avoid false positives in the multiple tests conducted in the study, additional analyses were carried out using the false discovery rate (FDR) corrections procedure (Benjamini & Hochberg, 1995). After FDR corrections, all compatibility effects reported in the manuscript as significant were still significant. All supplementary analyses are freely available at https://osf.io/yhnjf/?view_only=45c55b39f1d041bc8eb11e32677a62d3

UD incompatible trials, the NMC compatibility effect was found, $t(25) = 3.39$, $p = .002$, with more negative brain-wave amplitude in the NMC incompatible condition (- 0.88 μV) compared to the NMC compatible condition (- 0.65 μV). When the UD compatibility was examined depending on the NMC compatibility levels, the results revealed that in NMC compatible trials, the UD compatibility effect was not significant, $t(25) = -1.95$, $p = .062$. The UD compatibility was not significant in NMC incompatible trials either, $t(25) = 1.67$, $p = .107$.

In the fronto-central region, the interaction between NMC compatibility and UD compatibility was significant, $F(1, 25) = 5.15$, $p = .032$, $\eta_p^2 = .17$. The NMC compatibility effect was not significant in UD compatible trials, $t(25) = 0.45$, $p = .654$, but it was significant in UD incompatible trials, $t(25) = 3.13$, $p = .004$, with more negative amplitude in NMC incompatible trials (- 0.78 μV) than in NMC compatible trials (- 0.64 μV). When the UD compatibility was examined depending on the NMC compatibility levels, the results revealed that in NMC compatible trials, the UD compatibility effect was not significant, $t(25) = -1.44$, $p = .160$. The UD compatibility was not significant in NMC incompatible trials either, $t(25) = 1.03$, $p = .311$.

In the parietal region, the NMC compatibility x UD compatibility interaction was significant, $F(1, 25) = 7.11$, $p = .013$, $\eta_p^2 = .22$. The NMC effect was not significant in UD compatible trials, $t(25) = 0.99$, $p = .332$, but there was a trend towards a significant NMC effect in UD incompatible trials, $t(25) = 2.05$, $p = .051$, with 0.74 μV mean amplitude in UD compatible trials and 0.85 μV in UD incompatible trials. When the UD compatibility was examined depending on the NMC compatibility levels, the results revealed that, the UD compatibility effect was not significant in NMC compatible trials, $t(25) = 1.09$, $p = .284$. However, in NMC incompatible trials, the UD compatibility was significant, $t(25) = -2.62$, $p = .015$.

Over parieto-occipital regions, the NMC compatibility effect was not significant, $F(1, 25) = 3.11$, $p =.090$, $\eta_p^2 = .40$, nor was the UD compatibility main effect, $F(1, 25) = 0.83$, $p =.369$, $\eta_p^2 = .14$. Finally, the NMC compatibility x UD compatibility interaction was not significant, $F(1, 25) = 3.96$, $p =.057$, $\eta_p^2 = .48$ (see Figure 8 and Figure 9) (see Appendix 7).

500-600 ms time-window. The NMC compatibility was not significant, nor was the UD compatibility (Fs < 1). The NMC compatibility and the UD compatibility did not interact with any other factor (ps > .05).

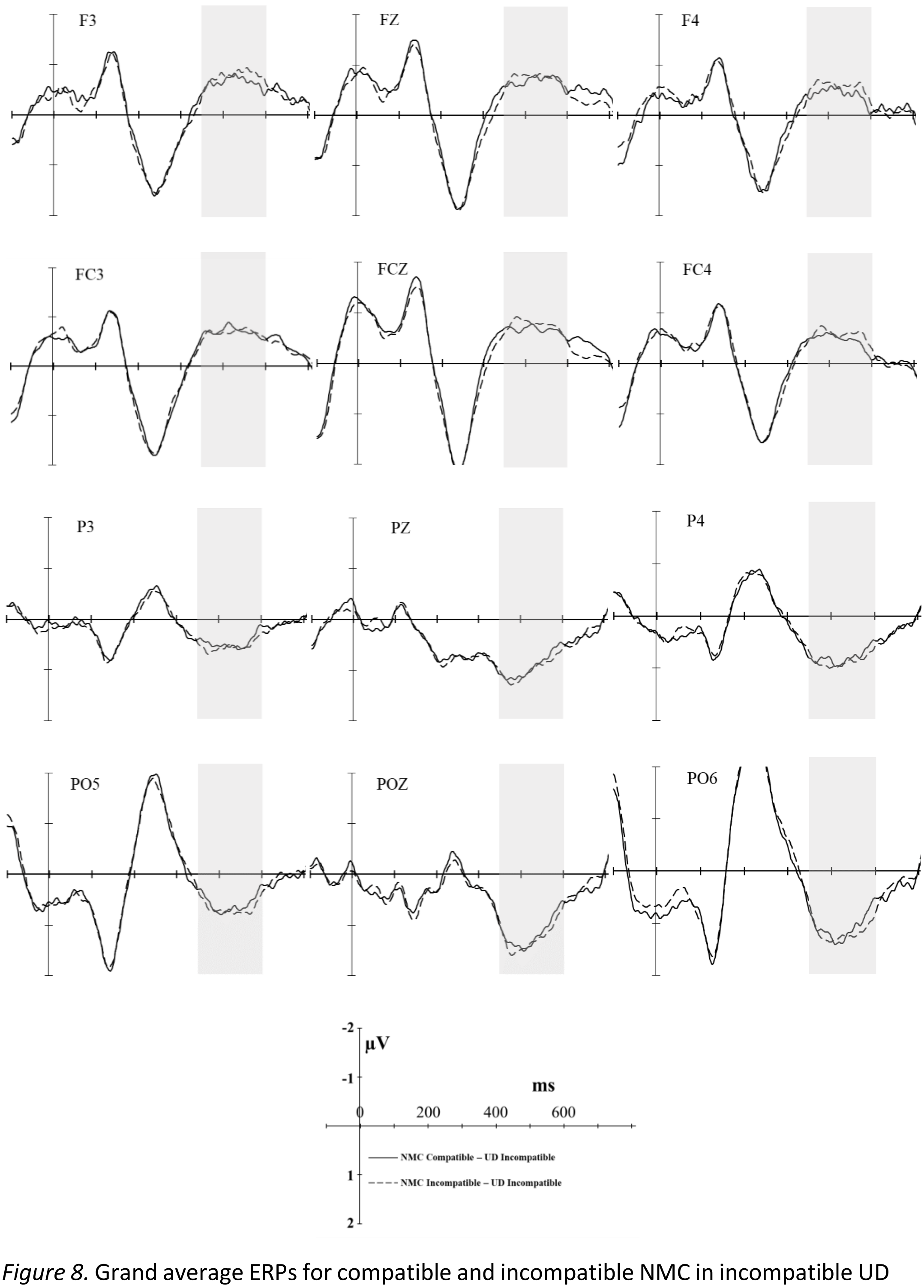

Figure 8. Grand average ERPs for compatible and incompatible NMC in incompatible UD trials. Grey boxes indicate the 350–500 ms time window.

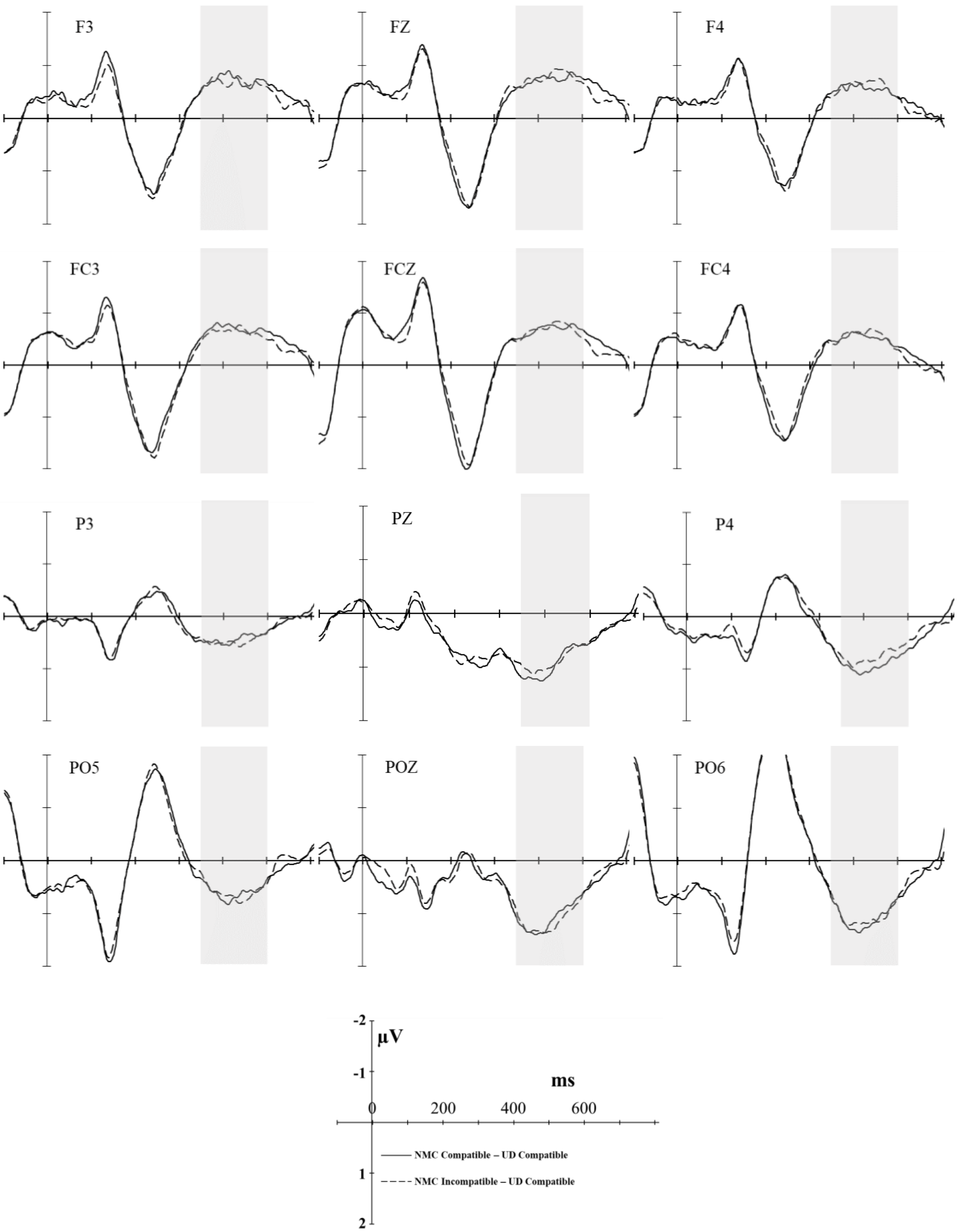

*Figure 9***.** Grand average ERPs for compatible and incompatible NMC in compatible UD trials. Grey boxes indicate the 350–500 ms time window.

Discussion

To our knowledge, there is no previous research evaluating the processing of multi-symbolic magnitudes composed of more than two symbols through the use of behavioral and electrophysiological measurements. In our study, we evaluated the processing of prices composed of three symbols (e.g., 49 euros) in which the decade (4), the unit (9) and the monetary category (euros) were the constituent symbols of the magnitudes. We considered both behavioral and electrophysiological measures to obtain converging data on two-digit price processing. As we pointed out in the introduction section, the vast majority of studies with multi-symbolic magnitude comparison tasks suggest the existence of a compositional processing according to which people analyze and compare the magnitude of each symbol separately (Bahnmueller et al., 2016; Huber et al., 2013; Klein et al., 2013; Korvorst & Damian, 2008; Man et al., 2012; Meyerhoff et al., 2012; Moeller et al., 2011). However, a recent behavioral study (Ojedo & Macizo, 2021) suggested that the comparison of two-digit prices could involve both compositional analysis (i.e., for the processing of the monetary category and the number) and holistic analysis (i.e., for the processing of the decade and the unit of the two-digit number embedded in the price). In our study, besides exploring the possibility of a hybrid processing of multi-digit prices (compositional and holistic), we aimed to evaluate the replicability of the behavioral data reported by Ojedo and Macizo (2021) as well as to incorporate electrophysiological indexes (i.e., N400-like component) that may be more sensitive than behavioral measures to capture the processes underlying the comparison of prices. Indeed, several experiments in cognitive neuroscience and experimental psychology show dissociations between behavioral measures (lack of effects on latency and/or response accuracy) and electrophysiological markers (significant effects on ERP components) (Bar-Haim et al., 2005; Marquardt et al., 2018; Thierry & Wu, 2007).

The behavioral results obtained in our study confirmed those reported in previous research in which the NMC compatibility effect was observed with one-digit prices (Macizo & Ojedo, 2018; Ojedo & Macizo, 2020) and two-digit prices (Ojedo & Macizo, 2021). Participants were more efficient (faster responses and higher accuracy rates) in NMC compatible trials than in NMC incompatible trials. This pattern of results suggests that the number and the monetary category were processed in a compositional manner which supports the general model of multi-symbolic magnitude processing according to which all symbols that constitute a magnitude are processed separately (Huber et al., 2016). However, no UD compatibility effects were found in the behavioral analyses. The absence of UD compatibility effect would suggest that the decade and the unit of the two-digit numbers contained in the prices were processed holistically. Therefore, the overall pattern of behavioral data (NMC compatibility effect but not UD compatibility effect) would be in favor of an hybrid model of multi-symbolic magnitude processing according to which, the monetary category and the number of the prices would be processed separately but the constituents of the numbers (the decade and the unit in our study) would be analyzed as a whole.

