Universidad de Granada

Programa Oficial de Doctorado en Psicología

LA REPRESENTACIÓN COMÚN DE LA MAGNITUD Y SUS BASES CEREBRALES

(THE COMMON CODING OF MAGNITUDE AND ITS BRAIN BASES)

José Isidro Martínez Cascales

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Universidad de Granada

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Jose Isidro Martínez Cascales

De todas las personas que he conocido,
hay una que ha tenido conmigo más
paciencia de la que pensaba fuera posible.
Este trabajo está dedicado a una tal
María Cascales, mi madre.

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Porciones del texto de la presente tesis han sido ya publicadas en el artículo aquí citado. Todos los autores han dado su consentimiento por escrito para utilizar esos contenidos en esta tesis.

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Resumen

La cuestión de cómo la mente y el cerebro son capaces de comprender y procesar conceptos abstractos ha capturado la atención de muchos programas de investigación en ciencia cognitiva. Durante muchos años hemos intentado explicar cómo el cerebro puede ir más allá del mundo físico y trabajar aparentemente sin gran esfuerzo con conceptos que los sentidos no son capaces de captar. Diferentes teorías han sido propuestas para explicar el procesamiento abstracto. Probablemente la más exitosa durante la segunda mitad del siglo XX fue la teoría clásica del procesamiento de la información, hasta que la evidencia de que la información perceptiva y motora está profundamente ligada a los procesos cognitivos comenzó a acumularse. Se propusieron teorías capaces de dar cuenta de estos hallazgos, siendo dos de las más importantes la Teoría de Metáforas Conceptuales (Lakoff & Johnson, 1980) y la hipótesis de la codificación común (o "common coding"), representada por ejemplo por A Theory of Magnitude (ATOM; Walsh, 2003).

En esta tesis nos propusimos poner a prueba importantes predicciones de la hipótesis de la codificación común, en concreto que el procesamiento de diferentes magnitudes debería estar estrechamente asociado. Utilizamos tareas de bisección, que consisten en la presentación de un intervalo definido por dos valores extremos, sobre el que los participantes tienen que estimar o juzgar el punto medio. Según la hipótesis de la codificación común, la bisección de diferentes magnitudes debería covariar para cada participante. Utilizamos estas tareas aplicadas tanto a dimensiones concretas como abstractas, y comparamos la ejecución de los participantes entre tareas.

Llevamos a cabo una serie de tres experimentos que incluyeron bisecciones espaciales, temporales y también numéricas, con la población general y también con pacientes psiquiátricos y neuropsicológicos. En particular utilizamos pacientes esquizofrénicos y con neglect, dos poblaciones que han sido caracterizadas por diferir de la población general en su ejecución en tareas de bisección de diferentes magnitudes. Encontramos sólo evidencia parcial a favor de la hipótesis de la codificación común, lo que sugiere que esta teoría podría probablemente beneficiarse de una elaboración más detallada.

Referencias:

Lakoff, G., & Johnson, M. (1980). *Metaphors We Live By*. Chicago; London: University of Chicago Press.

Walsh, V. (2003). A theory of magnitude: Common cortical metrics of time, space and quantity. *Trends in Cognitive Sciences, 7*(11), 483–488. http://doi.org/10.1016/j.tics.2003.09.002

Abstract

The question of how the mind/brain can understand and process abstract concepts has captured the attention of many research programmes in cognitive science. For many years we have attempted to explain how the brain can go beyond the physical world and work quite effortlessly with concepts that the senses cannot perceive. Different theories have been offered to explain abstract processing. Probably the most successful on the second half of the XX century was the classical information processing view, until evidence that perceptual and motor information is deeply involved in high level cognition started to accumulate. Theories that could account for these findings were proposed, being two of the most influential ones the Conceptual Metaphor Theory (Lakoff & Johnson, 1980) and the common coding hypothesis, represented for example by A Theory of Magnitude (ATOM; Walsh, 2003).

In this thesis we aimed to test crucial predictions of the common coding hypothesis, namely that the processing of different magnitudes should be closely associated. We used bisection tasks, which consist on the presentation of an interval defined by two edges (or anchors), and participants have to either estimate or judge the middle point. According to the common coding view, performance in the bisection of different magnitudes should covary within participants. We used these tasks with both concrete and abstract dimensions, and compared participants' performance between tasks.

We carried out a set of three experiments that included spatial, temporal and also numerical bisection, with the general population as well as psychiatric and neuropsychological patients. In particular, schizophrenic and neglect patients, populations that have been described to differ from the general population in performance of the bisection of different magnitudes. We found only partial evidence in favour of the common coding hypothesis, suggesting that the theory would probably benefit from a more detailed elaboration.

References:

Lakoff, G., & Johnson, M. (1980). *Metaphors We Live By*. Chicago; London: University of Chicago Press.

Walsh, V. (2003). A theory of magnitude: Common cortical metrics of time, space and quantity. *Trends in Cognitive Sciences, 7*(11), 483–488. http://doi.org/10.1016/j.tics.2003.09.002

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I. Introduction

Over the centuries we have tried to figure out how we are made on the inside and how the different parts work together. At the mental level philosophers and later on scientists have explored a wide variety of topics such as where ideas come from, how are memories stored, whether concepts are universal, and a long etcetera. Most of these questions are being debated still today and, despite centuries of discussion and the remarkable observations provided by modern science, in many of them we don't seem to be close to a consensus. The aim of this thesis is to make a contribution regarding the differences and similarities between concrete and abstract concepts in the mind and brain. Specifically, we studied the mental processes and brain basis underlying the representation of magnitudes that we can see, such as space, and abstract magnitudes like time and numerical value.

Let's begin this introduction with a statement on which we can hopefully agree: our senses (sight, hearing, taste...) give us the ability to gather information from the environment. Just like many other animal species, we use that information to find what we need (food, protection, opportunities), to detect and avoid dangers, etc. But our abilities reach far beyond this; we can also think about things that we cannot see, hear or touch such as *time*, *hope* or *intelligence*.

It would be difficult to imagine our lives without thinking about next week or next year, without moral values or even without the arbitrary rules of beauty that fashion provides. We are much less bonded to the purely mechanical and physical world than any species that we know. In fact, the goal of some techniques for mental well-being is to bring our mind back to the "here and now" for a change. And yet, our understanding of how the mind works when we are not interacting with the immediate physical surroundings is only at its early stages. This scenario has favoured a display of creativity in scientific thought, an enormous amount of theories, hypotheses and proposals, to a point where it has become difficult to follow all points of view even only in the relatively small branch of knowledge that is grounded cognition, let alone the whole of human thought.

In order to investigate our topic we need a somewhat specific starting point where predictions can be made and tested. We decided to investigate the relationships between concrete and abstract magnitude processing, a field where there is already abundant data available, many experimental effects described and some competing theories. The following sections in this chapter provide a theoretical background to our research purposes, including a brief explanation of major theories in the field. After that, the rationale for the experiments contained in this thesis will be elaborated. Chapter III contains the experiments themselves, and in Chapter IV we will summarize the contribution of this thesis and conclude with some final remarks.

1. Mental representations

A very common and traditionally accepted understanding of the mind has been to consider that it has the ability to internally re-create elements that we find in the external world. When we perceive an object we make a sort of mental copy of it (a representation), that we can retrieve when needed (see Flavell, 1988; McNamara, 1986; Paivio, 1990). We can also combine representations and generate mental simulations without external sensory input. For example, one could ask: what would happen if we put an ice cube in the microwave? We can conclude that the ice cube would melt. We can reach that conclusion without having those elements in front of us and even if we have never actually tried. We have everything we need already in the mind: the representations of those two elements and their properties, and the ability to put them together in a mental simulation.

This way to look at the mind is both widespread and intuitive, but not everyone shares this regard for a virtual place where we store our concepts. A considerable amount of theoretical and empirical work has focused instead on how to connect the physical world and the organism without intervening representations. In line with Gibson's ecological view of perception (1966, 1979), several authors have pointed out that there is no need to have representations for objects that are already there in front of us, with all their properties. This would be unnecessarily complicated. Furthermore, we don't even need to internally deduce the actions that we can do in our surroundings because they can be perceived directly from objects. If there is an orange in front of us we can see that it is possible to grab it. We don't need to deduce that. According to this view, the property "it can be grabbed" is already present in the orange and we can perceive it directly. These properties directly perceivable are called *affordances* in the literature (i.e. Gibson, 1977). The focus on the external world rather than internal processes in the study of cognition is shared by a variety of current theoretical views, being enactivism and related theories major representatives of this line of thought (see Dew et al., 2015; Rowlands, 2009; Thompson & Stapleton, 2009; but see also Carvalho, Pereira & Coelho, 2016, for a view that considers cybernetics as the cronological origin of the enactive approach in cognitive science).

These two ways to look at cognition can be considered as the two sides of a continuum, being the extreme version of each side as follows. On the far pole of the continuum, focused on the physical environment, it is suggested that cognition can be explained with no need for representations at all. This view is not mainstream in current cognitive science. A critique against this proposal could be that it is too focused on perception and action, and has no easy way to explain how we can deal with objects that are not present (e.g., imagination, episodic memory, morality, judgement, anxiety for next week's exam...).