Nevertheless, this preliminary conclusion does not seem to be feasible in light of the pattern of electrophysiological data obtained in our study. Specifically, in anterior regions (frontal regions and fronto-central regions), in the time-window associated to the N400-like component (350-500 ms), an interaction was found between the NMC compatibility and the UD compatibility. In UD compatible trials, the NMC compatibility was not observed. However, in UD incompatible trials, the NMC compatibility was found with larger brain-wave negativity in NMC incompatible trials than in NMC compatible trials. This N400-like effect associated to the NMC compatibility in UD incompatible trials seems to be indicative of conflict processing when participants performed the price comparison task. In fact, previous studies have shown larger negativity of the N400-like component in trials where there is conflict between the physical size of digits and their numerical value compared to non-conflict trials (e.g., numerical Stroop effect, Schwarz & Heinze, 1998; Szűcs & Soltész, 2007). Likewise, these N400-like modulations are found when participants perform a price comparison task with one-digit prices. Thus, Ojedo and Macizo (2020) observed a larger negativity of the N400 component in NMC incompatible trials (e.g., 4 euro - 7 cents, 4 < 7 but euro > cents) compared to NMC compatible trials (e.g., 7 euro - 4 cents, 7 > 4 and euro > cents). Hence, the results of this study seem to indicate that, in some occasions, electrophysiological indexes are more sensitive than behavioral measures to capture cognitive processes underlying the participants' performance on experimental tasks, in our case, the price comparison used in the current study (Bar-Haim et al., 2005; Marquardt et al., 2018; Thierry &

Wu, 2007). Furthermore, electrophysiological data were only sensitive to the conflict in numerical processing when the two types of compatibilities evaluated in our study converged, that is, in situations where the conflict in the processing of prices was at its peak. Thus, the larger negativity of the N400-like component in NMC incompatible vs. NMC compatible trials was observed when the decades and the units were also incompatible comparisons (UD incompatible trials) but not in UD compatible trials.

The interaction between the two types of compatibilities (NMC and UD) in the N400 time-window seems to suggest that the participants analyzed and compared the three symbols of the prices (the monetary category, and the decade and the unit of the two-digit number) in a compositional manner. As noted in the introduction section, this pattern of results agrees with that found by Huber et al. (2015) in comparison tasks with magnitudes composed of a polarity sign (negative, positive), a decade and a unit (i.e., e.g., -97 vs. +53). The authors observed an interaction between sign-decade compatibility and sign-unit compatibility, and this interaction was interpreted in favor of a compositional perspective according to which the three symbols of the magnitude were compared separately.

It could be asked whether the compositional processing observed in the present study with multi-symbolic magnitudes composed of three symbols occurred in parallel or through a combination of parallel and sequential analyses. As mentioned in the introduction section, the results of the research conducted by Korvorst and Damian (2008) (hundred-decade and hundred-unit compatibility effects) seemed to indicate the parallel processing of three-digit numbers. However, in studies where magnitudes with more than three digits are considered (i.e., six-digit numbers), Meyerhoff et al. (2012) observed compatibility effect between the first two digits of the numbers but no compatibility effect between adjacent number pairs at other positions. The presence of a compatibility between the first two digits suggested that they were processed in parallel while it was followed by a sequential processing which would explain the absence of compatibility effects in intermediate and final positions of six-digit numbers. The interaction between NMC compatibility and UD compatibility observed in our study with electrophysiological measures seems to indicate that the two-digit prices were processed in parallel. Otherwise, if the processing of prices would have started in parallel (e.g., chunking analysis of the decade-monetary category) followed by a sequential processing of the unit, the NMC compatibility effect would not have interacted with the UD compatibility since the unit of the number is irrelevant to perform the comparison task with two-digit prices.

To sum up, the electrophysiological results found in this study suggest that prices composed of two-digit numbers are processed in a fully compositional and parallel manner. This type of processing agrees with a general model of multi-symbolic magnitude processing (e.g., Huber et al., 2016). To our knowledge, the present study provides for the first time electrophysiological evidence of fully compositional and parallel analyses of multi-symbolic magnitudes composed of more than two symbols, in our case, when people process two-digit prices.

CHAPTER IX

The Value of Euro Banknotes: Relevance of Size, Colour and Design[8]

In the current study, we evaluate the relevance of three physical dimensions when people retrieve the monetary value of banknotes. To this end, three monetary comparison tasks were designed in which pairs of banknotes were presented and participants selected the one with higher monetary value. In each task, a different banknote dimension (size, colour and design) was examined and a congruent and an incongruent condition (the value of the physical dimension corresponded or not to its actual value, respectively) were compared to a neutral condition (no information about the physical dimension was provided). We found a pattern of facilitation and interference effects which suggests that size is the most relevant dimension for accessing the monetary value of banknotes followed by colour. However, the availability of a variety of designs across banknotes seemed to hinder the monetary comparison task.

[8]This study has been submitted as Ojedo, F., & Macizo, P. (2022b). The Value of Banknotes: Relevance of Size, Colour and Design. [Manuscript submitted for publication]. Department of Experimental Psychology, University of Granada.

Introduction

Dealing with money is a routine activity involved in a multitude of tasks that people perform in everyday life. For example, in 2016, consumers averaged 1.2 cash transactions per day (Esselink & Hernandez, 2017). These monetary tasks are usually carried out with different formats of money such as prices, coins and bills. At first, people could handle money properly attending to only the monetary category and the number imprinted on the cash. For example, 10 dollars is more money than 10 cents if we focus on the monetary category (i.e., the economic value of the dollar > cent), and 10 dollars is more money than 1 dollar if we consider the numerical magnitude (10 > 1). However, the handling of cash is not an easy activity. People have different biases when dealing with money (e.g., Coulter & Coulter, 2007). Furthermore, the processing of physical dimensions of currency such as format (e.g., coins vs. bills) and size lead to errors when people evaluate sums of money (Goldman et al., 2012; Hasegawa, 2020; Peetz & Solimna, 2016).

To illustrate, with regard to *price* processing, individuals perceive greater discounts on price pairs (current price/reduced price) containing smaller units (e.g., \$23/\$22) relative to prices with larger units (e.g., \$19/\$18) even though the discount is the same in both cases (i.e., \$1) (Coulter & Coulter, 2007). In addition, when people compare price pairs (e.g., 2 euros > 9 cents), the processing of the numbers may be misleading when the higher price contains a smaller number than the lower price (2 euros > 9 cents but 2 < 9) relative to price pairs in which the monetary category and the number lead to the same decision (9 euros - 2 cents, where euros > cents and 9

> 2) (Cao et al., 2015; Macizo & Ojedo, 2018; Ojedo & Macizo, 2020). Thus, people have processing biases such as the “illusion of money” under which one hundred cents appears greater than one dollar (Shafir et al., 1997). In addition, the physical format of prices also influences the evaluation of their monetary value. For example, people are less efficient at comparing prices when their physical size is incongruent with their economic value (e.g., \$12-\$10) versus a congruent situation in which their physical size is in line with their monetary value (e.g., \$12-\$10) (Coulter & Coulter, 2007).

On the other hand, *coins* are representations of amounts of money that differ in physical dimensions such as size and colour. It has been observed that, in general, coins are designed to favour the distinctiveness between them and the monetary value they reflect (e.g., Pavlek et al., 2020). Regarding the physical dimensions of coins, several studies have evaluated the relationship between size and monetary value (Fitousi, 2010; Goldman et al., 2012; Hasegawa, 2020; Peetz & Solimna, 2016). Goldman et al. showed that when people have to judge the monetary value of coins in the Israeli currency (the shekel, sh), the performance is less efficient when the size of the coins is inconsistent with their economic value (5sh - 10sh) compared to situations where one coin is larger than another in both size and value (1sh - 5sh). Thus, the physical size of the coins affects the evaluation of the amount of money they represent. Moreover, Peetz and Soliman (2016) showed that the physical size of coins makes people overvalue them. In their study, the authors used coins in the Canadian currency that were enlarged by 15% of their actual size.

Individuals rated these oversized coins as more valuable than coins displayed in the real size. Thus, people seem to overestimate the value of coins where greater size is interpreted as greater value (i.e., the “bigger is better” heuristic, Silvera et al., 2002). In turn, Hasegawa (2020) revealed the inverse relationship, that is, how the monetary value of coins modulates the estimation of their size (e.g., more vs. less valuable coins are judged as larger on size, Leiser & Izak, 1987; see also, den Daas et al., 2012; Dubois et al., 2010). In his study, Hasegawa selected two coins in the Japanese currency with equal physical size but different monetary value (10 yen - 100 yen). The size of these coins was edited to implement a congruent size condition in which the 100 yen coin was larger than the 10 yen coin and an incongruent condition where the 100 yen coin was smaller than the 10 yen coin. Individuals displayed worse performance in the incongruent condition than in the congruent condition indicating that they retrieved the monetary value while estimating the size of the coins.

On the other hand, there is recent research on how people perceive and produce the monetary value of *banknotes* (Di Muro & Noseworthy, 2013; Giuliani et al., 2018; Macizo & Herrera, 2013; Macizo & Morales, 2015; Manippa et al., 2019; Mishra et al., 2006; Raghubir & Srivastava, 2009; Ruiz et al., 2017). Banknotes represent amounts of money that people can identify with accuracy based on the monetary category and the number depicted on each bill. However, different factors modulate the amount of money that people attribute to banknotes in their daily lives. For example, people judge with less economic value the bills that seem used and shabby compared to bills that, despite representing the same amount of money, appear crisp and new (Di Muro & Noseworthy, 2013). In addition, people are more likely to spend money when the same economic amount is presented in smaller bills than when it is shown in a single bill of greater size (Mishra et al., 2006; Raghubir & Srivastava, 2009). Moreover, people tend to attribute greater economic value to bills that are more familiar to them (e.g., regular $1 bill) compared to less familiar bills (e.g., rare $2 bill) (Alter & Oppenheimer, 2008). On the other hand, the recognition of banknotes seems to depend on the visual field in which they are displayed. Giuliani et al. (2018) showed that 100 banknotes are recognized faster than 5 banknotes when these bills are presented in the right visual field while no differences are observed between the processing of bills when they are presented in the left visual field. Finally, the physical size determines the processing of banknotes in monetary comparison tasks as occurred with the processing of prices (Coulter & Coulter, 2007) and coins (Goldman et al., 2012). Thus, in a monetary comparison task with pairs of banknotes, the selection of the bill with higher economic value depends on the congruency between its value and physical size (Ruiz et al., 2017). Thus, Ruiz et al. showed that monetary comparisons are more efficient when there is congruency between the value and size of euro banknotes (e.g., 20€ - 100€ banknote pair in which the ratio of the bills' physical sizes was preserved) compared to pairs of banknotes in which their physical size was equated (e.g., 20€ - 100€ banknote pair presented with the same size).

Therefore, physical dimensions such as size determine how people estimate the economic value of banknotes (e.g., Ruiz et al., 2017). However, in many currencies (euro currency, US dollar, Canadian dollar, British pound, Indian rupee, Chinese renminbi, etc.) the bills differ in other dimensions such as colour and design (i.e., image printed on them). The objective of this study was to evaluate the relevance of the physical dimensions of banknotes (size, colour and design) when individuals determine their monetary value. To this end, we used a monetary comparison task in which pairs of banknotes were presented and individuals selected the one with higher monetary value. The task was done with euro banknotes (5€, 10€, 20€, 50€, 100€). These banknotes differ proportionally in size (120 x 62 mm, 127 x 67 mm, 133 x 72 mm, 140 x 77 mm and 147 x 82 mm, respectively), main colour (grey, red, blue, orange and green, respectively) and design (doors, windows and bridges of classical, Romanesque, Gothic, Renaissance and Baroque architecture, respectively).

In our study, we developed three banknote Stroop-like comparison tasks to evaluate the processing of the size, colour and design of banknotes. Three experimental conditions were used in each task (see Figure 10). In the congruent condition, the value of the three dimensions (size, colour and design) was the same as that of the banknotes in real life. In the neutral condition, one of the physical dimensions was cancelled so that the value of this dimension was not informative of the economic value of banknotes (e.g., in the size version of the banknote comparison task, the size of the banknote pair was matched). Finally, in the incongruent condition, the value of one of the dimensions was exchanged between the bills of the pair (e.g., a 20€ banknote with the size of a 100€ banknote, and a 100€ banknote with the size of a 20€ banknote). In case a physical dimension (e.g., size) was informative of the monetary value of banknotes, we expect to observe a facilitation effect with better comparison of the banknotes' value in the congruent condition, in which this dimension was informative (e.g., size ratio equal to the current size of euro banknotes), as opposed to the neutral condition in which the dimension was not informative (e.g., banknotes of equal size). In addition, in case people would automatically process the physical dimensions of banknotes, we expect to find an interference effect with worse performance in the incongruent condition, in which the value of that dimension was incorrect compared to the neutral condition.

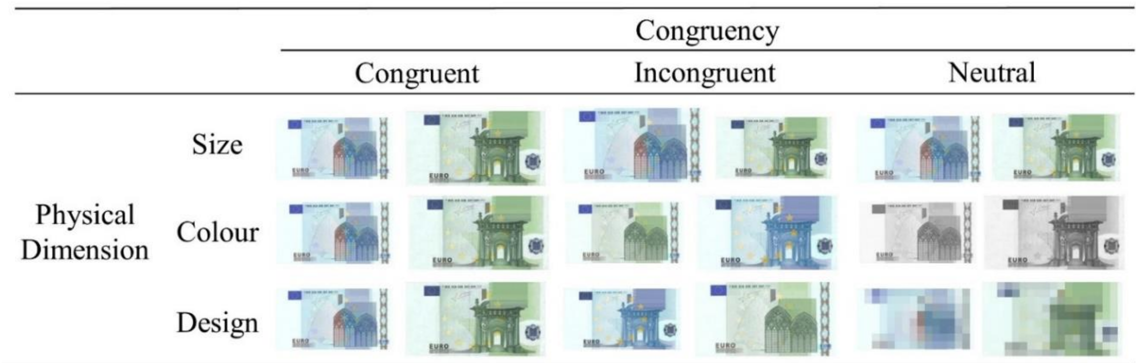

Figure 10. Example of trials in each experimental condition.

Critically, the magnitude of the facilitation and interference effects in the three versions of the banknote comparison task (size, colour and design) would indicate the relative importance of each dimension when individuals evaluate the amount of money represented on each banknote. A priori, we expect that physical size would be the most relevant dimension because size as well as monetary value represent magnitude information (physical and economic magnitudes, respectively). On the other hand, we expect colour to be more relevant than design for two reasons: (a) the differences in the main colour between pairs of banknotes are easily noticed. On the contrary, the comparison of the design of banknote pairs requires a careful analysis of the details printed on each banknote (e.g., to perceive architectural differences between the classical gate and the Romanesque gate represented on the 5€ and 10€ banknotes, respectively); (b) the colour of the euro banknotes has been a consistent dimension while their design has undergone variations over time. Thus, while the colour of the euro banknotes has remained the same since the currency came into circulation (year 2002), the design of banknotes has shown slight differences in the architectural elements imprinted on them (e.g., Europe series that came into circulation in 2013).

Experiment 7

Method

Participants

Sixty participants (51 women and 9 men) from the University of Granada with mean age of 21.68 years (*SD* = 2.95) took part in the experiment. All participants used the Euro currency on a daily basis. The participants signed an informed consent form before conducting the experiment and they received university credits for participating in the study. The sample size was computed using G*Power program

3.1.9.4 (Faul et al., 2007). It was calculated that for a 3 x 3 multivariate analysis of variance (MANOVA) to achieve 80% statistical power with α =.05 and an effect size of .25, the total sample size needed was N = 54. Thus, the number of participants who took part in the experiment was enough to capture the possible effects evaluated in our study.

Task

The stimuli and experimental task used in the study are fully and freely accessible at

https://osf.io/53fpv/?view_only=3f893b40a2094a4e96f7e713678dc151

The experiment was designed and controlled by the experimental software E-Prime 2.0 (Schneider et al., 2002). We developed three banknote Stroop-like comparison tasks where, in each trial, a pair of banknotes were presented on the screen and participants had to indicate the banknote with higher monetary value. The only difference between the three tasks was the physical dimension that was manipulated (size, colour and design). All the participants completed the three tasks, and the order in which they received these tasks was counterbalanced across participants.

In the study, the 5€, 10€, 20€, 50€ and 100€ banknotes were used. The Arabic numbers denoting the monetary value were removed from each banknote to prevent participants from performing the comparison task based on the numerical information only.

Three experimental conditions were implemented in each task (see Figure 10). In the congruent condition, the banknote pairs maintained the size, colour and design ratio to the actual values of euro banknotes. In the incongruent condition, the banknote pairs of each trial exchanged the value of the dimension under study (size, colour or design). For example, a 20€ bill in green shades and a 100€ bill in blue shades (i.e., incongruent condition in the colour version of the banknote Stroop task). Finally, in neutral trials, the pairs of bills had equal value in the dimension under study (i.e., same dimension in the size task, grey in the colour task, pixelated image in the design task) while maintaining the actual values of banknotes in the other two dimensions.

In the three versions of the banknote comparison task, pairs of euro bills were presented, one on the right and one on the left of the screen. Each euro banknote used in the study (5€, 10€, 20€, 50€ and 100€) was paired with the rest of banknotes, forming 10 possible combinations of banknotes (5€ - 10€, 5€ - 20€, 5€ - 50€, 5€ - 100€, 10€ - 20€, 10€ - 50€, 10€ - 100€, 20€ - 50€, 20€ - 100€, 50€ - 100€). These banknote pairs were presented twice to counterbalance the display layout (left and right) and the monetary value of banknotes (higher, lower). Thus, on 10 occasions, the banknote with the higher monetary value was displayed on the right (e.g., 5€ - 10€) and on 10 other occasions on the left (e.g., 10€ - 5€). These 20 pairs of banknotes were presented in the congruent, incongruent and neutral condition at random. Thus, each participant received 60 banknote pairs in each comparison task (size, colour and design version of the task).

Procedure

Participants were tested individually, seated 60-70 cm approximately from the computer screen (Capture E1903D, LCD, 1280 x 1024, 60 Hz, 19''). In each trial, a pair of banknotes was presented in the middle of the screen and participants were instructed to select the one with higher monetary value, as quickly as possible but without making errors, by pressing the Z or M key of the keyboard if the higher value banknote was located on the left or right side of the screen, respectively. The banknotes remained on the screen until the participants' response. The interval between trials lasted 300 ms (blank screen). Before starting each of the three versions of the banknote comparison task, the participants performed 5 practice trials. The duration of the experiment was approximately 45 minutes.

Results

All data and analyses of the present study are fully and freely available at the following link:

https://osf.io/53fpv/?view_only=3f893b40a2094a4e96f7e713678dc151

One participant was excluded from the analyses due to the high error rate (> 50% of the trials). Trials in which participants committed an error were excluded from the latency analysis and submitted to the error rate analysis, the percentage of errors was: 5.51% in the size-based task, 3.80% in the colour-based task, and 4.58% in the design-based task. Afterwards, the reaction times (RTs) associated with correct responses were trimmed following the procedure described by Tabachnick and Fidell (2007) in order to eliminate univariate outliers. Raw scores were converted to standard scores (*z*-scores). Data points which, after standardization, were 3 *SD* outside the normal distribution, were considered outliers. After removing outliers from the distribution, z-scores were calculated again. The filter was applied in recursive cycles until no observations were outside 3 *SD*. The percentage of outliers was 5.53% in the size-based task, 7.14% in the colour-based task, and 7.24% in the design-based task.

The RTs and error rates were submitted to an analysis of variance (ANOVA) with congruency (congruent, incongruent and neutral) and banknote dimension (size, colour and design) as within-participant factors. The Greenhouse–Geisser correction (Greenhouse & Geisser, 1959) for non-sphericity of variance was used for all *F*-ratios with more than one degree of freedom in the denominator; reported here are the original *df*, the corrected probability level, and the ε correction factor. In all analyses reported in text, the critical *p* level for significance was α =.05. The outcomes of these analyses are reported in Table 15 and Figure 11. Additional analyses conducted with the order in which the three comparison tasks were performed revealed that this factor did not interact with congruency. Furthermore, the Order x Congruency x Banknote dimension three-way interaction was not significant so the order of administration of the tasks was not considered any further.

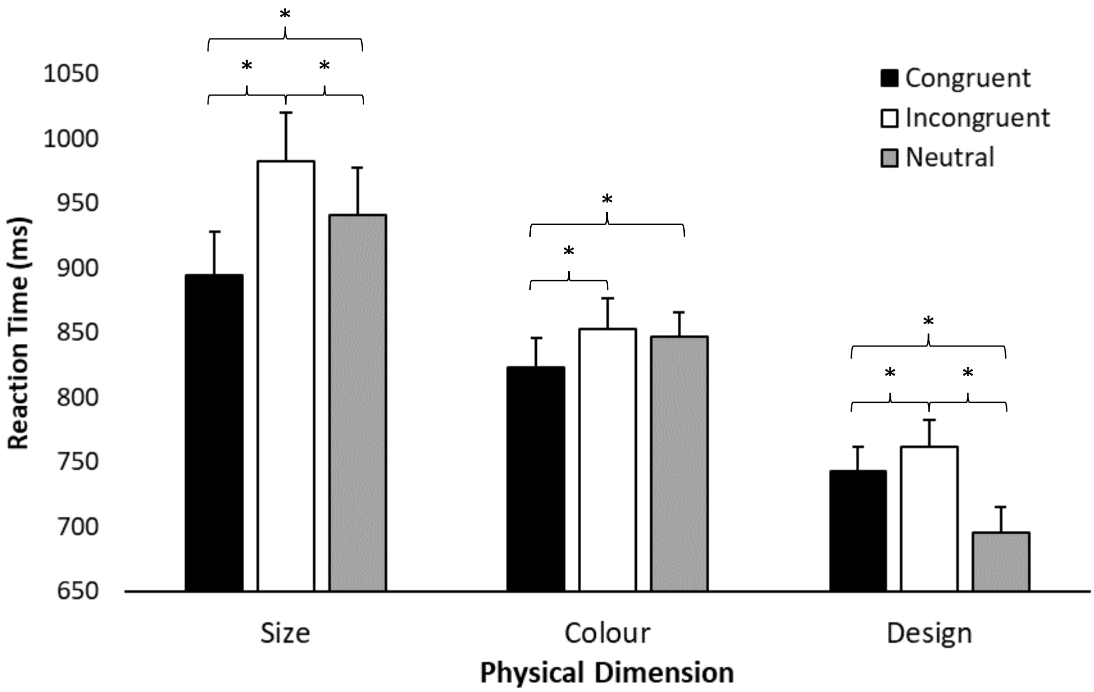

Figure 11. Reaction times (RTs in milliseconds, ms) obtained in each of the three Stroop-like banknote comparison tasks.

Table 15. *Facilitation and Interference Effect across Banknote Dimensions*

	Congruent		Incongruent		Neutral		Facilitation	Interference
	RT	E%	RT	E%	RT	E%		
Size	894 (19)	3.81 (0.71)	983 (21)	7.33 (1.69)	940 (19)	4.45 (0.74)	47^{**}	-42^{**}
Colour	822 (35)	1.73 (0.34)	852 (37)	4.58 (1.00)	846 (37)	1.8 (0.37)	24^{**}	-6^{ns}
Design	743 (23)	2.67 (0.50)	762 (24)	5.68 (1.76)	695 (19)	1.91 (0.35)	-47^{**}	-67^{**}

Note. Reaction times (RT) (in milliseconds), error percentage (E%) and standard error (in parentheses) obtained across the physical dimensions of banknotes in the congruent, incongruent and neutral condition. Facilitation = Neutral minus Congruent (RT). Interference = Neutral minus Incongruent (RT). $^{ns}p > .05$, $^{*}p < .01$, $^{**}p < .001$.

The main effect of congruency was significant in the latency analysis, $F(2, 116) = 50.24$, $p < .001$, $\varepsilon = .97$, $\eta^2 = .46$, and the error rate analysis, $F(2, 116) = 12.55$, $p < .001$, $\varepsilon = .57$, $\eta^2 = .18$. The main effect of banknote dimension was significant in the latency analysis, $F(2, 116) = 28.59$, $p < .001$, $\varepsilon = .81$, $\eta_p^2 = .33$, and the error rate analysis, $F(2, 116) = 4.26$, $p = .024$, $\varepsilon = .80$, $\eta_p^2 = .07$. The Congruency x Banknote dimension interaction was significant in the latency analysis, $F(4, 232) = 19.10$, $p < .001$, $\varepsilon = .84$, $\eta_p^2 = .25$, but not in the error rate analyses, $F(4, 232) = 0.25$, $p = .753$, $\varepsilon = .45$, $\eta_p^2 < .01$. The interaction found in the latency analysis was further analysed.

When the congruency effect was analysed for each banknote dimension separately, the results revealed that the congruency effect was significant in the size-based task, $F(2, 116) = 47.10$, $p < .001$, $\varepsilon = .82$, $\eta_p^2 = .45$. The RTs in the congruent size condition differed from the RTs in the incongruent size condition, $F(1, 58) = 65.98$, $p < .001$, $\eta_p^2 = .53$, and the neutral size condition, $F(1, 58) = 27.31$, $p < .001$, $\eta_p^2 = .32$. The difference between the neutral size condition and the incongruent size condition was significant also, $F(1, 58) = 34.01$, $p < .001$, $\eta_p^2 = .37$.

In the colour-based task, the congruency effect was significant, $F(2, 116) = 6.04$, $p = .003$, $\varepsilon = .99$ $\eta_p^2 = .09$. The RTs in the congruent colour condition differed from the RTs in the incongruent colour condition, $F(1, 58) = 11.28$, $p < .001$, $\eta_p^2 = .16$, and the neutral colour condition, $F(1, 58) = 6.83$, $p = .011$, $\eta_p^2 = .10$. The difference between the neutral colour condition and the incongruent colour condition was not significant, $F(1, 58) = 0.37$, $p = .543$, $\eta_p^2 = .01$.

Finally, in the design-based task, the congruency effect was significant, $F(2, 116) = 32.41$, $p < .001$, $\varepsilon = .89$, $\eta_p^2 = .36$. The RTs in the congruent design condition differed from the RTs in the incongruent design condition, $F(1, 58) = 7.10$, $p = .010$, $\eta_p^2 = .11$, and the neutral design condition, $F(1, 58) = 32.66$, $p < .001$, $\eta_p^2 = .36$. The difference between the neutral design condition and the incongruent design condition was significant also, $F(1, 58) = 45.95$, $p < .001$, $\eta_p^2 = .44$.

Additionally, we evaluated possible differences between the three comparison tasks at each level of the congruency factor separately. In the congruent condition, the banknote dimension effect was significant, $F(2, 116) = 15.45$, $p < .001$, $\varepsilon = .81$, $\eta_p^2 = .21$. The performance in the size-based task differed from the colour-based task, $F(1, 58) = 4.97$, $p = .030$, $\eta_p^2 = .08$, and the design-based task, $F(1, 58) = 55.19$, $p < .001$, $\eta_p^2 = .49$. The difference between the colour-based task and the design-based task was significant also, $F(1, 58) = 8.13$, $p = .006$, $\eta_p^2 = .12$.

In the incongruent condition, the banknote dimension effect was significant, $F(2, 116) = 29.03$, $p < .001$, $\varepsilon = .92$, $\eta_p^2 = .33$. The size-based task differed from the colour-based task, $F(1, 58) = 17.56$, $p < .001$, $\eta_p^2 = .23$, and the design-based task, $F(1, 58) = 80.33$, $p < .001$, $\eta_p^2 = .58$. The difference between the colour-based task and the design-based task was significant also, $F(1, 58) = 8.40$, $p = .005$, $\eta_p^2 = .12$.

Finally, in the neutral condition, the banknote dimension effect was significant, $F(2, 116) = 38.33$, $p < .001$, $\varepsilon = .75$, $\eta_p^2 = .40$. The size-based task differed from the colour-based task, $F(1, 58) = 8.08$, $p = .006$, $\eta_p^2 = .12$, and the design-based task, $F(1, 58) = 177.75$, $p < .001$, $\eta_p^2 = .75$. The difference between the colour-based task and the design-based task was significant also, $F(1, 58) = 23.68$, $p < .001$, $\eta_p^2 = .29$.

We conducted additional analyses to evaluate whether the magnitude of facilitation and interference effects differed among the three banknote dimensions. *T*-test analyses revealed a trend towards a greater facilitation effect (neutral condition minus congruent condition) in the size-based task (47 ms) than in the colour-based task (24 ms), $t(116) = 1.76$, $p = .08$. The magnitude of the facilitation effect was greater in the size-based task than in the design-based task (-47 ms), $t(116) = 7.72$, $p < .001$. Finally, the magnitude of the facilitation effect was greater in the colour-based task than in the design-based task, $t(116) = 5.77$, $p < .001$. Regarding the interference effect (neutral condition minus incongruent condition), the magnitude of the interference effect was greater in the size-based task (-42 ms) than in the colour-based task (-6 ms), $t(116) = 3.14$, $p = .002$. Furthermore, the magnitude of the interference effect was greater in the design-based task (-67 ms) compared to both the size-based task, $t(116) = 1.99$, $p = .048$, and the colour-based task, $t(116) = 4.55$, $p < .001$.