The other pole of the continuum, on the side of mental representations, would instead suggest that cognition can be realized offline, that is, without the participation of perceptual and motoric systems. Once the necessary information is acquired, cognition may happen in the brain without the rest of the body. This way to look at the mind and brain owes very much to the development of computers and the subsequent expansion of the computer metaphor in cognitive sciences.

For several decades now, computers have been used as a model to understand how the brain works. Both systems share considerable similarities. In both brains and computers there is an input of information, an internal processing and an output (e.g., a result in the computer screen, a verbal response, etc.). If we make a computer execute an operation (e.g., 4 x 45) it should give us the same result regardless the external conditions: what keyboard we are using to input the information, the brand of the hard disk or the room temperature should make no difference. Likewise, despite having different brains and different external conditions, both of us can reach the same conclusion about what would happen with the ice cube of the previous example. We can perform similar operations once we possess the necessary representations and mental abilities.

Some 50 years ago the debate between representations and no-representations in psychology was in favour of the former. It seemed clear that we receive information through the senses, which is coded in the brain, and from there our mind works with amodal and symbolic representations to elaborate a response. But little by little, evidence against this view has been accumulating, and now there is abundant data supporting that perceptual and motor information is entangled with high level cognition in a way that challenges some of the basic assumptions of the classical information processing account. For example, body posture can influence magnitude estimation (Eerland, Guadalupe & Zwaan, 2011), lateral eye turns affect the generation of random numbers (Loetscher et al., 2010), and when people move objects upwards they tend to retrieve more positive autobiographical memories (Casasanto & Dijkstra, 2010). In computers this could be like finding that the result of an operation could depend on the mouse that we use or the room temperature. These findings pose a strong theoretical challenge to the computer metaphor and the classical view of representations. Fortunately, there are newer theories that account for these results, and thus fall somewhere between the two poles of the continuum. A cornerstone for these theories will be to explain how abstract representations are originated. Thus, before we go into them we should clarify what we mean by concrete and abstract.

2. Concrete vs abstract

If we want to study how we perceive physical objects, finding a starting point is relatively simple. If for example we want to investigate vision, we can look at the eye and the optic nerve, see with what parts of the brain that nerve connects and continue from there. We can follow a similar approach for the other senses. But how about things we cannot perceive? In the case of time, for example, there is no vision, hearing or touching. Yet we can talk and think about time. What networks are we using to do that? This question has proven to be more difficult than tracking sensory information, particularly with time (e.g., Ivry & Schlerf, 2008; Matthews & Meck, 2014), but also in general for non-sensory information. In the context of this work, we will define concrete and abstract using this basic distinction between sensory and non-sensory. A cat, the smell of lavender and the sound of "happy birthday" are here considered as concrete entities (even though they are not all solid objects) whereas *time*, *luck* or *ambiguity* will be considered abstract. This distinction seems very straightforward: if you can see it, touch it, hear it, etc., is concrete; if you cannot, it is abstract. However, additional considerations can make the task more complicated.

We can say for example that a chair in front of us is something concrete. Now, if we remember a chair that we saw but is not in front of us, is that still concrete? And what if we are thinking about the concept of chair, with no particular color, material or style? A symbolic representation of a physical object, is it concrete or abstract? Are there levels of abstractness? Conversely, one can say that beauty is clearly an abstract concept. But if we are looking at an exquisite painting, the statement "I see beauty there" could be considered truthful.

Perhaps every conceptualization has their drawbacks. In this work we will differentiate concrete and abstract as follows. When a concept or domain is directly associated with modality specific brain areas (visual, auditory, tactile...) it is concrete. The concept *chair* is a concrete one (even though concepts are not physical entities, *chair* refers to something we perceive) and *space* would be a concrete domain. When they are not directly related to modality specific brain areas we consider them abstract. *Beauty* is an abstract concept as it is not particularly linked to any modality (a painting can be beautiful, so can be a gesture, a day, a relationship). Likewise, *time* would be an abstract domain.

A potential limitation of this conceptualization is that it relies on the nervous system, which is not exactly the same for all people. According to our definition, for a person that is blind from birth *red* would be an abstract concept, since there is no modality specific activation related to it. We can take this even further. There are animals known to navigate using electromagnetic fields. For them, electromagnetic waves are something concrete. But even if those fields are physical entities, as much as the light we see, we don't sense them. We can measure them with a machine... like we can measure time. Should we consider electromagnetism an abstract domain like time? Does this mean that what a human being cannot perceive is abstract, regardless of its physical reality? This could be a good starting point for a philosophical dissertation, but that is not our present goal. Since we don't need to go that deep into these concepts, our working definition should be more than enough for our purposes.

A particular case worth commenting (because it will play a central part in the pages to come) is numbers and numerosity. The mental processes involved when we see, for example, five dots in a computer screen (numerosity) or the digit "5" (numerical value) should be different. Concerning our distinction between concrete and abstract, we would consider numerosity a perceptual property and therefore concrete, whereas the value of a number should be considered abstract; it is symbolic and not conscribed to any particular modality: it could as well mean five personalities, five languages or five planets.

It is currently accepted, after much debate in the last two decades, that perceptual and motor information has a crucial role in abstract processing. Classical information processing theories do not easily accommodate these conclusions but more recent views have been elaborated to account for the new data.

3. Adding bodily experience to cognition

A few decades ago, with the birth of cognitive science, there was a consensus that we do have mental symbolic and amodal representations, and these can operate offline (i.e., independently from what the body is perceiving and its muscular actions) (e.g., Baars, 1986). However, consistent findings defying this view started to accumulate. A rich source of evidence against the traditional view have been experiments that combine sensorial or motoric activity with a cognitive task. Results have consistently shown that under many circumstances we cannot disentangle bodily information from higher cognitive processes. For example, Tucker and Ellis (2001) asked participants to categorize a stimulus as natural or manufactured using a response device that required either precision or certain strength. They found that response times were influenced by the size of the objects presented, an irrelevant property for the task. Responses to small stimuli were faster with the precision response, regardless if they were natural or manufactured, and power responses were faster for bigger objects. In line with this approach, Stanfield and Zwaan (2001) asked participants to read sentences that differed in the positions that objects would be likely to adopt (i.e., "John put the pencil in the cup" vs. "John put the pencil in the drawer"; in the first sentence the pencil is likely to adopt a vertical position, in the latter a horizontal position). Participants were then shown pictures of objects that could vary in orientation, and asked to respond whether that object had appeared previously in the sentence. They were faster to respond to the objects when they matched in orientation with the sentence previously read. Many more examples can be found in the literature (see for example Barsalou, 2008, for a review).

Brain imaging has also provided abundant support in this direction. When a concept is activated, modal areas of the brain also become active, including regions for shape, sound, colour, touch or action (Goldberg, Perfetti & Schneider, 2006; González et al., 2006; Kan et al., 2003). If sensory and motor systems are not needed in high level cognition, how can we explain these activations? One can argue that this is merely a co-activation with no real importance, but then, how do we explain such inadaptive waste of resources? Results like these caught the attention of the scientific community. And as the classical information processing view found difficulties to explain them, alternative theories made an entrance in the mainstream cognitive science.

Grounded cognition (or grounding) and embodiment are rather general terms that have been used with a diversity of meanings, but in general they all share a focus on perceptual and motor information as a core element in cognition. Rather than having its own realm away from the external world, cognition is understood as an activity that is bonded to our sensory and motor systems. The term *embodiment* refers more specifically to the influence of the own body in cognitive processes, whereas *grounding* is more general, considering not only the body but also language and material culture (i.e., Barsalou, 2008, 2010).

Part of the success of grounding theories comes from the consistency of some effects that were not predicted by classical cognitive psychology. A clear representative of these is the SNARC effect (Spatial Numerical Association of Response Codes): we are generally faster to respond to large numbers (in value) with the right hand and small numbers with the left than vice versa (Dehaene, Bossini & Giraux, 1993). This has been interpreted as evidence that the mind represents numbers spatially, in a horizontal axis with smaller numbers on the left and larger numbers on the right: the mental number line (i.e., Fias & Fischer, 2005; Göbel, Walsh & Rushworth, 2001). The theory also explains how this seemingly arbitrary association can be formed: throughout our life we are exposed to a large amount of numbers, which very consistently appear ordered with numbers increasing rightwards (rulers, charts, calendars, etc.). This experience with numbers organized in a spatial axis would shape an internal association between these two dimensions that manifests for example in the SNARC effect. When we use a mapping that is congruent with our internal representation, this facilitates execution and hence the gain in response time and accuracy observed in experiments.

In a similar fashion, we can also find an association between time and space: we are faster and make fewer errors with the mapping left-past/right-future than with the opposite one (Bonato, Zorzi & Umiltà, 2012; Santiago et al., 2007), and also with short periods of time on the left and long time on the right. This again would be originated from experience, which at least in western countries appears unambiguous and consistent. For example, in temporal charts time increases rightwards, in comics the story advances rightwards, in a written narrative events are usually described chronologically and the text direction is rightwards, therefore future events appear to the right of past ones. This extended experience with these two dimensions where later time is located on the right would result in a mental representation of time in a spatial axis with the past on the left and future on the right, the mental time line (Santiago et al., 2007; Tversky, Kugelmass & Winter, 1991).