Discussion

The banknotes are pieces of paper that are legal tender in a country or region and are intended to represent different economic values. Banknotes, along with coins, are cash that people use in their daily lives to engage in economic transactions. The banknotes vary between currencies (euros, dollars, British pound, Chinese renminbi, etc.). Within the same circulating currency, banknotes that represent different economic amounts usually differ from each other mainly in three physical dimensions: size, color and design. Earlier studies have examined the role of physical size when people estimate the monetary value of banknotes (e.g., Ruiz et al., 2017). However, to our knowledge, there is no previous research evaluating together the relative weight of size, color and design of banknotes in monetary tasks (e.g., comparison of the economic value of banknotes). In our study, we addressed this issue directly. We examined the possible facilitation effect derived from having the correct value of a physical dimension (i.e., congruent condition) and the possible interference effect of processing banknotes with an incorrect value in that dimension (i.e., incongruent condition) compared to a situation where the physical dimension under study was not informative (i.e., neutral condition). The analysis of these effects would allow to determine the relevance of size, color and design when people compared the monetary value of banknotes.

The results obtained in our study seem to indicate that the order of relevance of the banknotes' physical dimensions to know their economic value are the size, followed by the color and finally the design. This conclusion stems from two observations. First, the magnitude of the facilitation effect (congruent vs. neutral condition) was higher in the comparison task based on size > color > design. While in the neutral condition the dimension under study does not allow the discrimination between banknotes, the congruent condition shows the influence of this dimension in the banknote comparison task. Thus, the facilitation effect would be an index of the degree to which the information provided by size, color and design benefits the retrieval of the banknotes' monetary value. On the other hand, in the neutral condition, participants revealed poorer performance in the size > color > design condition. This pattern of outcomes again suggests that size was the most relevant dimension for performing the monetary task. Thus, in the neutral size condition, the informational value of this dimension was cancelled out, so the participants had to retrieve necessarily the monetary value of the banknotes by analyzing the remaining dimensions (color and design). Consequently, the performance in the neutral size condition would indicate the difficulty of accessing the monetary value of the banknotes due to the impossibility of attending to this dimension.

It was striking to observe in our study the same pattern of results in the congruent condition as in the neutral condition across the physical dimensions of the banknotes (i.e., longer response latency in the size > color > design). These differences between dimensions in the congruent condition were not expected since the stimuli in this condition were the same across all three monetary comparison tasks (i.e., pairs of banknotes that maintained the size, color, and design ratios of the actual banknotes). This pattern of results cannot be explained by differences among the participants since they all performed the three comparison tasks. In addition, the order in which the tasks were completed did not affect the participants' performance. Therefore, the similarity between the neutral and congruent condition seems to suggest that the lack of the informational value of one dimension (i.e., neutral condition) impacts the way in which banknotes are processed in the rest of the conditions (i.e., congruent and incongruent conditions). In other words, in a monetary comparison task (e.g., design-based task), the participants would preferentially process the dimensions that are informative in all conditions, congruent, incongruent and neutral (e.g., color and size) at the expense of the less informative dimension in that task (e.g., design) because it is predictive of the monetary value of banknotes in only one condition (e.g., congruent condition).

An unexpected finding in our study was obtained in the comparison task based on the design dimension. Specifically, the participants did not show facilitation but interference effect with longer response times in the congruent condition than in the neutral condition (47 ms difference). While in the neutral design condition the design of banknotes was not informative of their monetary value, in the congruent design condition participants could attend to this dimension when performing the task. Thus, including a new dimension in the congruent condition (i.e., design) hindered the monetary comparison, even though that dimension reflected the real design of the banknotes. This pattern of results seems to indicate that the design is the most difficult dimension to process compared to the size and color of banknotes. This observation would be supported by the fact that, in general, people have a greater facility for global vs. local perception of visual stimuli (global precedence, Navon, 1977). This global precedence would entail a more efficient processing of size and color compared to the design of the banknotes. In particular, size and color discrimination can be carried out by a holistic inspection of the banknotes while a monetary comparison based on the banknote design would involve the careful analysis of the image details (differences between the architectural style of gates and windows printed on euro banknotes).

Thus, the outcomes of our study suggest that the analysis of the design dimension seems to make difficult the retrieval of the economic value of the banknotes. On the contrary, size and color would be relevant dimensions to perform monetary comparison tasks. However, at this point, we could question why the size of the banknotes turned out to be the most relevant dimension. The answer to this issue seems to lie in the fact that both the monetary value and the size of the banknotes refer to the same type of semantic content (i.e., magnitude information). In fact, the facilitation and interference effects observed in the size-based comparison task resemble those found in numerical tasks where the physical size of numbers is evaluated (e.g., number-size congruency effect, Arend & Henik, 2015; Besner & Coltheart, 1979; Henik & Tzelgov, 1982; Santens & Verguts ,2011). In these studies, the participants' performance is less efficient when the size and the numerical magnitude of number pairs are incongruent (e.g., 8-2) compared to congruent number pairs in which the size and the numerical magnitude point in the same direction (e.g., 8-2).

The current study has practical implications for the issuance of legal tender (i.e., banknotes in circulation). The results of our work suggest that banknotes denoting different economic amounts should ideally differ both in size and color since both physical dimensions facilitate monetary comparisons when they contain relevant information (i.e., congruent condition) versus when they do not (i.e., neutral and incongruent condition). In addition, the most significant dimension that should be present in circulating currency would be size since it facilitates the performance of monetary task to a greater extent than the color dimension. On the other hand, the processing of banknote designs produces interference rather than facilitation when people compare banknotes that keep the design of banknotes in real life (congruent condition) relative to the comparison of banknotes without any design (neutral condition). Therefore, from the study reported here, it would be advisable to put into circulation banknotes with the same design but variability in size and color depending on the amount of money banknotes represent.

-PART 3-

General Discussion and Conclusions

CHAPTER X

General Discussion and Conclusions

How are prices represented and processed? Are prices represented holistically, compositionally or both ways? How do people process money? Is the processing of prices modulated by the number of digits or the format in which they are presented? To answer these questions we performed five studies, each described in a chapter of the experimental section. The main objective of the chapters V to VIII was to study how one-digit prices (Chapters V and VI) and two-digit prices (Chapters VII and VIII) are processed and whether they are represented holistically, compositionally or in a hybrid manner. For this, we examined the compatibility effect in a price comparison task by taking behavioural (Chapters V to VIII) and electrophysiological measures (Chapters VI and VIII). Whereas chapters V to VIII focused on prices as represented by numerical values, the last chapter of the experimental section (Chapter IX) investigated the compatibility effect when the prices to be compared are banknotes. The objective of this last study was to evaluate the relevance of a physical dimension, such as size, when accessing the value of banknotes. In the following pages, we summarise and discuss the main findings of these studies.

The processing of prices as a multi-symbolic magnitude

Most models on the representation of numerical magnitudes (Huber et al., 2014, 2016) assume that multi-symbolic magnitudes are represented and processed compositionally, including magnitudes composed of different types of symbols. However, in a previous study using a price comparison task, Cao et al. (2012, 2015) reported evidence for holistic processing, suggesting that prices might be of a special magnitude when it comes to the way they are represented. The purpose of chapters V to VIII was to address this question. In the following paragraphs, we summarise the results of these chapters. First, we discuss the behavioural and EEG experiments where prices were composed of one-digit numbers (one euro, five cents, etc.) and later introduced our experiments on two-digit numbers (62 euros, 25 cents, etc.). In both, one-digit and two-digits experiments, we examined whether prices are represented holistically or compositionally.

One-digit price processing. Our first experiment was directed to replicate the results by Cao et al. (2012, 2015), as these were the only previous studies assessing whether prices were processed holistically or compositionally. Thus, we investigated whether a holistic distance effect (and not a digit distance effect) was observed when the participants were asked to indicate the magnitude of prices compared to a standard price. This pattern was interpreted by Cao et al. (2012) as indicating that only holistic processing was taking place contrary to the prediction of multi-symbolic processing theories in which compositional processing was assumed.

The results of our first experiment, with an identical procedure, replicated the pattern obtained by Cao et al. (2012, 2015) since we observed a holistic distance effect (digit plus monetary unit), whereas the digit distance effect (only digit) was not observed, indicating that the price components (number and monetary unit) have not been processed separately and only the total magnitude has been processed as a whole. Although these results seem to go against the predictions of multi-symbolic magnitude theories, where compositional processing is assumed, methodological reasons precluded us from concluding that prices are processed differently from other symbolic magnitudes. Both Cao's studies and our replication study lacked some controls that are usually introduced to study compatibility effects in other numerical cognition experiments.

Thus, in our next experiments on the effects of price compatibility in comparison tasks, we controlled for variables, such as holistic and inter-digit distances, intra/inter-trial ratio or the mode of presentation of the stimuli. The control and/or manipulation of these variables were made to determine whether the compatibility effect would exhibit the same behaviour as when it is studied in other numerical magnitudes (Macizo, 2017; Macizo & Herrera, 2010; 2011; 2013; Macizo et al., 2010; Macizo et al., 2011a; 2013a; Moeller et al., 2013; Nuerk et al., 2001; 2004). Similarly, we introduced manipulations on the mode of presentation of the prices (simultaneous/sequential) to be able to compare our results with both previous studies of price processing (where a sequential presentation of the stimuli and retention of information in memory had been used) and with studies of the compatibility effect on other numerical magnitudes (where a simultaneous presentation of the stimuli to be compared had been mostly used). The results of our experiments were clear: after controlling for holistic distance, compatible trials (e.g., eight euro–four cent, 8 > 4, and euro > cent) were processed faster than incompatible trials (e.g., eight cent–four euro, 8 > 4, but cent < euro) for both simultaneous and sequential presentation of prices. In addition, the compatibility effect depended on the ratio of intra-monetary category comparisons (eight euro–six euro) and inter-monetary category comparisons (eight euro–four cents). Hence, the pattern of compatibility effects in these experiments suggested that the processing of prices is not holistic but componential when appropriate controls are established. These data are in line with the idea of a general model of multi-symbolic magnitude processing (Huber et al., 2014, 2016) and with its assumption that any multi-symbolic magnitude composed of either numbers (e.g., 7, 62, etc.) or numbers and another character (e.g., the number and the monetary category as in seven euros) is processed compositionally.

Overall, our behavioural results provided further evidence for the multi-symbolic magnitude processing model and extended it to magnitudes composed of different types of symbols. In addition, they challenged the idea that prices are a special magnitude when it comes to the way they are represented by providing evidence that their representation is similar to that of multi-digit numbers.

Similarly, the results of the electrophysiological experiments provided evidence of the compositional nature of price processing. Electrophysiological recordings were important since Cao et al. (2012) also provided neural evidence indicating that prices were processed as unitary/holistic entities. Although, as mentioned, their studies had certain methodological limitations, we thought it is important to study the neural signatures of price processing and the compatibility effect when proper control was taken. In their experiments, Cao et al. (2012) observed that the holistic distance, but not the distance between the digits, modulated the mean amplitude in the 350–450 ms time window. Specifically, there was greater negativity in close-distance prices than long-distance prices. However, this pattern does not entirely agree with previous studies, where the distance effect was observed in earlier temporal windows (P2p time window, Dehaene, 1996; Temple & Posner, 1998). Hence, the interpretation of their results as evidence of holistic magnitude processing is open to questions.

In fact, the results of our EEG experiment on a one-digit number showed a different pattern. In particular, an N400-like component was observed in the 350–450 ms time window, with incompatible trials showing larger negative amplitudes than compatible trials in anterior regions. We interpreted this compatibility effect as supporting the notion of compositional processing. Previous studies of number comparison tasks have also shown modulations of the N400 component in conditions where the congruence between the physical size and the magnitude of the two numbers to be compared was manipulated (Schwarz & Heinze, 1998; Szucs

& Soltesz, 2007; West et al., 2005), with incongruent trials producing larger negativities. This more pronounced N400 for incongruent trials has been interpreted as an index of conflict detection. Hence, the increment in negative amplitude in incompatible trials in our experiments can be taken as neural evidence of the conflict produced by compositionally incongruent comparisons.

Therefore, the results of the experiments on the one-digit process showed evidence of the compatibility effect through both behavioural and electrophysiological data, the latter being the first time that it has been reported. Taken together, these results once again provide support to a general model of multi-symbolic processing (Huber et al. 2016) in which compositional processing is assumed independently of the nature of the numerical magnitude, including prices (i.e., each of the price components is processed independently). Nevertheless, it is important to keep in mind that while the presence of compatibility effects would discard a purely holistic processing perspective, it is compatible with both a fully compositional processing perspective and a hybrid perspective, where both types of processing take place. Further research should try to disentangle these two possibilities.

Two-digit price processing. The objective of our third chapter was twofold. First, we aimed to explore the processing of prices formed by two-digit numbers, since there was no previous research on multi-digit number prices. Second, we aimed to examine the possible differences in price processing as a consequence of the format in which the prices were presented. To investigate these two goals, both the number-monetary category (NMC) compatibility and the compatibility between the decade and unit composing the number (UD compatibility) were considered in three different price comparison tasks, using a different price presentation format for each one (Arabic digits, written number words and auditory number words).

The NMC compatibility effect was observed across all presentation formats, extending the evidence found in previous studies with single-digit prices using the Arabic numeral presentation format (Macizo & Ojedo, 2018; Ojedo & Macizo, 2020). Importantly, we found, for the first time, the compatibility effect with prices composed of two-digit numbers, extending thus the evidence of the compositional perspective to multi-digit prices (previously supported by the evidence suggesting separate processing of the number and the currency unit). Although the magnitude of the effects varied between formats, the compatibility effect was consistently found with both Arabic numerals and verbal numbers (written and auditory numerals), which indicates that compositional processing is independent of its initial encoding and of the way the magnitude is represented, as predicted by the general model of multi-symbolic magnitude processing (Huber et al., 2016).

In contrast, the UD effect was not observed in any of the price presentation formats examined. The absence of the effect on the verbal presentation of prices was expected based on previous results with languages such as Spanish, Italian or English, where the decade precedes the unit in the verbal version of the number (Macizo & Herrera, 2008; Macizo et al., 2010; Macizo et al., 2011a, 2011b; Nuerk et al., 2005). This pattern, together with results showing compatibility effects in languages such as German, in which the verbal version of the number follows the unit-decade order, suggests that people process number words according to the internal structure of the language they speak. Thus, in our studies, the influence of a language such as Spanish, in which more relevance is given to the processing of the decade than to the unit, leads to the absence of this effect when exploring the effect of compatibility in two-digit numbers, suggesting that the decade and the unit have not been processed separately but as a whole (holistic processing). Note, however, that the absence of UD in the verbal format has been observed only in prices, since the UD effect had been previously found when comparing pairs of two-digit numbers independently of language (Macizo et al., 2010, 2011a, 2011b; Macizo & Herrera, 2008, 2010, 2011; Moeller et al., 2011, 2013; Nuerk et al., 2001, 2005).

Taken together, the results of this study exploring for the first time the processing of two-digit prices would support the hybrid perspective, with greater weight of compositional processing in the analysis of the number and the monetary category but greater relevance of holistic processing in the analysis of the two components of the number (decade and unit). Therefore, the overall behavioural results could be interpreted as supporting the hybrid model of multi-symbolic magnitude processing according to which the monetary category and the number of the prices would be processed separately but the constituents of the numbers (the decade and the unit in our study) would be analysed as a whole.

However, the electrophysiological data obtained in the Chapter VIII did not seem to support the conclusions reached from the behavioural analysis. More specifically, in this experiment, we replicated the conditions of the previous behavioural experiment but also recorded EEG while participants compared two-digit prices. The electrophysiological results showed an interaction between NMC compatibility and UD compatibility in the 350–500 ms time window at anterior regions (frontal regions and fronto-central regions), consistent with the N400-like component. In particular, no NMC compatibility effect was observed in the compatible UD trials, but a significant NMC compatibility effect was observed in the incompatible UD trials (larger brain-wave negativity in incompatible NMC trials compared with compatible NMC trials). As mentioned, this N400-like component has been interpreted as an index of conflict processing (see Ojedo & Macizo, 2020, for single-digit price comparisons, and Schwarz & Heinze, 1998; Szűcs & Soltész, 2007 for numerical Stroop effects).

Thus, the electrophysiological data appeared to have been sensitive to the effect of NMC compatibility only in UD incompatible trials; in other words, the larger negativity of the N400-like component in NMC incompatible vs. NMC compatible trials was observed when the decades and the units were also UD incompatible (e.g., 49 euros - 57 cents, 4 < 5 and 7 < 9) but not in UD compatible trials (e.g., 47 euros - 59 cents, 4 < 5 and 7 < 9). This might indicate that the more sensitive electrophysiological data might have been able to capture compatibility effects in situations in which price processing conflict was at its peak. There are several examples in the cognitive neuroscience and experimental psychology literature in which differences can be observed between behavioural measures and electrophysiological markers in which despite a lack of latency or accuracy effects, significant differences in ERP components are observed (Bar-Haim et al., 2005; Marquardt et al., 2018; Thierry & Wu, 2007). Hence, it is not at odds that the more sensitive electrophysiological measure is capturing and interacting, which behavioural measures were not able to assess.

This is important because the interaction between the two compatibilities (NMC and UD) would support the fully compositional approach, as it would indicate that participants would be processing each of the three components (the monetary category and the decade and the unit of the two-digit number) individually and thus in a compositional manner. Furthermore, this result would indicate not only that each component is processed separately but also that the processing of these components would not take place sequentially, nor would there be any chunking process. Otherwise, it would not be possible to observe such a conflict situation as the interaction between the two compatibilities seems to be. The electrophysiological pattern observed, as with one-digit prices, would indicate that the processing of two-digit prices might also follow a fully compositional and parallel type of processing.

Analysis of the relevance of physical dimensions for access to the value of banknotes

Prices can be translated into monetary value that, in turn, can be represented by coins and banknotes. Whereas in the previous experiments we represented prices by numerical values in different numerical formats and examined the compatibility effect, in the last chapter of the experimental section also investigated the processing of money, but in this case focusing on the processing of banknotes. The objective of this last study was to evaluate the relevance of three physical dimensions (size, colour and design) in processing and accessing the monetary value of banknotes. The importance of the physical size of banknotes in accessing banknote value has been observed in previous studies (Ruiz et al., 2017). However, there is no study in which several physical magnitudes are evaluated. The relevance of each of the magnitudes was determined by comparing facilitation and interference effects with tasks in which banknotes were presented and participants selected the one with the higher monetary value. We created three tasks that varied on whether we manipulated the size, colour or design of the banknote, and we defined a congruent condition when the presentation of banknotes had a correct value of the manipulated physical dimension, an incongruent condition in which the presentation of banknotes had an incorrect value on the manipulated dimension, and a neutral condition in which the dimension manipulated was not informative.

Two observations suggested that the physical dimension with the greatest relevance for accessing the monetary value of banknotes was size, followed by colour and then design. The first observation was that the magnitude of the facilitation effects (congruent vs. neutral condition) depended on the dimension and followed this same order (size>colour>design). Since facilitation effects are assumed to indicate how much the information provided by a particular dimension benefits performance when the dimension is congruent with monetary value, larger facilitation effects for size indicate its larger role in facilitating access to the monetary value. Secondly, comparisons of the neutral conditions for each task indicated that the worst performance was for the size condition, followed by colour and design. This pattern can also be interpreted as representing the order of relevance of each dimension for accessing banknote value since better or worse performance in the neutral conditions would indicate the difficulty of accessing the monetary value of the banknotes when attention to a particular dimension is not possible. Interestingly, manipulation of the design yielded no facilitation effect, but on the contrary, participants performed better in the neutral condition than in the congruent condition, suggesting that although the congruent condition reflects the design of the actual banknote, the information provided by this dimension might hinder access to the monetary value of the banknote.

To sum up the conclusions drawn from the data of this study, the dimensions of size and colour appear to be relevant for accessing the monetary value of banknotes, so the information provided by these dimensions has facilitated the performance of the monetary comparison task. In contrast, the design dimension seems to have hindered rather than facilitated the task.

Although this study represents only a preliminary approach to the format and physical dimension of the representation of monetary values, it opens a line of investigation in which multiple issues regarding the representation of money and prices in daily life situations can be raised.

Conclusion

In the present doctoral thesis, we have examined the processing of money from two different perspectives. On the one hand, we aimed to answer the question of how prices are processed and whether this is different from other multi-symbolic magnitudes that have also been studied. On the other hand, we aimed to study how access to the monetary value of banknotes proceeds and, in particular, what the physical dimensions on the banknote that facilitates access to this value are.

In terms of price processing, we found across four studies that the number-monetary category compatibility effect can be found through behavioural and electrophysiological measures in both single-digit and two-digit price comparison tasks, indicating that these two price components are processed separately and not as a whole, as was suggested in previous studies. Moreover, although the UD compatibility effect was not observed at the behavioural level, an interaction between the NMC and the UD effects was observed in the electrophysiological results, also suggesting that the unit and the decade are processed separately when they are part of a two-digit price.

In relation to the elements representing monetary value in banknotes, our study indicates that of the physical dimensions (size, colour and design) in which the banknotes usually differ, size was the most relevant dimension providing access to the monetary value of the banknote. Other dimensions, such as colour or design, which are difficult to translate into magnitudes, play a smaller role (colour) or might even interfere with the retrieval of the economic value of the banknotes. These findings are important for understanding the processing of money in real-life situations and for providing procedures to start investigating how physical dimensions, such as size, combine with the numerical value in the banknote to represent monetary value.

CHAPTER XI

Resumen y Conclusiones

En la presente tesis doctoral se propone examinar cómo las personas procesamos el dinero desde dos perspectivas diferentes. Por un lado, se intentó responder a la pregunta de si los precios son una magnitud multi-simbólicas diferentes, como se ha sugerido en estudios previos, y si estos son procesados de la misma manera que el resto de las magnitudes multi-simbólicas investigadas. Estudiar esto nos ayudaría no solo a comprender mejor lo relativo al procesamiento de los precios, siendo esto relevante de por si al ser unas unidades usadas por todos en nuestro día a día, sino que también añadiría más evidencia a un modelo general de procesamiento de magnitudes multi-simbólicas (Huber et al., 2016). Por otro lado, en este trabajo también se propuso estudiar cómo se lleva a cabo el acceso al valor monetario de los billetes, en concreto cuales son las dimensiones físicas de estos más relevantes para el acceso a su valor. A continuación se resumen cada una de estas dos líneas experimentales, tanto la introducción teórica como los experimentos realizados y sus resultados.

La representación de las magnitudes multi-simbólicas: ¿Son los precios diferentes?

A lo largo de nuestro día a día estamos constantemente realizando acciones en las debemos de procesar magnitudes, accediendo al valor de las mismas. Ya estemos hablando de representaciones de magnitudes no simbólicas, como podrían ser el número de elementos en un conjunto (por ejemplo, al contar el número los puntos de cada cara de un dado), o bien de magnitudes simbólicas, aquellas que son representadas a través símbolos para hacer referencia a una magnitud en concreto (como podrían ser los números arábigos que marcan la hora en nuestro reloj) (Gallistel & Gelman, 2005). Es por este motivo por el cual el entender cómo las personas accedemos al valor de las magnitudes, permitiéndonos esto realizar multitud de acciones que llevamos a cabo en nuestro día a día, es considerado un objeto de estudio relevante que debe de ser abordado desde una perspectiva cognitiva.

La mayoría de las investigaciones llevadas a cabo para estudiar cómo las personas representan las magnitudes simbólicas se han centrado en aquellas formadas por un solo componente, para ser más específicos, en el estudio de la representación y procesamiento de los números de un solo dígito. En estos estudios se ha llegado con unanimidad a la conclusión de que estas magnitudes simbólicas compuestas por un solo componente son representadas como unidades unitarias a lo largo de lo que se ha denominado línea mental numérica (e.g., Buckley & Gillman, 1974; Dehaene et al., 1990). De esta manera se explica por ejemplo el llamado efecto de distancia, el cual hace referencia al hecho de que las personas al comparar la magnitud de dos números tienen un mejor desempeño a mayor es la distancia numérica entre ambos (ej.: más rapidez en indicar que 9 > 2 que en indicar que 6 > 4). La explicación de este fenómeno viene por el hecho de que a menor distancia entre los dos números en dicha línea mental numérica, más solapamiento hay entre ambos, dificultándose así la comparación (e.g., Moyer & Landauer, 1967).

Mientras que hay un consenso amplio en lo relativo a las magnitudes simbólicas de un solo componente, no ocurre lo mismo con las magnitudes multi-simbólicas. Entendemos como magnitudes multi-simbólicas aquellas formadas por dos o más componentes, siendo el caso más sencillo y frecuente aquellos números formados por una decena y una unidad (p. ej., 92), aunque también entrarían dentro de esta categoría cualquier unidad de medida formada por uno o más dígitos más un símbolo indicativo de la unidad en sí (p. ej., 4 ms, 785 o 34 euros). En el caso de las magnitudes multi-simbólicas son varias las opciones que se plantean para explicar cómo pueden ser estas representadas y procesadas. Desde una perspectiva holística se asumiría que cuando comparamos el valor de dos números de dos dígitos (p. ej.: 67 vs. 83) se accedería al valor total de cada número de manera directa para compararlo con el otro posteriormente, no siendo analizados individualmente cada uno de los componentes que forman el número en si (decena y unidad) (Dehaene et al., 1990; Hinrichs et al.,1981). De manera contraria, desde una perspectiva composicional se plantearía que se accedería de manera independiente al valor de cada digito que forma el número, en este caso a la decena (6 vs. 8) y a la unidad (6 vs. 8), accediendo de esta manera al total del número y realizando así la comparación (Nuerk et al., 2001, 2004). Por último, la perspectiva híbrida sería una combinación de los dos anteriores, en la cual se asumirían que ambos tipos de procesamiento se llevarían a cabo (ver Nuerk et al., 2011, para una revisión).

La idea de un procesamiento puramente holístico ha sido mayormente descartada gracias a un amplio número de estudios en los cuales se ha encontrado evidencia a favor de la existencia de un procesamiento composicional (Huber, Bahnmueller, et al., 2015; Huber, Cornelsen, et al., 2015; Macizo, 2017; Macizo et al., 2010; Macizo et al., 2011a; Macizo & Herrera, 2008, 2010, 2011a, 2011b; Macizo & Herrera, 2013a; Moeller et al., 2013; Nuerk et al., 2001). Dicha evidencia viene principalmente del llamado efecto de compatibilidad (Nuerk et al. 2001). Este efecto hace referencia a la situación de conflicto que se genera a hora de comparar por ejemplo un par de números de dos dígitos, observándose como las personas son más lentas en los ensayos denominados incompatibles (p. ej.: 83 vs. 67; 8 > 6 pero 3 < 7) que en aquellos denominados compatibles (p. ej.: 87 vs. 63; 8 > 6 y 7 > 3). Esto se interpretaría como una evidencia de un procesamiento por separado de la decena y la unidad, ya que este resultado no podría explicarse si por el contrario se hiciera únicamente accediendo de manera directa al valor total de número. Este efecto de compatibilidad no solo ha sido observado con números de dos dígitos, sino también en números de más dígitos (Korvorst & Damian, 2008), y en otras magnitudes multi-simbólicas formadas por unidades de medidas (Huber, Bahnmueller, et al., 2015).

Además, también se han observado correlatos de dicho efecto a nivel neural, tanto a través de estudios con medidas electrofisiológicas como los Potenciales Relacionados con el Evento (ERPs, por sus siglas en inglés Event-Related Potentials) (Szűcs & Soltész, 2010) como con resonancia magnética funcional (Wood, Nuerk, & Willmes, 2006) . Por lo tanto, el conjunto de todos esto resultados apuntaría a un modelo general del procesamiento de magnitudes multi-simbólicas donde se asumiría un procesamiento composicional (Huber et al., 2016).