If experience is responsible for these associations, then certain phenomena should be observed. First, the vast majority of experiments are carried out on a language with left-to-right orthography (English, Spanish, German,...). If the conventions of writing and reading direction are (at least in part) responsible for the association between time and space described in the last paragraphs, then in cultures with the opposite directionality, like Hebrew and Arabic, the opposite mapping should be observed. This reversal has been reported by several works (e.g., Bergen & Chan Lau, 2012; Furhman & Boroditsky, 2010; Ouellet et al., 2010).

Second, if experience is responsible for the association between a concrete and an abstract dimension, then if we have an extended experience with two different mappings, we should be able to observe both in psychology experiments. As pointed out above, we have experience with the association left-past/right-future. But we also have experience with time in the front-back spatial axis in a very relevant way (i.e., Lakoff & Johnson, 1980). For example, when we move through space it is usually forward, and as we walk or drive, the further we advance, the further we are in the future. This should associate back with the past and front with the future in our minds, as it is also revealed by metaphoric expressions like "if I could go back in time" or "I look forward to the holidays". Indeed, there is experimental evidence of the existence of both axes (e.g., Torralbo, Santiago & Lupiáñez, 2006). According to Santiago, Román and Ouellet (2011), we can have different mappings and use them as needed depending on the situation. Those mappings can be even contradicting, but when they are activated we use a set of them that are compatible with each other.

A further development in this field has been the demonstration that the perceptual and motor experience we have been exposed to throughout our life are not the only factors involved in the mappings between concrete and abstract dimensions. Actually, sometimes they can be modified with just 15 minutes of a different experience. A few works have shown that with only one session of priming with a reading direction different from the usual, participants' mental time line can change accordingly (Casasanto & Bottini, 2014; Román et al., 2015). To account for this representational flexibility, Casasanto and Bottini (2014) proposed the Hierarchical Mental Metaphors theory, according to which, mappings between space and time that have been culturally conditioned are specific cases of a more general one, which would be influenced by how those two domains relate in the physical world.

We should point out that the examples elaborated here don't make justice to the scope of current research in grounded cognition. Many relationships between abstract and concrete dimensions that are being currently studied have not been mentioned here, and on those that we have described there is more and deeper information available (see Barsalou, 2008; Borghi & Pecher, 2011; Shapiro, 2010, 2014). For example, the intricacies between the temporal and spatial dimensions go far beyond those addressed in the last few paragraphs (see, e.g., Boroditsky & Gaby, 2010; Casasanto, Fotakopoulou & Boroditsky, 2010; de la Fuente et al., 2014; Ding et al., 2015; Eikmeier & Ulrich, 2014; Graf, 2011; Kranjec & Chatterjee, 2010; Ouellet et al., 2010; Santiago et al., 2010; Shinohara & Pardeshi, 2011; Ulrich et al., 2012). And this is the case that we have elaborated more comprehensively. Our goal in this section has not been to offer a review of the current knowledge in grounded cognition but merely to outline its principles.

The basic ideas of grounded cognition commented here have been slightly modified or further developed by several authors, resulting in a rather complex picture of partly overlapping, heterogeneous theories which sometimes use different terms to refer to similar concepts, and other times use the same terms to explain different phenomena or mechanisms (e.g., Gentsch et al., 2016).

To mention a few of them, we have for example the Body-specificity hypothesis (Casasanto, 2009), Flexible foundations view by Santiago et al. (2011), the Spatial Agency Bias (SAB) (Chatterjee, Southwood & Basilico, 1999; Maass & Russo, 2003), Embodied Niche-Construction (ENC) hypothesis (Stutz, 2014), the Offloading hypothesis (Machery, 2016), the Perceptual Manipulations Theory (PMT) by Landy, Allen and Zednik (2014), the Temporal Focus Hypothesis (de la Fuente et al., 2014), Barsalou's, 2003, Perceptual Symbols Theory (PST), or the Radical Embodied Neuroscience (REN; Matyja & Dolega, 2015). Despite these developments, a recurrent criticism of grounding theories has been that they have low explanatory power. As expressed in Körner, Topolinski and Strack (2015), "research on embodiment is rich in impressive demonstrations but somewhat poor in comprehensive explanations" (p. 1). There are however several theories that offer testable predictions regarding the relationship between concrete and abstract concepts and dimensions, and have become particularly relevant in the last years, especially in the domain of concepts of magnitude, the focus of interest of this dissertation. Such is the case of the Conceptual Metaphor Theory (Lakoff & Johnson, 1980), A Theory of Magnitude (Walsh, 2003) and, perhaps with less fame but still relevant, the Polarity Matching Principle (Proctor & Cho, 2006).

- Conceptual Metaphor Theory (CMT)

Very often, when we talk about an abstract concept, we express it in relation to something concrete. For example in the expressions "my life is at a <u>crossroads</u>", "she is a very <u>bright</u> student" or "he carries a <u>heavy</u> burden", we are speaking about abstract concepts in physical terms. This observation was made by Lakoff and Johnson when they were studying how abstract concepts are acquired. In 1980 they proposed a linguistic theory: the Conceptual Metaphor Theory (CMT). Soon, researchers in cognitive psychology derived behavioural predictions which could be tested.

According to CMT, metaphors are not only expressions that have become usual in speech or a way to express ideas with some beauty. Metaphors can also reflect the actual processes that take place in the mind, that is, how thought is happening. In everyday language we can find numerous expressions that link an abstract domain with a concrete one. For example, if we say "winter is getting <u>closer</u>", we are referring to a temporal concept in spatial terms; thus the underlying metaphor would be *time is space*. More formally, in a conceptual metaphor we define a target domain (which is typically abstract) in terms of a source domain (typically concrete). According to CMT, in this example we are using the domain of space to understand time.

Conceptual metaphors offer an answer to the question of how we can grasp concepts for which we have no direct experience: borrowing from conceptual domains for which we do. Concrete concepts would originate from experience with the environment, and abstract concepts would be generated out of concrete ones, giving them a new (abstract) meaning through conceptual metaphors. A crucial implication of this is directionality: we need concrete domains to process abstract ones, but not vice versa. Casasanto and Boroditsky (2008) tested this prediction experimentally. Participants had to estimate the length of a line (concrete) or a temporal interval (abstract). Results showed that disrupting space (exposing participants to irrelevant spatial information) influenced the estimation of time, but disrupting time did not affect the estimation of distance.

Another key feature of conceptual metaphors is their universality: hundreds of them have been described across languages and cultures. This does not mean that we all possess the same metaphors however. Cultural convention may shape specific associations between concrete and abstract domains. But, according to CMT, the use of conceptual metaphors as a way to understand abstract domains is universal (Lakoff & Johnson, 1980, 1999).

CMT has provoked much discussion and inspired very interesting research endeavours. However, it struggles at least in one aspect. There is substantial evidence of bidirectional effects between concrete and abstract domains (see for example Bueti & Walsh, 2009; Cai & Connell, 2015). This is difficult to explain for CMT.

- A theory of Magnitude (ATOM)

A Theory of Magnitude (Walsh, 2003) has also exerted considerable influence in the field, inspiring further research and motivating scientific events or special issues in journals on its own right (e.g., Vicario, 2013). ATOM stands out on biological plausibility; in addition to offering a cognitive model it also relates it to the brain, which makes the theory not only more complete but also easier to test in cognitive neuroscience. This theory postulates that there is a region in the brain where space, time, number and in general all prothetic dimensions (those that can be experienced as "more than" or "less than") are processed. The locus of this generalized magnitude system is proposed to be the inferior parietal lobe. Walsh supports his proposal with a rich variety of data, from laboratory experiments using different dimensions simultaneously to results with transcranial magnetic stimulation (TMS) or research describing the performance of patients after brain damage.

A key prediction of this common coding of magnitude would be that the relationship between dimensions should be symmetrical. Contrary to CMT, ATOM does not suggest that concrete dimensions are needed to process abstract ones, but all of them are treated equally in the specified brain region (therefore, no directionality from concrete to abstract is expected). Santiago et al. (2012) presented words in a computer screen that differed in emotional value (positive or negative) and location (up or down). As expected, they found that positive words were faster to judge when they appeared up in the screen, and negative ones when they were shown in the lower position. This was congruent with the metaphoric mapping *happy is up*. Then they asked participants to judge the position of the words, and checked whether the emotional value of these words could affect their reaction time (i.e., congruency effect). In other words, they checked whether the abstract domain could influence the concrete one. They found that this effect could be observed manipulating attentional cues. They concluded that attentional cueing can modify the manifestation and the symmetry of the congruency effect. All in all, the literature provides evidence of symmetrical and also asymmetrical relationships between concrete and abstract domains.

Another prediction, related to the previous one, would be that the processing of different magnitudes should be correlated, both in the performance of healthy adults as well as in the patterns of dysfunction in neuropsychological patients. So far, previous studies have found both evidence supporting this prediction (Bueti & Walsh, 2009; Bonato et al., 2012) and against it (Doricchi et al., 2005).