Como hemos mencionado anteriormente, aunque la mayoría de los estudios se han llevado a cabo con números de dos dígitos, la idea del procesamiento composicional se asumiría a priori para todo tipo de magnitudes multi-simbólicas (Huber et al., 2016). Sin embargo, el primer estudio llevado a cabo con precios (magnitudes multi-simbólicas formadas por uno o varios números y una unidad monetaria) sugirió que estos eran procesados holísticamente y no de manera composicional (Cao et al, 2012). Esto resultados nos llevaron a explorar el procesamiento de los precios y estudiar si estos son procesados de una manera composicional, holística o híbrida. Con este objetivo llevamos a cabo cuatro estudios ubicados cada uno de ellos en un capítulo distinto de la sección experimental de la tesis, en las que nos propusimos examinar el efecto de compatibilidad en tareas de comparación de precios. En estos estudios, se diseñaron tareas de comparación entre precios de un dígito (Capítulos V y VI) y entre precios de dos dígitos (Capítulos VII y VIII), donde se evaluó el efecto de compatibilidad a través de medidas conductuales (Capítulos V al VIII) y electrofisiológicas (Capítulo VI y VIII).

En Capitulo V nos propusimos estudiar el procesamiento de los precios de un digito a través de diferentes tareas de comparación de precios. En el primer experimento se pretendió replicar los resultados de Cao et al. (2012), y ampliar lo observado a la moneda Euro, observando así la influencia de la distancia entre dígitos y la distancia holística durante la realización de la tarea de comparación de precios. En el segundo experimento de esta primera línea observamos por primera vez un efecto de compatibilidad entre el número y la moneda en tareas de comparación de precios, utilizando tanto una presentación simultanea (experimento 2a) como secuencial (experimento 2b), pudiendo así comparar nuestros resultados tanto con las investigaciones previas del procesamiento de precios (uso de presentación secuencial) como con la mayoría de investigaciones donde se había explorado previamente el efecto de compatibilidad (mayoría de uso de presentación simultanea). El encontrar el efecto de compatibilidad indicaba que se estaba realizando un procesamiento composicional de los precios, rechazando a priori así la idea de que estos fueran diferentes a otras representaciones multi-simbólicas. Por último, en el tercer experimento de este capítulo exploramos factores contextuales que pudieran modular el efecto de compatibilidad en la tarea de comparación de precios de un digito. El observar cómo estos efectos modulaban el efecto de compatibilidad de la misma manera que se había encontrado previamente en tareas de comparación de números de dos dígitos reforzaba la idea del procesamiento composicional de los precios, señalando de nuevo que el procesamiento de estos no difería de el de otras magnitudes multi-simbólicas.

En el Capítulo VI el objetivo fue estudiar el procesamiento de precios de un digito a través de una tarea de comparación de precios, pero registrando no solo medidas conductuales si no también la actividad electrofisiológica de los participantes durante la tarea. En este experimento se replicaron a nivel conductual los resultados previos relativos al efecto de compatibilidad, pero observando además un correlato de dicho efecto a nivel electrofisiológico. En concreto se observó como el efecto de compatibilidad modulaba el componente N400-like localizado en la zona fronto-central y en la ventana temporal de 350-450 ms, con una amplitud negativa mayor en los ensayos incompatibles en comparación con los ensayos compatibles. Esta diferencia se interpretaría como un correlato electrofisiológico de la resolución de conflicto dada en la tarea, reforzándose así la perspectiva del procesamiento composicional de los precios.

El siguiente paso que llevamos a cabo en el Capítulo VII fue estudiar el procesamiento de precios formados por dos dígitos, con el objetivo de explorar si esta representación de magnitud multi-simbólicas más compleja era procesada de una manera totalmente composicional (cada componente procesado por separado), de una manera holística (toda la magnitud procesada como un todo) o de manera híbrida (una combinación de los dos procesamientos anteriores). Además, también estudiamos cómo el formato de presentación en el que se presentaban los precios podría modular el tipo de procesamiento que se llevara a cabo. Para ello, diseñamos tres tareas de comparación de precios de dos dígitos variando cada una de ellas en el formato de presentación (números arábigos, números escritos y números presentados auditivamente). Se exploraron dos efectos de compatibilidad simultáneamente, el efecto de compatibilidad Número-Moneda (CNM) al igual que con los precios de un solo digito, y el efecto clásico de compatibilidad Decena-Unidad (CDU). Las predicciones en este sentido eran simples: si ambos efectos de compatibilidad eran observados, se vería reforzada la perspectiva totalmente composicional del procesamiento de los precios, ya que se estaría reflejando como cada uno de los componentes es procesado de manera independiente; en el caso de solo encontrar uno de los dos efectos de compatibilidad se reforzaría la perspectiva híbrida, ya que ambos tipos de procesamiento estarían teniendo lugar; por último si no se observara ninguno de los efectos de compatibilidad se vería reforzada la perspectiva holística, sugiriendo que el conjunto del precio se habría procesado como un todo. En cuanto a las hipótesis de la manipulación de formato, siguiendo la línea de lo observado en estudios previos de dos dígitos (Macizo & Herrera, 2008; Macizo et al., 2010, 2011a; Nuerk et al., 2005), se esperaba confirmar que el efecto CDU fuera observado cuando los precios se presentaran con números arábigos, pero no cuando estos se presentaran de cualquiera de las dos maneras verbales. Por otro lado, el efecto CNM no había sido explorado previamente a través de diferentes formatos de presentación, pero se esperaba que el hecho de que la disposición de la lengua española favorezca el procesamiento del primer componente de las magnitudes (en este caso el número) se observara un mayor efecto de compatibilidad en la tarea que usaba un formato de presentación oral de los precios, en comparación con aquellos que utilizaran números arábigos. Se observó un efecto de compatibilidad CNM en todos los formatos de presentación, extendiéndose así a los precios formados por dos dígitos lo observado previamente en números de un digito (Macizo & Ojedo, 2018; Ojedo & Macizo, 2020), e indicando que el procesamiento composicional es independiente de la manera de descodificar y representación de la magnitud en cuestión, tal y como sería explicado por un modelo general de procesamiento de magnitudes multi-simbólicas (Huber et al., 2016). Sin embargo, el efecto CDU no fue observado en ninguna de los tres formatos de presentación explorados. El conjunto de los resultado podrían interpretarse a favor de la perspectiva híbrida, ya que se habría observado tanto un procesamiento composicional (en el análisis del número y de la unidad monetaria, los cuales habrían sido procesado por separado) y un procesamiento holístico (en el análisis de la decena y la unidad, las cuales habrían sido procesados como un todo de manera unitaria).

Por último, en el estudio mostrado en el Capítulo VIII evaluamos el procesamiento de precios de dos dígitos a través de medidas conductuales y electrofisiológicas. El objetivo de este estudio fue examinar de nuevo los efectos CNM y CDU, usando medidas electrofisiológicas que nos permitieran comprender mejor los resultados conductuales previamente observados. A nivel conductual se replicaron los resultados del anterior estudio, encontrando solo un efecto de compatibilidad NM, pero no un efecto de compatibilidad DU. Sin embargo, los datos electrofisiológicos mostraron una interacción entre los efectos de compatibilidad NMC y DU en la ventana temporal de los 350-500 ms, en regiones anteriores (región frontal y fronto-central), consistente con el componente N400. Está componente ha sido interpretado como índice de procesamiento de conflicto (Ojedo & Macizo, 2020; Schwarz & Heinze, 1998; Szűcs & Soltész, 2007), por lo que nos podría estar indicando que las medidas electrofisiológicas, al ser más sensibles que las conductuales, si estarían siendo capaces de capturar el efecto de compatibilidad. Esta interacción entre ambos efectos de compatibilidad estaría apoyando una perspectiva totalmente composicional, ya que nos estaría indicando que los tres componentes de los precios (decena, unidad y unidad monetaria) habrían sido procesados individualmente por separado, y por lo tanto de manera composicional.

Para concluir, los resultados de la investigación del procesamiento de los precios a lo largo de los cuatro estudios realizados muestran que como el efecto de compatibilidad entre el número y la unidad monetaria ha sido observado tanto a través de medidas conductuales como electrofisiológicas, lo que indicaría que estos dos componentes estarían siendo procesados por separado. Por otro lado, el efecto de compatibilidad entre la decena y la unidad que forman parte de los precios de dos dígitos no fue observado a nivel conductual, sin embargo la interacción observada a nivel electrofisiológico entre ambos efectos indicaría que estos dos componentes también estarían siendo procesados por separado. El conjunto de estos estudios señalaría a un procesamiento totalmente composicional de los precios, contradiciendo aquellos estudios previos que los señalaban como un tipo de magnitud-multi-simbólicas diferente, y apoyando la idea del modelo general de procesamiento de magnitudes multi-simbólicas (Huber et al., 2016).

Procesando el valor de los billetes

Las personas realizamos en nuestro día a día multitud de conductas que conllevan tratar y procesar el dinero. Estas operaciones se llevan a cabo con dinero en todas sus diferentes formas, ya sea calcular el precio final de un descuento, seleccionar el importe exacto de monedas para pagar el billete de autobús, o contar el valor total del conjunto de billetes que llevamos en la cartera. A continuación nos vamos a centrar en el caso de estos últimos, los billetes. Entendemos por billetes aquellas piezas de papel de curso legal en un país o región que representan diferentes valores económicos, variando estos entre las diferentes monedas (euros, dólares, libras, etc.). Son varios los estudios que han examinado las características particularidades del procesamiento de los billetes, así como los sesgos asociados a ello (Di Muro & Noseworthy, 2013; Giuliani et al., 2018; Macizo & Herrera, 2013b; Macizo & Morales, 2015; Manippa et al., 2019; Mishra et al., 2006; Raghubir & Srivastava, 2009; Ruiz et al., 2017). Por ejemplo, se han realizado estudios previos donde se ha investigado el rol del tamaño físico de los billetes a la hora procesar su valor monetario (Ruiz et al., 2017). Sin embargo, hasta donde tenemos constancia, no hay estudios previos en los que se haya evaluado en conjunto la relevancia de diferentes magnitudes físicas en el acceso al valor de los billetes. Es por eso por lo que en el Capítulo IX no nos centramos en el estudio de los precios, sino en el estudio de cómo procesamos el valor de los billetes, en concreto en explorar las relevancia de tres dimensiones físicas (tamaño, color y diseño) a la hora de acceder al valor de los billetes. Estudiar esta cuestión nos ayudaría a entender mejor de qué manera las personas procesamos las dimensiones de los billetes, pudiéndonos ayudar esto en un futuro a implementar un diseño del dinero en metálico optimizado en cuanto a facilitar su procesamiento y uso.

Para ello desarrollamos un estudio donde diseñamos tres tareas tipo Stroop de comparación de billetes, donde en cada ensayo los participantes debían de indicar el billete con mayor valor monetario de un par presentado. El objetivo de este estudio fue evaluar en cada tarea el procesamiento de una dimensión física diferente: el tamaño, el color y el diseño. En cada una de las tareas se crearon tres condiciones diferentes. Una condición congruente donde ambos billetes eran presentados sin ninguna modificación, una condición incongruente donde se manipulaba la dimensión a estudiar dicha tarea de tal forma que se invirtiera el contenido de esa dimensión en particular (así por ejemplo, en la tarea de manipulación del tamaño, podrían aparecer un par de billetes a comparar donde uno fuera de 20 € pero con el tamaño de uno de 100€, y otro billete de 100 € con el tamaño de uno de 20 €), y por último una condición neutra en la cual se anulara la condición a explorar (por ejemplo, en la tarea de manipulación del tamaño se presentarían un billete de 20 € y otro de 100 € pero ambos con el mismo tamaño). A través de estas manipulaciones esperábamos observar cuál de las dimensiones exploradas facilitaba más una mejor realización de la tarea, comparando la condición congruente con la condición neutra (efecto de facilitación), así como observar cuando el desempeño de los participantes se ve más perjudicado al invertir la presentación de una dimensión, comparando la condición neutra con la condición incongruente (efecto de interferencia).

Aunque es necesaria más investigación, lo encontrado en este estudio apuntaría a que el tamaño es la dimensión que más nos ayuda a la hora de diferenciar entre distintos tipos de billetes, seguida por el color de los mismos. Estas dos dimensiones facilitaron la realización de la tarea de comparación de billetes, observándose un mejor desempeño en la condición en la que la información relativa a estas dimensiones estaba presente y era relevante para la ejecución de la tarea (condición congruente), en comparación con aquella condición donde no estaba presente dicha información (condición neutra). Por otro lado, se observó como el procesamiento de la información correspondiente al diseño de los billetes perjudicaba en vez de facilitar su procesamiento, observándose un mejor desempeño en la condición donde la información correspondiente a esta dimensión no estaba presente (condición neutra) en comparación con aquellos billetes que se presentaban tal y como eran en la vida real (condición congruente).

Como conclusión, los resultados de este estudio nos podrían ayudar a entender cómo las personas accedemos al valor de los billetes y tener una futura implicación práctica, pudiendo ayudar a un diseño de los billetes que favorezca un procesamiento más eficiente de los mismos.

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Appendix

Appendix 1. Additional information about the data trimming processing

The percentage of outliers excluded in each iteration was as follows: Iteration 1 = 0.21%, iteration 2 = 2.04%, iteration 3 = 2.74%, iteration 4 = 2.25%, iteration 5 = 1.47%, iteration 6 = 1.09%, iteration 7 = 0.65%, iteration 8 = 0.28%, iteration 9 = 0.16%, iteration 10 = 0.05%. Following the recommendations of an anonymous reviewer, the compatibility effect was examined across iterations. The compatibility effect was not significant after iteration 1, $F(1, 25) = 2.29$, $p = .14$, $\eta^2 = .08$, and iteration 2, $F(1, 25) = 0.62$, $p = .44$, $\eta^2 = .02$. However, the compatibility effect was marginal after the iteration 3, $F(1, 25) = 3.51$, $p = .07$, $\eta^2 = .12$, and it was significant after the iteration 4, $F(1, 25) = 5.86$, $p = .02$, $\eta^2 = .19$, the iteration 5, $F(1, 25) = 9.80$, $p = .004$, $\eta^2 = .28$, the iteration 6, $F(1, 25) = 6.68$, $p = .02$, $\eta^2 = .21$, the iteration 7, $F(1, 25) = 7.04$, $p = .01$, $\eta^2 = .22$, the iteration 8, $F(1, 25) = 6.24$, $p = .02$, $\eta^2 = .20$, the iteration 9, $F(1, 25) = 6.39$, $p = .02$, $\eta^2 = .20$, and the iteration 10, $F(1, 25) = 6.75$, $p = .01$, $\eta^2 = .21$. Thus, the pattern of behavioral data remained even with fewer iterations in the filtering process (4 iterations). In addition, we examined whether the trimming procedure critically affected any type of items evaluated in the study. The percentage of compatible and incompatible trials that entered the analysis after the trimming process was similar (50.10% and 49.90%, respectively). Therefore, the filtering process affected equally the two experimental conditions of the study (compatible condition and incompatible condition).