A weakness of ATOM compared to CMT is that the former is not as comprehensive, as it only considers quantitative, prothetic dimensions. It does not provide an answer to the question of general abstract thinking or mental representations but, to be fair, neither is its intent. The evidence supporting ATOM is considerable, but evidence of dissociations between different magnitudes and asymmetrical influences between them is far from exceptional in the literature (e.g., Agrillo, Ranpura & Butterworth, 2010; Cappelletti, Freeman & Cipolotti, 2009; Dormal, Seron & Pesenti, 2006; Lu et al., 2009; Oliveri et al., 2008).

- **The Polarity Correspondence Principle**

While CMT and ATOM propose two distinct views of how abstract concepts or dimensions are dealt with by the mind-brain, the Polarity Correspondence Principle (Proctor & Cho, 2006) offers a more specific account with less theoretical elaboration, but which on the other hand accounts for effects that the other theories (and even the basic principles of grounded cognition) struggle with.

A very typical experiment in grounded cognition to test the association between two conceptual dimensions (usually one concrete and one abstract) is to present stimuli that differ in one of the dimensions and ask the participants to discriminate them and give their responses using motor actions which differ in the other dimension (typically spatial responses like left-right or up-down response buttons). We can, for example, present numbers from 1 to 4 and from 6 to 9 in a computer screen, and ask our participants to respond with a right response button to numbers above 5 and with the left button to numbers below five in part of the experiment. In another part, they should use the opposite stimulus-response mapping.

Under these conditions, we would typically see that the first mapping (small-left, large-right) is faster and more precise than the second mapping, i.e., the SNARC effect described previously. We could also use other response mappings (e.g., up-down) or any other kind of stimuli (temporal, tactile, different sounds, etc.).

Grounded cognition theories usually understand these stimulus-response mappings as evidence for a conceptual relationship in our mind between those dimensions. This explanation seems very satisfactory, for example, to explain the SNARC effect: we represent numbers spatially, the mental number line. But let's take now another finding called the MARC effect (linguistic Markedness Association of Response Codes; e.g., Nuerk et al., 2002). The MARC effect is another association between space and number, in this case based on parity: performance is better with the mapping *odd numbers-left/even numbers-right* than vice versa. In this case, how exactly would the numerical-spatial representation be and what kind of perceptuo-motor experience would generate it? This appears very difficult to explain for CMT or ATOM, and most embodied theories. Proctor and Cho (2006) offered an answer to this question that does not require hypothetical associations between dimensions. In their own words, the Polarity Correspondence Principle posits:

> *"For a variety of binary classification tasks, people code the stimulus alternatives and the response alternatives as + polarity and - polarity, and the response selection is faster when the polarities correspond than when they do not."* (p. 418)

According to the authors, binary stimuli and responses (such as large-small, past-future, left-right, up-down, etc.) are coded with a property called *polarity* so that for each pair, one would be +polar and the other -polar. The +polar would be the default, the more representative of the pair; for example, in the dimension of brightness, *bright* would be the +polar and *dark* the -polar. In weight, *heavy* would be +polar and *light* -polar. Likewise, *large*, *future*, *right* and *up* would be +polar (*small*, *past*, *left* and *down* would be -polar), etc. A way to find out which is the default element of the pair is often to observe how we talk about it. For example, if we want to know about the weight of an object we can ask "how <u>heavy</u> is it?"; it may be light or heavy. But if we asked "how <u>light</u> is it?", we would be somehow implying that it cannot be heavy. So in a way, *heavy* (+polar) represents the whole dimension whereas *light* (-polar) only stands for its side of the dimension.

According to the Polarity Correspondence Principle, when the polarity of stimulus and response match, there is a gain in response speed. This alone can explain the effects mentioned above with no need to invoke internal spatial representations such as a time line or a number line. For example, in the SNARC effect, large numbers and right side responses would be both +polar. This matching in polarity would be responsible for the speed increase of that stimulus-response combination. In turn, small numbers and the left response are both -polar, and this match would also enhance the response speed. With the other mapping (large-left/small-right) polarities don't match and consequently responses are slower. A similar explanation can be elaborated for the finding that responses are faster with the mapping past-left /future-right than vice versa: *right* and *future* are +polar, *left* and *past* are -polar.

And what about the MARC effect? For other theories it is difficult to explain the mapping of even numbers on the right and odd ones on the left, but here it is very straightforward: *even* is +polar, like *right* responses; *odd* is -polar, matching with the *left* responses. Once again the matching of polarities is consistent with the effects found in the laboratory, in this case the MARC effect. As we see, Polarity Matching offers an explanation where others really don't, and a very simple one: in short, if dimensions match in polarity, responses are faster.

An important addition can be found for example in Lakens (2011): apart from responses being faster when polarities match, we also respond faster to +polar than to -polar stimuli, and these two factors combine additively. Taken together, Polarity Matching gives an explanation to various results that is more simple and parsimonious than what more popular views propose. Proctor and Cho (2006) also argue that it is the only one that at the time could explain effects like the advantage of the *up-right/down-left* mapping in psychology experiments: the fact that this mapping is overall faster than the opposite one, regardless the stimuli (the explanation would be once more quite simple: *up* and *right* are +polar, *down* and *left* are -polar). More examples are elaborated in their original paper.

There are quantitative differences between the predictions of polarity matching and CMT. Whereas in the latter we would expect an effect of similar size for the +polar and the -polar combination, in polarity matching there are a number of factors that should modulate the effect: stimulus valence, spatial location of the stimulus, response code and the polarity correspondence between them. Lakens (2011) carried out a meta-analysis which revealed that the results in previous studies are more parsimoniously explained by structural overlap in polarity than by metaphor congruency (that is, CMT). Later on, Lynott and Coventry (2013) again tested polarity and conceptual metaphor against each other. In various experiments with the valence-spatial association (good is up, bad is down) results consistently favoured predictions of polarity rather than metaphors. However, these authors acknowledge that there are also experiments whose results are difficult to account for by polarity. Furthermore, some studies have not found support for predictions of polarity matching (see Santiago & Lakens, 2015).

A built-in limitation of polarity is that it deals only with binary classification tasks. It does not apply for, instance, to stimuli that have more than two levels; such would be the case of bisection tasks, that will be central for the present work. Polarity also does not offer clear predictions when more than one stimulus and one response are combined. Also relevant aspects of the theory may not be spelled very explicitly. For example, the definition of what is +polar and -polar may not be straightforward in every case, and which is the default pole may be difficult to define or even depend on subjective opinion in certain cases. In addition to this, it is also possible to make -polar stimuli share features of +polar by increasing their relative frequency (Lakens, 2011; Lynott & Coventry, 2013). This finding is a development of the theory but perhaps in turn it does not simplify the question of defining +polar and -polar. Finally, the theory does not elaborate very comprehensively how polarities may be originated or what may be their reflection at the neuronal level.

4. Where are we now?

Researchers concerned with the involvement of previous experience, the body and the environment in cognition have produced in the last few decades a wealth of data and possible explanations for their results, and the field is still capturing the attention of many research programmes. Not all of them have enjoyed the same popularity, but overall the field can be considered very successful within cognitive science. These theories have also spread from their roots to other fields of knowledge. The postulates of Conceptual Metaphors are currently being used far beyond linguistics, and grounded cognition in general is now relevant in disciplines like robotics or artificial intelligence. Embodied cognition, in the words of Dove (2015), "represents one of the most important theoretical developments in contemporary cognitive science" (p. 1).

Research from these theories has provided unforeseen results that are also easy to advertise (e.g., "did you know that holding a hot beverage in your hands can make you judge people as more friendly?", see Williams & Bargh, 2008; or "processing the word red can enhance women's perceptions of men's attractiveness", Pazda & Elliot, 2016). Their findings will probably not surprise in the future anymore, but so far they have challenged the way we have traditionally understood the brain in cognitive psychology: roughly speaking, a computing device that uses symbolic representations to elaborate a response. Now it seems that the output produced depends significantly on the perceptuo-motor experience of the individual as well as the environment and the physical state while we do our mental activity. The interest generated by some of these experiments encouraged even more research, resulting in a rapid growth of data available and hypotheses in the last years to a point where it has even been proposed that radical embodiment is what cognitive science needs to go forward (Kiverstein & Miller, 2015).

But not all is fame and glory. Other works have highlighted the lack of comprehensive understanding of these theories. Some authors have pointed out that grounded cognition and related proposals simply state evident facts (i.e. that cognition makes use of information gathered by the senses), they provide surprising results but not clear interpretations, and their predictive power is limited. Simply said, they don't help that much in understanding the mind and brain. Arguments against the traditional view of cognition have been responded in kind in recent papers, some of them with certainly forthright titles, like "The poverty of embodied cognition" (Goldinger et al., 2016) or even "The burden of embodied cognition" (Mahon, 2015a; see also Leshinskaya & Caramazza, 2016).