In addition to the analyses reported in the text, a new set of analyses were performed by applying the filtering process to the data of each experimental condition separately. Thus, the data for each experimental condition were standardized using the mean and *SD* of each condition. Afterwards, data points that were found 3 *SD* outside the normal distribution in each condition were excluded from analyses. The number of outliers was similar in the analysis reported in text and this new analyses (only eight fewer outliers were eliminated with this new trimming procedure by conditions compared to the analyses reported in the main text). The results obtained in the new analyses revealed that the compatibility effect was again significant, $F(1,25) = 7.90$, $p < .01$, $\eta^2 = .24$. Participants were faster in compatible trials (M = 824 ms, SE = 21) than in incompatible trials (M = 843 ms, SE = 23). This new filtering procedure as well as the new analyses are fully available at https://osf.io/rx8u5/?view_only=48470ebc44bd47e191a6c92b5a831d87.

Appendix 2. Additional information about the False discovery rate (FDR)

False discovery rate (FDR) corrections were computed (Benjamini & Hochberg, 1995) to control for false positive results when multiple tests were conducted in the time-widows where the compatibility effect interacted with other variables (Compatibility x Lateral-medial axis interaction in the 100-150 ms time-window, and Compatibility x Anterior-posterior axis interaction in the 250-350 ms and 350-450 ms time-windows). Following the Benjamini-Hochberg procedure, the *p* values associated with each comparison were ranked from lowest to highest where the smallest *p* value had a rank of $i = 1$ and the largest a value of $i = 11$ (3 comparisons when the Compatibility x Lateral-medial axis interaction was considered in the 100-150 time-window, 4 comparisons when the Compatibility x Anterior-posterior axis interaction was considered in the 350-450 time-window, and 4 comparisons when the Compatibility x Anterior-posterior axis interaction was considered in the 350-450 time-window). Afterwards, the Benjamini-Hochberg critical value, $(i/m)Q$, was computed, where *i* was the rank, *m* the total number of comparisons, and *Q* the false discovery rate. The *Q* value was set at .15 following McDonald's recommendations (2014, p. 260, *Q* value between .10 and .20). According to the Benjamini-Hochberg procedure, the largest *p* value that has $p < (i/m)Q$ is significant, and all of the *p* values smaller than it are also significant. In the 100-150 time-window, the compatibility effect was significant on the right hemisphere, $p = .048 < (i/m)Q = .068$, and also on the left hemisphere, $p = .028 < (i/m)Q = .027$, but not on the midline region, $p = .356 > (i/m)Q = .150$. In the 250-350 ms time-window, the compatibility effect was significant on the frontal region, p = .045 < $(i/m)Q$ = .055, but not on the fronto-central region, p = .114 > $(i/m)Q$ = .095, the parietal region, p = .209 > $(i/m)Q$ = .123, or the occipito-parietal region, p = .112 > $(i/m)Q$ = .082. Finally, in the 350-450 ms time-window, the compatibility effect was significant on the frontal region, p = .029 < $(i/m)Q$ = .041, and the fronto-central region, p = .012 < $(i/m)Q$ = .014, but not on the parietal region, p = .252 > $(i/m)Q$ = .136, or the occipito-parietal region, p = .126 > $(i/m)Q$ = .109. Thus, after FDR corrections, the compatibility effect was significant in the same regions as those reported in the main text.

In order to verify that the differences found in the compatibility effect are independent of the high percentage of outliers found, an additional analysis was carried out using a different trimming procedure. Following the procedure recommended in Tabachnick and Fidell (2001), In this new latency analyses, the compatibility effect was significant, $F(1,25) = 7.90$, $p < .01$, $\eta^2 = .24$. Participants were faster in compatible trials (M = 824 ms, SE = 21) than in incompatible trials (M = 843 ms, SE = 23).

This new filtering procedure as well as the new analyses are fully available at https://osf.io/rx8u5/?view_only=48470ebc44bd47e191a6c92b5a831d87

Appendix 3. ERP Analysis of the Magnitude of Prices

Following the suggestion of a reviewer of the previous version of our work, we attempted to explore the processing of the magnitude of prices regardless of the compatibility between the digits and the monetary category. Specifically, we planned to explore the holistic magnitude attending to the absolute distance in cents between each price pair, and the magnitude of the digits on the basis of the distance between the digits of each price pair. We performed a median split to establish the two levels of absolute distance, so that the trials were classified as far distance trials or close distance trials depending on whether the difference between the monetary values of the two prices was higher or lower than the median. Unfortunately, as this analysis was not planned a priori, the effect of the absolute distance between prices could not be analyzed since there were not an equal number of compatible and incompatible trials in the close and far absolute distance conditions. However, we focus on the effect of the digit distance, a crucial effect in evaluating whether prices are processed in a componential manner. To this end, we considered trials with far digit distance (trials whose distance between the digits was 4 and 5) and trials with close digit distance (trials whose distance between the digits was 1 and 2). The number of compatible and incompatible trials was equated in the far and close digit distance trials.

As in the previous analyses reported in the manuscript, statistical analyses were performed on the mean amplitude in two temporal windows, which were time-locked to the onset of the second price. The time-windows were selected according to previous research of Cao et al. (2012): the 180-250 ms time-window, and the 250-450 ms. As the distance effects are usually located in parietal regions (e.g., Temple & Posner, 1998), analyses were performed with electrodes located in this region. Thus, ANOVAs for the ERPs analyses were conducted with Distance (two levels: close, far), Laterality (two levels: left, right) and Electrode (four levels: P3/P4, P5/P6, P7/P8 and PO7/PO8) as within-participant factors. The Greenhouse-Geisser correction (Greenhouse & Geisser, 1959) for nonsphericity of variance was used for all *F*-ratios with more than one degree of freedom in the denominator; reported here are the original *df*, the corrected probability level, and the ε correction factor. One participant was removed from the analyses because the average number of observations in the far distance condition did not have a sufficient number of trials after data pre-processing.

180-250 ms time-window. The ANOVA conducted in this time-window revealed a significant main effect of Distance, $F(1, 24) = 4.42$, $p = .046$, $\eta_p^2 = .15$. Mean amplitudes in the close and far digit distance conditions were M = -0,674 µV, and M = -0,889 µV, respectively. The other two main effects were also significant; Laterality, $F(1, 24) = 11.50$, $p = .002$, $\eta_p^2 = .32$, and Electrode, $F(3, 72) = 16.60$, $p < .001$, $\varepsilon = .80$, $\eta_p^2 = .41$. The interaction between Laterality and Electrode was significant, $F(3, 72) = 4.20$, $p = .011$, $\varepsilon = .90$, $\eta_p^2 = .1$. Other interactions were not significant (*p*s > .05) (see Figure 12).

250-450 ms time-window. The ANOVA conducted in this time-window did not reveal a significant main effect of Distance, $F(1, 24) = 0.13$, $p = .720$, $\eta_p^2 = .01$.

The main effect of Laterality was not significant, $F(1, 24) = 0.10$, $p = .749$, $\eta_p^2 = .01$. The main effect of Electrode was significant, $F(3, 72) = 7.77$, $p < .001$, $\varepsilon = .76$, $\eta_p^2 = .24$. The Distance x Laterality interaction was significant, $F(1, 24) = 5.29$, $p = .030$, $\eta_p^2 = .18$. However, the distance effect was not significant in either the left hemisphere, $F(4, 21) = 0.55$, $p = .697$, $\eta_p^2 = .09$, or right hemisphere, $F(4, 21) = 2.09$, $p = .118$, $\eta_p^2 = .28$. The interaction between other factors was not significant.

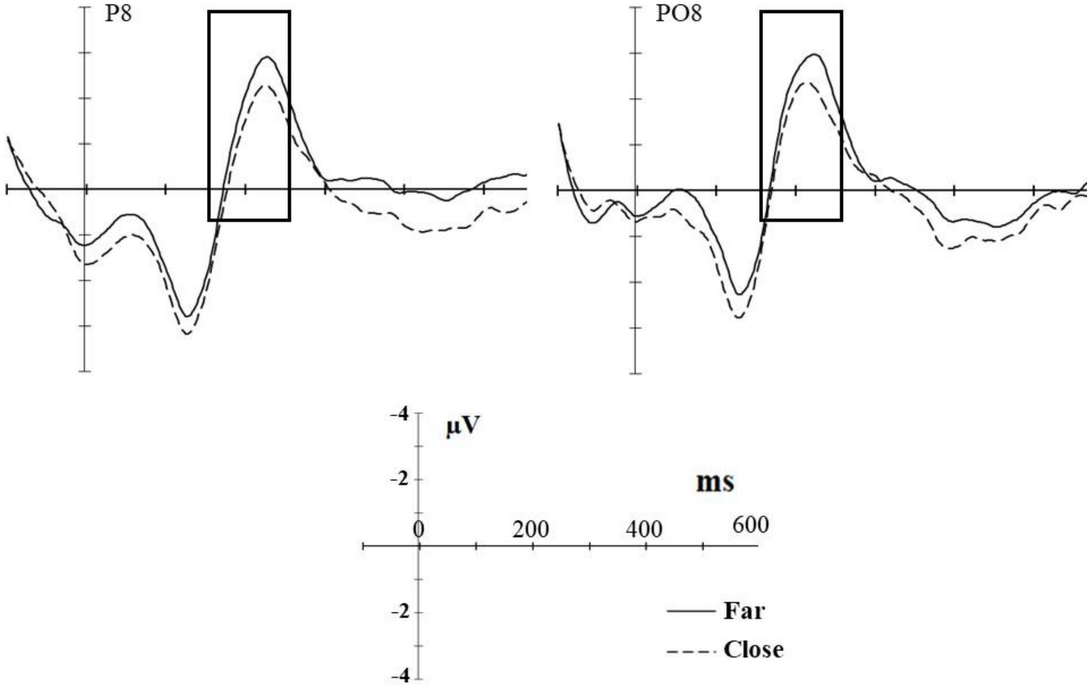

Figure 12. Digit distance effect obtained on two representative electrodes. Boxes show the time window in which the digit distance effect was significant (180-250 time window).

In this analysis, an effect of the digit distance was found in the 180-250 time window; the average amplitude of the brain wave was modulated by the distance of the digits (close, far). The early ERP modulations found in our study depending on the digit distance of the prices is consistent with previous electrophysiological studies on the processing of numerical magnitude (Dehaene, 1996; Libertus et al., 2007; Pinel et al., 2001; Temple & Posner, 1998). Consequently, the results suggest that participants processed the magnitude of the digits that constituted the prices. This pattern of results is consistent with a compositional processing of prices according to which, the constituents of a multi-symbol number are processed separately and in a componential manner.

Appendix 4. Grand Average. ERPs Obtained in the Study

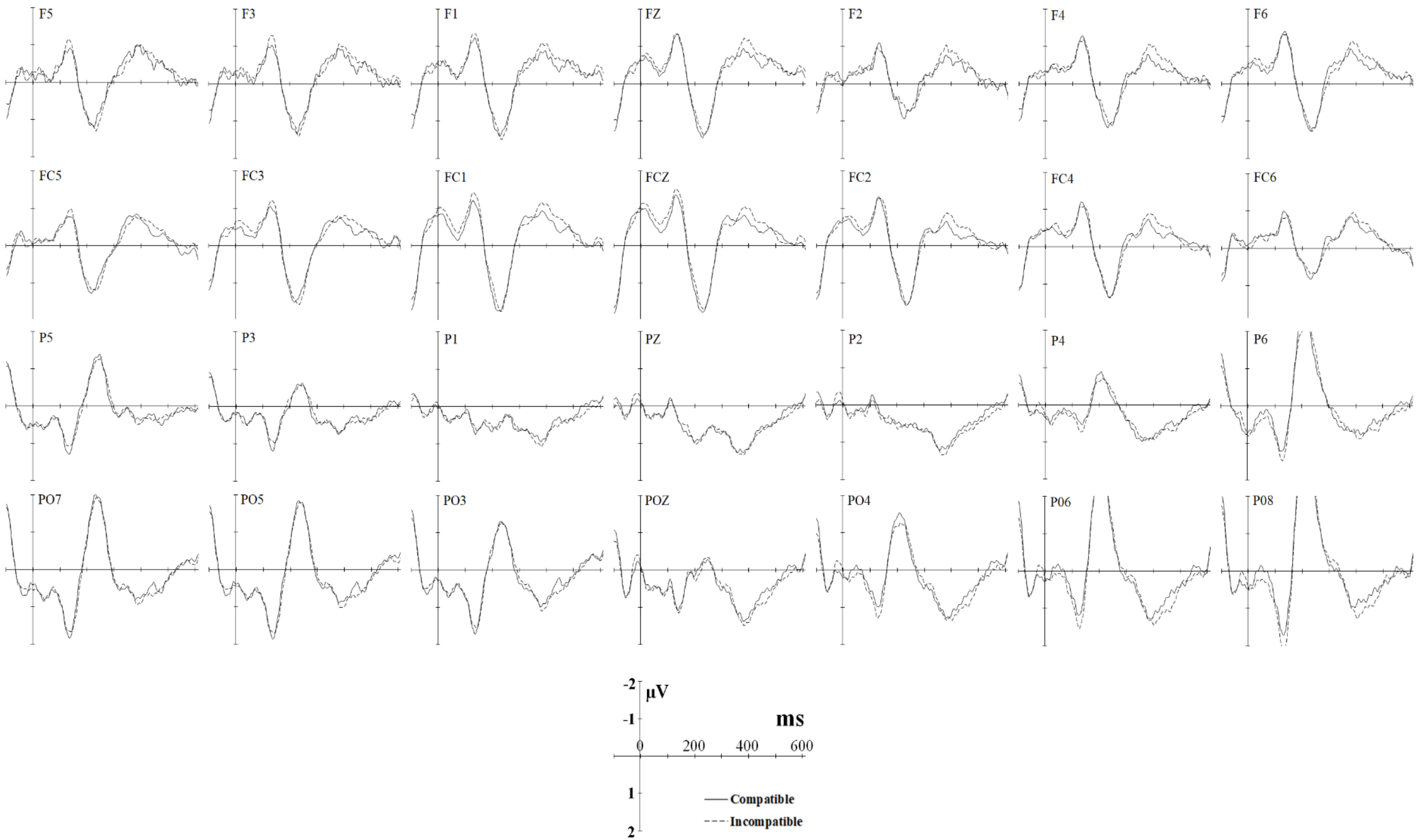

Figure 13. Grand Average ERPs

Appendix 5. Reverse compatibility effect found when numbers are coded in verbal format

In most experiments, the overall distance between the two numbers in compatible and incompatible trials is typically matched. To compute the overall distance, the unit distance has to be added to the decade distance in compatible trials while the unit distance has to be subtracted from the decade distance in incompatible trials, and thus, the decade distance always has to be larger for incompatible vs. compatible trials. To illustrate, consider the compatible trial number pair 53 – 68 and the incompatible trial number pair 59 – 74. In the example, the overall distance of 15 in the compatible trial 53 – 68 results from 10 x the decade distance (6 – 5 = 1) plus the unit distance (8 – 3 = 5), (10 x 1) + (5) = 15. The overall distance of 15 in the incompatible trial 59 – 74 results from 10 x the decade distance (7 – 5 = 2) minus the unit distance (9 – 4 = 5), (10 x 2) – (5) = 15. Therefore, the decade distance has to be larger for incompatible vs. compatible trials to be able to subtract the unit distance. Moreover, because of this subtraction, the difference in decade distance between compatible and incompatible trials must be greater with large unit distances. Therefore, by virtue of these computational constraints, if participants only focus on the decade, they should be faster to make decisions on incompatible than compatible trials, an outcome that would be consistent with the distance effect (Moyer & Landauer, 1967). Please note that this explanatory note has been cited in other studies conducted in our research group evaluating the unit-decade compatibility effect with verbal numbers (e.g., Macizo et al., 2011).