This lively debate has eventually become difficult to follow. The versions of each theory that have been released, claims attributed to different authors, clarifications and replies to critiques across journals and other scientific forums makes it complicated to have a clear idea of where we are at the moment. As expressed by Dove (2016) in the particular case of embodiment,

> *"A great deal of research has focused on the question of whether or not concepts are embodied as a rule. Supporters of embodiment have pointed to studies that implicate affective and sensorimotor systems in cognitive tasks, while critics of embodiment have offered nonembodied explanations of these results and pointed to studies that implicate amodal systems."* (p. 1)

This said, the view of this PhD candidate is that even though from both sides there are voices suggesting that the other should be left behind (e.g. *all cognition should be embodied* vs. *we should forget about embodiment*), the disagreements seem to be more about how to define theoretical constructs than about what is actually happening in the brain. Amongst all the discussion, there is not much dispute regarding whether perceptual and motor experience influence cognitive processes.

Whenever we have tried to explain cognition lessening the importance of high level abstract processes, the result has been a theory that lacks explanatory power. These theories usually centre the debate on relatively narrow topics, since they are currently not reaching the whole of the human mental experience. Neglecting the importance of the body and the environment on cognition, on the other hand, may lead to the inability to explain much of the data that are being reported in the last years. In the midst of this discussion, it is also possible to look for a middle point: the brain may use amodal representations and/or perceptuo-motor information as needed. This conciliatory option has the advantage of avoiding much of the criticism mentioned above (from both sides), but at the cost of less clear predictions. They are also harder to implement biologically. For example, it may require to hypothesize, in addition to everything else, a *clutch* mechanism with the function of shifting from amodal to perceptuo-motor when required (see Mahon, 2015b).

In order to address realistically the current situation of grounded cognition, we also need to add considerations about the day-to-day work in research. Several authors have warned in the last years about common practices that can originate errors in the interpretation of results, both in behavioural studies and neuroimaging, and the worrying problems of reproducibility that these can originate (see de-Wit et al., 2016; Open Science Collaboration, 2015; Pashler & Wagenmakers, 2012; for a different opinion on this topic, see Gilbert et al., 2016). The pressure on productivity that lies upon the average cognitive neuroscientist nowadays may reach the point where it conflicts with quality and reliability of our work. It is currently more difficult to get results published when they are negative (Fanelli, 2012), and this may also encourage researchers to select those methods and analyses that are more likely to provide a significant result. How this scenario interacts with the current discussions in grounded cognition is an issue to keep a close look on. We have a vast accumulation of information but we are not totally certain of what we can confidently trust and what bits should be taken more cautiously.

Current science is nothing like the British Royal Society of the XVIII century. Reaching an agreement is not as relevant anymore, and discussing a topic is most useful when it can be published. For almost every claim we can find evidence that supports it and also that contradicts it in the literature, and both sides enjoy the status of scientific evidence and can therefore be used to support further work in each direction.

All of these factors together make it difficult to judge the validity of the claims made by the different models, hypotheses and theories in cognitive neuroscience. One can only hope that we will do our best to minimize the effects of motivations other than the quest for knowledge that has accompanied our species over the centuries.

II. Goals of this thesis

The central goal of this thesis was to test out predictions of theories proposing that concrete and abstract processing are closely associated. In particular, we focused our interest on the common coding view of A Theory of Magnitude, which hypothesizes a system in the parietal cortex involved in the processing of space, time, numerosity and all other prothetic dimensions. This theory offers a potential explanation of how concrete and abstract magnitudes are processed. Experiments in this field have typically combined two dimensions in interference or priming tasks, and measured reaction times and/or brain activity under a variety of conditions. In the context of ATOM, finding reciprocal interactions between domains is interpreted as evidence in favour of the theory. Neuropsicological cases have also been used to support the common coding view. In this case the coincidence of deficits of different modalities has been taken as evidence for ATOM.

We decided to test one of ATOM's major implications following a less common approach: we measured the performance in different prothetic dimensions (concrete and abstract), one by one, in stable and presumably optimal external conditions. For each magnitude we estimated the perceptual bias and accuracy of each participant. If there is a common system responsible for all prothetic dimensions, then detecting a bias in the perception of one magnitude should be an indicator of a bias in the system itself, and therefore a similar bias should be observed in the processing of other magnitudes. Finding evidence of correlation between domains would be compatible with the predictions of ATOM. No such correlations would instead argue in favour of alternative hypotheses which pose different underlying processes and/or representations for different prothetic dimensions.

The next question therefore was: what task could we use for these purposes? We needed a perceptual bias that could be observed in different dimensions. Pseudoneglect and bisection tasks seemed the perfect candidate for the job.

1. Bisection tasks and pseudoneglect

There is a neuropsychological condition named hemispatial neglect (also called neglect syndrome or hemiagnosia), characterized by brain damage (typically in the right parietal lobe) that results in a deficiency to attend to one side of space, usually the left. Neglect patients consequently exhibit a considerable bias in their perception and awareness of space (see Li & Malhotra, 2015, for a recent review). Although much less striking, the general population has been reported to exhibit a spatial bias as well. If we are presented a sheet of paper with a straight line printed on it, and we are asked to mark the centre of the line, we will probably fail to mark the exact middle point. Interestingly, if we repeat this several times (with a new sheet of paper each time), the errors to the left and to the right will typically not balance out but be consistently biased towards one side, usually to the left. This effect is known as pseudoneglect (Bowers & Heilman, 1980; see also Jewell & McCourt, 2000).

The task just described, line bisection, provides a measure of bias in the perception of space. There is another version of the task where instead of marking the middle of a line, participants are given a line with a mark already on it, and they have to estimate whether the mark is closer to the left or right end of the line. That is, instead of producing the middle point, it requires the judgement of the relative position of a probe stimulus (the mark) in the line. The task just described has been called the Landmarks task in the literature (Harvey, Milner & Roberts, 1995).

Crucially for our purposes, line bisection can also be adapted to other dimensions, like temporal and numerical intervals, for which perceptual biases have also been observed (Jewell & McCourt, 2000; Kopec & Brody, 2010; Loftus et al., 2009). For each dimension it is possible to set up production as well as judgement bisection tasks.

In the most standard form of the temporal bisection task, participants are first trained to discriminate between two stimuli that differ in duration. In a subsequent phase, they are required to estimate whether probe stimuli with different durations are closer to the short or long anchor durations of the training phase. These judgements are then used to estimate the subjective middle point of the temporal interval determined by the two anchors, as well as the degree of acuity or discriminability between similar durations. A version of the task that requires production of the middle by the participant is less frequent, however possible. To produce a temporal interval, participants are usually asked to push a button and hold it for the duration of the interval, or press it at the beginning and once more when they estimate the interval should end.

In a typical number bisection task participants are given two numbers corresponding to the limits of a numerical interval (e.g., 23 and 76), and a third number between them. In a similar fashion to time bisection, the task consists on judging to which of the two limits the middle number is closer in value. From these judgements we can calculate the subjective bias and acuity for each individual. A version where participants have to produce the middle point of the numerical interval is rather frequent in the case of numbers. Instead of judging the relative position of a probe stimulus, in the production version participants are asked to estimate (without calculating) the number midway between the two that they are given. The methodology that we used for each magnitude of interest will be described in detail in the next chapter.

2. Experiments proposed and hypotheses

We decided to test the performance of a sample of undergraduate students (that we consider representatives of the general population) in a spatial and two temporal bisection tasks. We used the classical line and time bisection tasks and a novel temporal bisection with more ecological stimuli and that also explored durations greater than what has been usually studied in the literature: we used 30 seconds long video clips with a human face aging from childhood to elderly. In all tasks, data were analyzed in a way that allows the assessment of psychophysical properties of the underlying representation, such as their subjective midpoint and perceptual acuity. From the results obtained in this initial experiment, our research continued to explore these predictions with populations of psychiatric and neuropsychological patients, as described in detail in the following sections.

Even though performance in these tasks may differ from one person to another, pseudoneglect should be stable for each participant. More important than the effect of pseudoneglect itself, for our purposes the crucial observation was within subject variation. According to the predictions of the common coding hypothesis, significant correlations between tasks should be observed within participants.

III. Experimental series

This section describes the experimental part of this thesis. Each experiment contains a general overview, justification and hypotheses, followed by a description of materials and methods, results and a brief discussion.

1. Experiment 1: bisection tasks in the general population

In this first experiment we wanted to test whether we could find a link between spatial and temporal bisection in the general population. We measured bias and precision in the performance of one spatial and two temporal bisection tasks, as well as their correlation within participants. In the spatial domain we used the standard Line Bisection task. To assess performance on the temporal dimension we used a classical Time Bisection and the novel Aging Faces task, which we describe in the following section.

Finding a high correlation in bias or discriminability across dimensions would be compatible with a common coding of magnitude, and also with the grounding of abstract dimensions on concrete ones (in this case, time onto spatial representations). Conversely, no evidence of covariation between tasks in the different groups of participants would be compatible with independent underlying systems for each magnitude.

MATERIALS AND METHODS

Participants

Twenty five (5 male, one left hander, average 23.8 years, range 18–49) students from the psychology degree at University of Granada took part in this experiment. They received course credit for their participation.

Tasks

- Line Bisection

Participants were asked to mark with a pen the middle point of a horizontal line (1 mm wide, 200 mm long) printed centred on a sheet of paper. After the response, the sheet was removed from the desk and another identical sheet was presented. Each participant bisected a total of 24 lines.