Appendix 6. The Processing of Prices across Numerical Formats (Additional Analyses)

The three-way interaction was not significant in either the latency analyses or the accuracy analyses. Therefore, it is not statistically justified to decompose this interaction. However, in order to have a complete profile of the pattern of results, further analyses were conducted. For each numerical format, three separate analysis of variance (ANOVA) were conducted with NMC Compatibility (two levels: NMC compatible trials, NMC incompatible trials) and UD Compatibility (two levels: UD compatible trials, UD incompatible trials) as within-participant factors (see Table 11).

Arabic digits

In the latency analyses, the NMC compatibility effect was significant, $F(1, 28) = 37.35$, $p < .001$, $\eta^2 = .57$. Participants were faster in NMC compatible trials (M = 667 ms, SE = 34) than in NMC incompatible trials (M = 699 ms, SE = 35). However, the UD compatibility was not significant, $F(1, 28) = 0.20$, $p = .66$, $\eta^2 = .01$. The mean RTs in the UD compatible condition was M = 684 (SE = 34), and it was M = 682 (SE = 35) in the UD incompatible condition. The interaction between the two compatibility effects was not significant, $F(1, 28) = 0.02$, $p = .90$, $\eta^2 = .01$. Similarly, in the accuracy analysis, the NMC compatibility effect was significant, $F(1, 28) = 25.41$, $p < .001$, $\eta^2 = .48$. Participants committed fewer errors in NMC compatible trials (M = 3.13%, SE = 0.59) than in NMC incompatible trials (M = 6.25%, SE = 0.76). UD compatibility was not significant, $F(1, 28) = 0.59$, $p = .45$, $\eta^2 = .02$. There were no differences between the UD compatible (M = 4.60%, SE = 0.65) and the UD incompatible condition (M = 4.78%, SE = 0.58). The interaction between the two compatibility effects was not significant either, $F(1, 28) = 1.71$, $p = .20$, $\eta^2 = .06$.

Written numbers

Latency analyses showed a near-significant NMC compatibility effect, $F(1, 27) = 3.49$, $p = .07$, $\eta^2 = .11$. There was a trend towards faster responses in NMC compatible trials ($M = 774$ ms, $SE = 41$) than in NMC incompatible trials ($M = 787$ ms, $SE = 43$). The UD compatibility was not significant, $F(1,27) = 1.73$, $p = .20$, $\eta^2 = .06$. The mean RTs in the UD compatible condition was $M = 777$ ($SE = 42$), and it was $M = 783$ ($SE = 42$) in the UD incompatible condition. The interaction between the two compatibilities was not significant, $F(1, 27) = 1.26$, $p = .27$, $\eta^2 = .04$. In the accuracy analyses, the NMC compatibility effect was significant, $F(1, 27) = 10.57$, $p < .001$, $\eta^2 = .28$. Participants committed fewer errors in NMC compatible trials ($M = 3.48\%$, $SE = 0.69$) than in NMC incompatible trials ($M = 5.07\%$, $SE = 0.88$). The UD compatibility was not found significant, $F(1, 27) = 1.69$, $p = .20$, $\eta^2 = .06$. There were no differences between the UD compatible ($M = 4.49\%$, $SE = 0.78$) and the UD incompatible condition ($M = 4.06\%$, $SE = 0.76$). The interaction between the two compatibilities was not significant, $F(1, 27) = 1.68$, $p = .20$, $\eta^2 = .06$.

Auditory numbers

In the latency analyses, the NMC compatibility effect was significant, $F(1, 26) = 27.50$, $p < .001$, $\eta^2 = .51$. Participants were faster in NMC compatible trials ($M = 1574$ ms, $SE = 68$) than in NMC incompatible trials ($M = 1755$ ms, $SE = 39$). The UD compatibility was not significant, $F(1, 26) = 1.30$, $p = .26$, $\eta^2 = .04$. The mean RTs in the UD compatible condition was $M = 1669$ ($SE = 53$), and it was $M = 1660$ ($SE = 53$) in the UD incompatible condition. The interaction between the two compatibility effects was not significant, $F(1, 26) = 1.07$, $p = .31$, $\eta^2 = .04$. In the accuracy analysis, the NMC compatibility effect was significant, $F(1, 26) = 15.89$, $p < .001$, $\eta^2 = .38$.

Participants committed fewer errors in NMC compatible trials (*M* = 3.94%, *SE* = 1.03) than in NMC incompatible trials (*M* = 5.46%, *SE* = 1.12). The UD compatibility was not significant, $F(1, 26) = 1.14$, $p = .29$, $\eta^2 = .04$. There were no differences between the UD compatible (*M* = 4.52%, *SE* = 1.03) and the UD incompatible condition (*M* = 4.88%, *SE* = 1.09). The interaction between the two compatibility effects was not significant, $F(1, 26) = 0.05$, $p = .83$, $\eta^2 = .01$.

Appendix 7. Grand average ERPs for compatible and incompatible UD in compatible and incompatible NMC

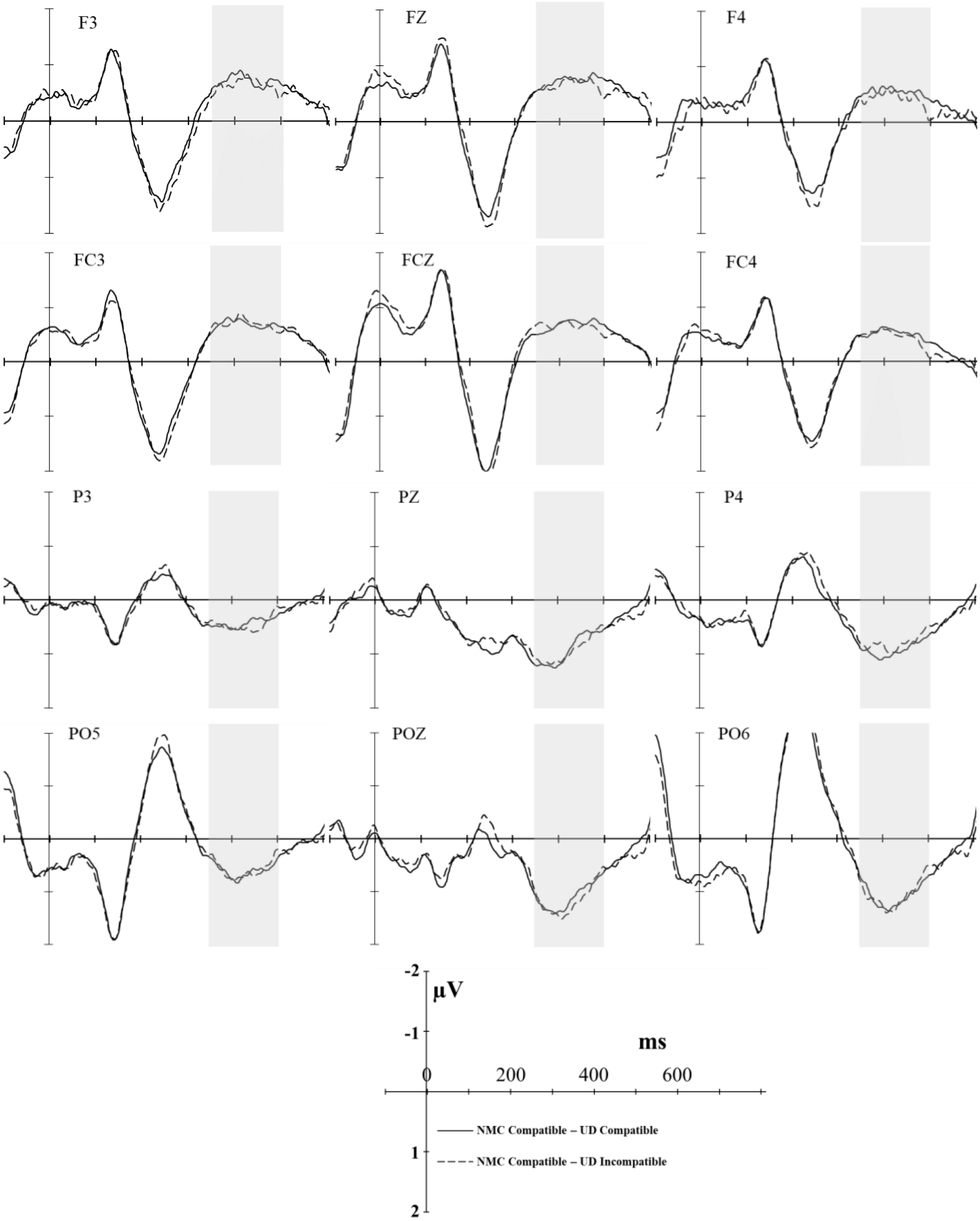

Figure 14. Grand average ERPs for compatible and incompatible UD in compatible NMC trials. Grey boxes indicates the 350–500 ms time window.

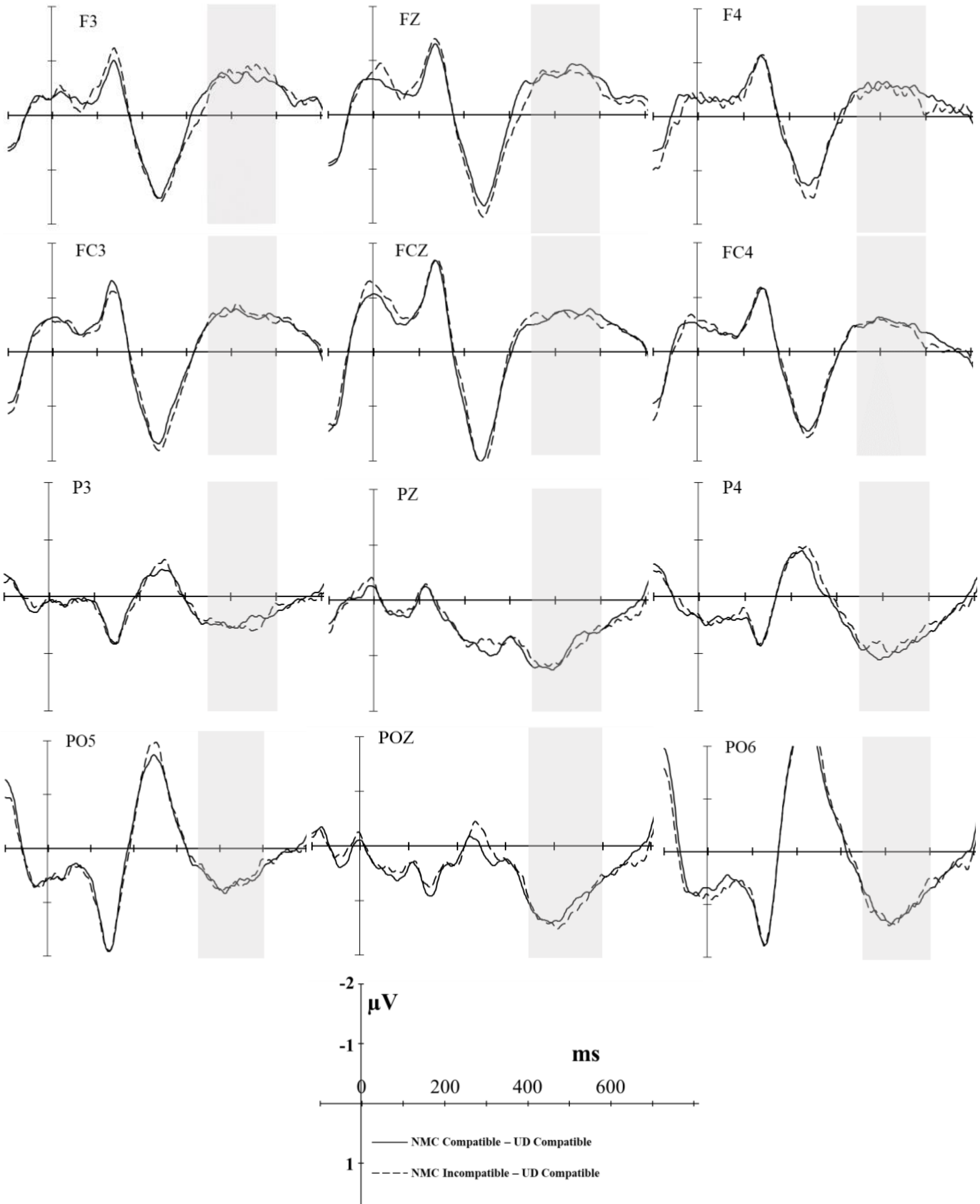

Figure 15. Grand average ERPs for compatible and incompatible UD in incompatible NMC trials. Grey boxes indicates the 350–500 ms time window.