All lines from each participant were then scanned and the distance between the mark and the actual centre was measured using a graphics processing program (precision: ±0.1 mm). Positive values represent deviations to the right of the centre, and negative to the left. We used this distance to characterize participants' performance. Our index of bias was the average bias (in mm) over the 24 bisected lines, and as an index of response variability we used the standard deviation of these measurements.

- Standard Time Bisection

The stimulus used for this task was a blue square (6.8 x 6.8 degrees of visual angle) presented at the centre of a 15'' screen monitor for a duration ranging from 1000 to 4000 ms. Participants first received a training block of 20 trials to learn to discriminate between the two extreme (or anchor) durations, 1000 and 4000 ms. Only the two anchors were presented in this block, 10 times each one in random order. All participants learnt to discriminate the anchors during training (final accuracy range 95-100%). Next, they received 154 trials where the durations 1000, 1500, 2000, 2500, 3000, 3500, and 4000 ms were randomly presented. Participants were asked to estimate, for each stimulus, whether its duration was closer to the short or long anchor. The two anchors appeared three times more often than the intermediate durations in order to keep refreshing them throughout the task. In order to prevent any spatial activation generated by the action of responding, responses were given verbally and the experimenter coded them simultaneously by means of keypresses out of the participant's sight.

The probe durations in our task were equally spaced over the interval determined by the two anchors, with 500 ms difference between any probe stimulus and the closest one. In other words, they were linearly spaced. Another way to choose probe durations would be spacing them logarithmically. Both options are well represented in the literature. In a meta-analysis of the findings with this task, Kopec and Brody (2010) reported that with logarithmic spacing the bisection point is usually smaller, that is, closer to the centre of the interval. We preferred a linear spacing of stimuli in order to be able to capture a higher degree of variation in individual performance.

Stimulus duration was converted to a continuous scale from 0, the shortest duration, to 10, the longest duration, and the proportion of “long” responses for each stimulus duration was computed for each participant. These data typically took the shape of a cumulative curve. The curve was then fitted to a linear model. The slope and intercept of this line were used to calculate the Point of Subjective Equality (PSE) and the Just Noticeable Difference (JND) for each participant (PSE = - intercept/slope, which is mathematically equivalent to the stimulus duration at which the best fitted line crosses the 0.5 proportion; JND = 0.675/slope, which corresponds to subtracting the stimulus duration at which the function crosses the 0.75 proportion from the duration at which the same function crosses the 0.25 proportion and then dividing it by two; see Coren, Ward & Enns, 1999).

The PSE indexes the subjective midpoint of the temporal interval between the two anchors and allows the assessment of constant bias. The JND estimates the minimum distance between two points in the interval that the participant is able to recognize as different, and thus it serves as an index of perceptual acuity. A low JND indicates that the participant is able to discriminate between stimuli with small differences in duration, her responses have a high precision and therefore low variability. A high JND then indicates high response variability which means low perceptual acuity.

In this and the following task, Eprime 2.0 software (Psychology Software Tools Inc.) was used for stimulus presentation and data collection. PSE and JND indexes were calculated using Microsoft Excel, and all data together were analysed with Statistica 8 (StatSoft Inc.) and JASP 0.8 (Univ. of Amsterdam).

- Aging Faces

Participants saw four videos, each showing a face (two male, two female) that aged gradually from childhood to elderly. Videos were extracted from a demo video clip of the April Age Progression software (downloaded from Youtube: https://www.youtube.com/watch?v=fa5rzZroNyU). Each clip lasted for about 30 s, and was presented twice. Figure 1 shows three frames of one of the videos as an example. These stimuli have the advantage of capturing the attention of the perceiver to the stimulus face as it changes from being a child to an elderly person, thereby avoiding distraction and boredom, as well as counting and other idiosyncratic strategies.

Following the second presentation of a clip, 36 frames extracted at regular intervals were presented in random order. Each frame was presented three times, totalling 108 trials per clip. Participants estimated whether the frame was temporally closer to the beginning or to the end of the clip. As in the previous task, responses were given verbally and coded online by the experimenter through hidden keypresses. After all frames on a given video clip were presented, the procedure was repeated for the next video. The proportion of "end" responses for each frame were analysed following an analogous procedure to the standard Time Bisection, rendering the Point of Subjective Equality (PSE) and Just Noticeable Difference (JND) indexes.

Figure 1. Three frames extracted from initial, middle, and final moments in one of the video clips of the Aging Faces task.

The Aging Faces task, as used here, is adapted from tasks which have already been used to study temporal processing in prior studies. Santiago et al. (2010; Experiment 1) presented their participants with video clips extracted from commercial movies. After watching the clip, participants saw frames from the clip and produced left and right keypresses to indicate whether the frame belonged to the first or second half of the clip. Subsequent experiments in that series used analogous tasks, using sequences of six pictures depicting everyday events (e.g., preparing breakfast) instead of video clips. A similar approach was used by Fuhrman and Boroditsky (2010) and Fuhrman et al. (2011) using sequences of three pictures such as the face of Julia Roberts at different ages, a banana being eaten, and so on. In all these studies, the results showed a congruency effect between space and time (Santiago et al., 2007): participants were faster to respond when “beginning” or “past” was mapped to the left hand and “end” or “future” to the right hand than when using the opposite mapping. The Aging Faces task builds on those procedures but without the use of lateralized manual responses, in order to avoid any induction of the use of a spatial representation.

Summing up, bias indexes include the average distance from the mark to the actual centre of the line in the Line Bisection task, and the Point of Subjective Equality (PSE) in the Standard Time Bisection and Aging Faces tasks. Henceforth, these will be referred to as “bias.” Precision indexes include the standard deviation of the distance of the marks to the actual centre in Line Bisection, and the Just Noticeable Difference (JND) in the two temporal tasks. These will be referred to as “response variability”.

Procedure

Participants were tested individually in a single session. Task order was kept constant throughout the experiment. The Standard Time Bisection task was presented first, followed by Aging Faces and finally Line Bisection. Temporal bisections were administered before Line Bisection in order to prevent a preactivation of the spatial dimension in the temporal tasks. Participants were suggested to rest after each block and between tasks. In all tasks there was no time limit to give their responses, although they were encouraged not to take too long. At the end of the experiment they were debriefed and received credit course for their participation.

Statistical analysis

In this and the rest of experiments we will use both the classic (Neyman-Pearson) significance testing and Bayesian analysis. In significance testing, the *p-value* refers to the probability of rejecting the null hypothesis, given it is really true. If our data are unlikely considering the null being true ($p < .05$), it means that the null is probably wrong, and with this criterion we will make a mistaken conclusion 5% of the times. In this type of testing we calculate how likely our data are, being the null hypothesis true.

But note that this does not give a straight estimation of how likely is our hypothesis to be true, as it does not inform of the probability to obtain our data given the alternative hypothesis. Our data might be similarly unlikely to obtain given either hypothesis, and therefore even if the p-value was significant, it would not be really meaningful to conclude anything. The Bayes factor does not refer to the probability of our data, but directly to how likely is one of the hypotheses to be true (or false) with respect to the likelihood of the other hypothesis. It informs therefore to the support to H1 as well as to H0. Null results in significant testing allow for little interpretation, but Bayesian analysis allows making conclusions about the likelihood of a particular theory not being accurate.

The Bayes factor that will be presented throughout this thesis (*B*) is the support for H1 over H0, or BF_{10}. A value of 1 means that we found equal support for both hypotheses. Values between 1 and 3 can be considered weak support for H1, and above 4 would be substantial support for it. Values below 1/4 are considered a strong support for H0 (see Dienes, 2008, p. 108).

RESULTS

The bias indexes were analysed by means of two-tailed *t*-tests against the central value of each task. The deviation from the midpoint in Line Bisection reached significance ($t(24) = -2.47$, $p = .021$, $B = 2.567$). Participants bisected lines slightly to the left of the middle, the average bias in Line Bisection was -0.7 mm. In Standard Time Bisection the B factor fell below 1/4, indicating a strong support for the lack of bias in this task ($t(24) = -0.06$, $p = .95$, $B = 0.211$). However, in the Aging Faces task participants clearly deviated from the midpoint of the clip ($t(24) = 3.43$, $p = .002$, $B = 17.60$), towards the end of the interval. In other words, they produced more "beginning" than "end" responses (Figure 2).

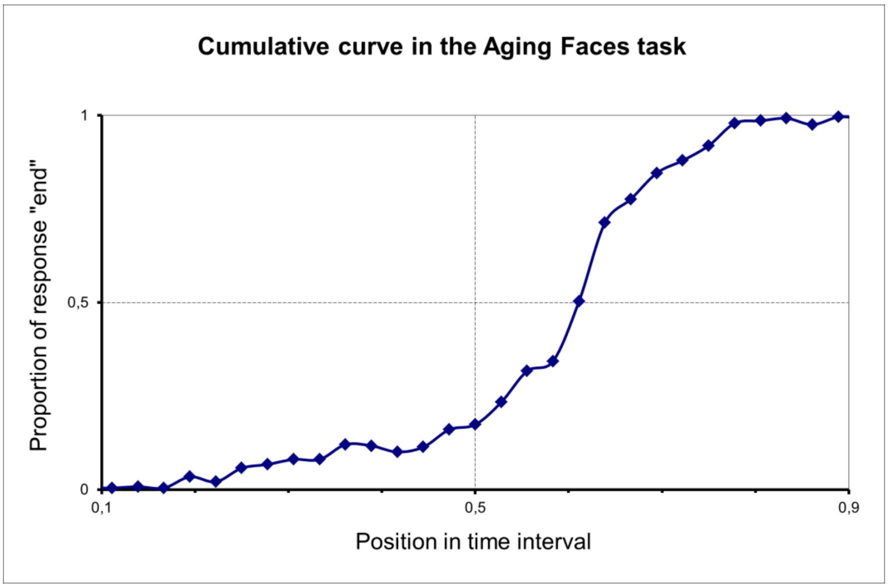

Figure 2. Proportion of trials with “end” response as a function of temporal position in the video clip in the Aging Faces task in Experiment 1 (healthy participants).

Importantly for our hypotheses, we tested whether the indexes of bias and precision covaried over participants across the dimensions of space and time by means of Pearson’s correlation coefficients (in all cases, $p > .1$, $B < 0.7$). All correlations between spatial and temporal tasks were close to zero and non-significant. The two temporal tasks were also not correlated to each other. In the correlation between the bias in Line Bisection and Aging Faces ($r = -0.008$, $p = .97$, $B = 0.248$), the B factor indicates that these two variables are indeed uncorrelated. In the rest of comparisons, the B factor was above 0.25 (and below 0.7) and therefore did not provide conclusive evidence for or against such correlations.

DISCUSSION

We replicated the leftwards pseudoneglect effect in the Line Bisection task described in the literature (e.g., Jewell & McCourt, 2000), but no bias was observed in the Standard Time Bisection. In contrast, there was an end bias (a tendency to locate the midpoint of the interval closer to the end) in the Aging Faces task. This finding is difficult to interpret. On one hand, the task may provide different results from the classical temporal bisection because it includes aspects of semantic memory and uses much longer temporal intervals, but on the other hand both tasks should also be related, since they both involve the processing of time. One possibility is that, although the instructions explicitly asked participants to decide whether a given frame was closer to the beginning or the end of the video, participants may have interpreted the task as deciding whether a picture of a person is closer to the beginning or the end of his or her life. This subjective vital midpoint may not have coincided exactly with the midpoint of the clip. As it is likely that what a participant considers to be the midpoint of somebody else's life is linked to what she takes to be the midpoint of her own life, and because this probably varies depending on participant's age, Experiment 2 (where we collected data from older participants) will help clarifying this point.

The null bias observed in Standard Time bisection contrasts with several previous findings in this task. However, there are also methodological differences between our version of the task and others previously used. For example, Elvevåg et al. (2003) used the picture of a big bird and a small bird associated with the long and short tones that determined the anchor durations during their training phase. In Carroll et al. (2008, 2009a), participants responded by keypresses that were associated to "long" and "short", but they do not refer to a counterbalance of the mapping between duration and key position. In studies following these methodologies, a preactivation of the mental associations between the temporal dimension and size or spatial position may have occurred, and therefore the significant bias found in their temporal bisection tasks may have been influenced by other dimensions. In our version of the task we used a constant visual stimulus for all durations, and avoided any manual responses by participants. This may be at least part of the reason for the differences between our results and previous works.

The main result of this first study is a lack of support for a link between space and time processing in the general population, as shown by different patterns of bias across the spatial and temporal tasks, and null correlations across tasks. However, the absence of cross-task correlations in one single group does not constitute strong evidence against the hypothesis of common coding. In our second experiment, we searched for a relationship between space and time in a group of schizophrenic patients, whose spatial and temporal processing has frequently been reported to differ from the general population.

2. Experiment 2: bisection with schizophrenic patients

The lack of significant correlations between tasks in our sample of undergraduate students suggested that magnitude processing might not follow the predictions of the common coding hypothesis, at least under our experimental setup. We then decided to challenge this preliminary conclusion measuring performance in our bisection tasks in a group of schizophrenic patients and a matched control group. These patients have been reported to differ from the general population in bisection tasks, not only in perceptual bias but also in response accuracy under certain conditions. This constitutes a very interesting testbed for our hypotheses.

One of the tasks where patients with schizophrenia have been reported to differ from the general population is the line bisection task. The picture, however, is complex. McCourt et al. (2008) replicated the well-known small leftward bias (pseudoneglect) usually observed in healthy participants (Jewell & McCourt, 2000) but found no bias in schizophrenic patients. Zivotofsky et al. (2007), in a study without a control group, replicated the schizophrenics' lack of bias in the line bisection task. In contrast, Michel et al. (2007) as well as Cavézian et al. (2007) found a stronger leftward bias in patients than in healthy controls. On a different note, Barnett (2006) reported a similar bias for both groups but a higher variation with experimental conditions for schizophrenic patients. Finally, Tian et al. (2011) reported a stronger leftward bias in schizophrenic patients than healthy controls, who in this study did not show any bias. Thus, available studies show that both schizophrenic patients and healthy participants can sometimes bisect to the left or show no bias in line bisection. Their bisection biases are often different, and schizophrenics may sometimes bisect to the right, and sometimes to the left, of healthy participants.

Time perception, on the other hand, is generally agreed to be impaired in schizophrenia. Some studies have used time bisection tasks to address this temporal deficit. Carroll et al. (2008), using auditory and visual presentations of stimuli ranging from 300 to 600 ms, found that whereas both patients and controls were more accurate on auditory than visual intervals, schizophrenics were worse than controls only in the auditory modality. Carroll et al. (2009a), using only auditory stimuli, replicated the reduced temporal acuity in the 300–600 ms range and extended it to the 3000–6000 ms range. Lee et al. (2009) also found decreased accuracy in the discrimination of auditory durations both in the 400–800 and 1000–2000 ranges, and they also observed a fixed bias toward underestimating intervals in the 400–800 condition (that is, a greater proportion of "short" responses, leading to a subjective middle shifted toward the "long" duration). Finally, Elvevåg et al. (2003) also found decreased temporal precision with auditory stimuli between 200 and 800 ms, plus a constant bias which again took the form of interval underestimation. Thus, available evidence suggests that schizophrenics have a deficit in time perception in the auditory modality that spans intervals in the range from 200 to 6000 ms. There is also some evidence for a constant bias toward perceiving sub-second intervals as shorter than they actually are, although this bias has not always been replicated. However, their temporal bisection with visual stimuli might be spared.

Other time perception tasks have also shown temporal deficits in schizophrenia. When tapping to a rhythm of 2 tones per second and then trying to keep the same rhythm without external guidance, schizophrenics show increased variability and a tendency to shorten the intervals (Carroll et al., 2009b). Patients also show more errors than controls when comparing a subsequent auditory duration (range 310–490 ms) to a prior standard duration (400 ms). Tasks assessing longer intervals, in the range of tens of seconds, have typically asked patients to either stop an interval at a specified duration (say, after 20 s), or to estimate verbally the duration of an interval in seconds. Common findings are: (1) a tendency to overestimate intervals (Tysk, 1983), which runs contrary to the bias toward shorter intervals discussed above; (2) markedly different individual patterns, with some patients being clear underestimators and other overestimators (Tysk, 1984); and (3) a lack of clear differences with healthy controls (e.g., Tracy et al., 1998). Given that these longer intervals are often unfilled, these tasks are open to the use of strategies (mainly, counting) and to the effects of boredom and distraction, and so they may reflect attentional deficits more than proper temporal processing.

In sum, schizophrenic patients seem to display a different pattern from the general population in their performance of spatial and temporal bisection tasks. Whereas in line bisection they sometimes bisect to the left or the right of controls, in temporal bisection they tend to exhibit a poorer discrimination of stimuli. Few studies have tried a temporal bisection with visual stimuli however (they are usually auditory). We are not aware of any previous study that may have tested the same schizophrenic patients on temporal and spatial bisection tasks using the same (visual) modality.

Based on previous findings, reviewed above, we expected schizophrenics to differ from the control group in bias in line bisection, and possibly also in response variability in the temporal bisection tasks. From the common coding hypothesis we would predict that these differences should generalize across domains. If patients differ from the general population in perceptual bias in line bisection (Cavézian et al., 2007; McCourt et al., 2008; Michel et al., 2007; Tian et al., 2011), then according to ATOM a similar pattern should be observed in the temporal tasks. Additionally, if the general population do exhibit a greater acuity in temporal bisection (Carroll et al., 2009a; Elvevåg et al., 2003; Lee et al., 2009; but see Carroll et al., 2008), this should also be observed in the processing of space; and in our experiment, also in the novel aging faces task. Schizophrenia should provide an additional source of variability in the data, and new opportunities for links between concrete and abstract domains to be found. Conversely, low correlations or finding different patterns of performance between tasks in this experiment would add up to the suggestion that the processing of different magnitudes may not be as strongly connected as proposed by ATOM and the common coding hypothesis. The findings of this study have already been published (Martinez-Cascales et al., 2013).

MATERIALS AND METHODS

Participants

Twelve schizophrenic patients (five female, one left hander) and a control group of 12 participants with no previous psychiatric diagnosis (four female, one left hander) gave their consent to participate in this study (see Table 1 for detailed participant information). The two groups were not different in handedness, age ($t(22) = 1.57$, $p = .26$, $B = 0.61$) and educational level ($t(22) = -0.42$, $p = .68$, $B = 0.4$). Both groups had zero experience in participating in psychology experiments or taking computerized tests, and they all had very low experience with computers in general. Participants received a small gift for their cooperation. All participants in the schizophrenic group were outpatients who met the DSM-IV criteria for schizophrenia, were clinically stable, and were taking medication at the time of the study.

For each patient, three severity indexes were considered in the following analyses. The first was the Global Assessment of Functioning (GAF), presented and described in the DSM-IV-TR (American Psychiatric Association, 2000), which ranges from 1 to 100 (being 100 the best functioning individuals). Because all patients had very similar GAF assessments, we used two additional severity indexes. The second index consisted on a ranking (from 1 to 12) of the patients from the less severe to the most severe case. This ranking was made by a colleague (Julio Santiago Sr.), an experienced psychiatrist who had treated all of the patients in this study since the inception of their illness (in all cases over many years). The judge was asked to rank all patients depending on their severity, taking into account the severity of the schizophrenic symptoms, degree of cognitive deterioration, family support and ability to adapt in society (as we wanted to capture the overall impression of severity from a specialist who deeply knows each case in all its dimensions, no specific weighting of these factors was suggested, and it is possible that they were weighted differently in different cases). These are all factors that the GAF takes into account, but this index (which we will call the Severity Ranking henceforth) allowed us to make finer distinctions within the group of patients. Crucially, the ranking was made without knowledge of the individual results of the patients in the experimental tasks.

A final index, the Chlorpromazine Index, was based on the doses of neuroleptic medication being administered to each patient at the moment of the study. In order to convert the different drugs to a common scale, neuroleptic doses were converted to Chlorpromazine equivalents, and when the prescription included more than one neuroleptic, their Chlorpromazine equivalents were added up (see Table 1 for details and references). The Chlorpromazine Index is a rough proxy to severity, because different neuroleptics (especially since the introduction of atypical neuroleptics) vary in their affinities for different receptors, each receptor mediating different cognitive functions, and therefore, their effects do not line up along a single dimension. However, it is still widely used in clinical research on schizophrenia. For the sake of data analysis we assigned the control participants a score of 90 in GAF, 0 in the Severity Ranking, and 0 in the Chlorpromazine Index.

Tasks

We used the same three tasks as in Experiment 1: Line Bisection, Standard Time Bisection and Aging Faces temporal bisection. The number of trials in Standard Time Bisection was reduced in order to make it easier for schizophrenic participants to keep a steady level of attention throughout the experiment. In this version of the task, after 20 trials of practice with the anchors, each level of duration (1000, 1500, 2000, 2500, 3000, 3500, and 4000 ms) was presented 12 times, totalling 84 trials.

Procedure

Participants were tested individually. The three tasks were presented sequentially, always in the same order, with a break after each one. The pace of all tasks was adapted to each participant. Most participants (11 patients and 9 controls) did the experiment in two sessions separated by at least 24 h. The first task was Aging Faces, followed by Line Bisection if the participant was willing to continue. The second session consisted of the Standard Time Bisection task followed by Line Bisection if it had not been done previously. Participants who finished the experiment in a single session did Aging Faces first, followed by the Standard Time Bisection, and finally Line Bisection. Both temporal tasks were therefore kept apart for most participants, and the spatial task was always presented last in a session, in order to prevent a preactivation of the spatial dimension in the temporal tasks.

Table 1. Demographic and clinical variables of participants in Experiment 2.

Group	Gender	Age	Hand.	Educ.	DSM IV	DSM IV code	Severity Rank	GAF	Chl. Equiv.	Medication
Control	Female	36	Right	13		-	-	-		-
Control	Male	22	Right	12		-	-	-		-
Control	Male	40	Right	8		-	-	-		-
Control	Male	27	Right	8		-	-	-		-
Control	Female	35	Right	13		-	-	-		-
Control	Male	30	Left	12		-	-	-		-
Control	Female	43	Right	12		-	-	-		-
Control	Male	31	Right	8		-	-	-		-
Control	Male	40	Right	8		-	-	-		-
Control	Male	45	Right	8		-	-	-		-
Control	Male	28	Right	9		-	-	-		-
Control	Female	25	Right	9		-	-	-		-
Patient	Female	36	Right	12	Schizophrenia-paranoid	295.30	12	50	861	Paliperidone, Ziprasidone, Risperidone
Patient	Female	32	Right	8	Schizophrenia-paranoid	295.30	7	42	100	Topiramate, Levomepromazine maleato
Patient	Male	25	Right	6	Schizophrenia-paranoid, mental retardation	295.30, 317	11	44	1033	Paliperidone, Amisulpride, Levomepromazine maleato
Patient	Male	30	Right	5	Schizophrenia-paranoid	295.30	10	46	700	Amisulpride, Levomperomazine maleato

(Table 1 cont)

Group	Gender	Age	Hand.	Educ.	DSM IV	DSM IV code	Severity Rank	GAF	Chl. Equiv.	Medication
Patient	Male	45	Right	12	Schizophrenia-paranoid	295.30	5	52	456	Zuclopenthixol decanoate, Ziprasidone
Patient	Male	48	Right	7	Schizophrenia-paranoid	295.30	6	50	220	Paliperidone
Patient	Male	45	Right	8	Schizophrenia-paranoid	295.30	9	36	596	Risperidone, Fluphenazine decanoate
Patient	Female	38	Right	12	Schizoafective disorder	295.70	3	52	0	Lithium carbonate, Escitalopram oxalate
Patient	Female	33	Left	12	Schizophrenia-disorganized	295.10	4	44	775	Quetiapine fumarate, Ziprasidone
Patient	Male	39	Right	11	Schizophrenia-paranoid	295.30	1	50	376	Ziprasidone, Clozapine
Patient	Female	31	Right	10	Schizoafective disorder	295.70	8	48	800	Clotiapine, Clonazepam
Patient	Male	41	Right	12	Schizophrenia-paranoid	295.30	2	56	1067	Clozapine, Amisulpride, Aripripazole

Education level is coded as number of schooling years since age 6. For each patient, the following information is presented: (1) DSM-IV diagnosis; (2) the Severity Rank (see description in main text); (3) the Global Assessment of Functioning (GAF; DSM-IV-TR, A.P.A., 2000); (4) Chlorpromazine equivalents for the medication and dosage of each patient.; and (5) Medication, in DCI names. The following conversion rates were used (in mgr/day equivalents to a dosis of 100 mgr/day of chlorpromazine): Amisulpride (100)[a], Aripripazole(7.5)[a], Clotiapine (10)[b], Clozapine (100)[a], Fluphenazine decanoate (2)[c] , Levomepromazine maleato (100)[a], Paliperidone (1.5)[d] , Quetiapine fumarate (77)[a], Risperidone (1.5)[a], Ziprasidone (62.5)[a], Zuclopenthixol decanoate (14.3)[a]. The superscript in each drug refers to the source where equivalent doses were obtained from: (a) Kroken et al. (2009); (b) Tibaldi et al. (1997); (c) Atkins et al. (1997); (d) Woods (2011).

RESULTS

Most of the variables measured in this experiment followed a normal distribution, but some of them did not. This is not entirely surprising giving the relatively small sample sizes that we worked with. Deviations from normality were checked with the Shapiro-Wilk test. All variables related to Line Bisection and the bias in the Standard Time Bisection task did pass the criterion of normality. Response variability in the Standard Time Bisection did not adjust to normality in the group of schizophrenic patients as well as pooling all participants together. The Aging Faces task did not fit a normal distribution in the bias and response variability of the control group. Grouping all participants together, response variability in Aging Faces did not fit a normal distribution either (in all these cases, $W \leq .903$, $p \leq .033$). Comparisons involving indexes that did not fit to a normal distribution were carried out using non-parametric alternatives: t-tests were replaced with the Mann-Whitney U when comparing groups, and with the Sign Test when comparing against a fixed value. Pearson's r were replaced with Spearman's rho (r_s) for correlations.

Two-tailed t-tests showed no deviation from the actual midpoint in Line Bisection and standard Time Bisection in either group (in all cases, $p > .22$, $0.29 < B < 0.6$). Here we did not find the pseudoneglect reported in Experiment 1 in Line Bisection neither in controls nor patients. However, the B factor suggests that the data are still inconclusive. In the Aging Faces task we again found a significant bias toward the “end” side of the time interval, but only in the control group ($Z(11) = 3.175$, $p = .002$, $B = 244$); whereas we did not find a significant bias in the schizophrenic group ($t(11) = 1.73$, $p = .11$, $B = 0.91$). Importantly, the difference in bias in this task (Aging Faces) between both groups was significant ($U(22) = 111$, $p = .024$, $B = 2.30$) (Figure 3). Thus, taking into account the limitations due to the small sample sizes, it can safely be concluded that schizophrenic patients showed a smaller bias in the Aging Faces task, whereas control participants produced a greater proportion of “beginning” responses, leading to a displacement of the subjective middle towards the end of the interval. This difference cannot be due to age, educational level, familiarity with computers or computerized testing, as both groups were matched in these variables.

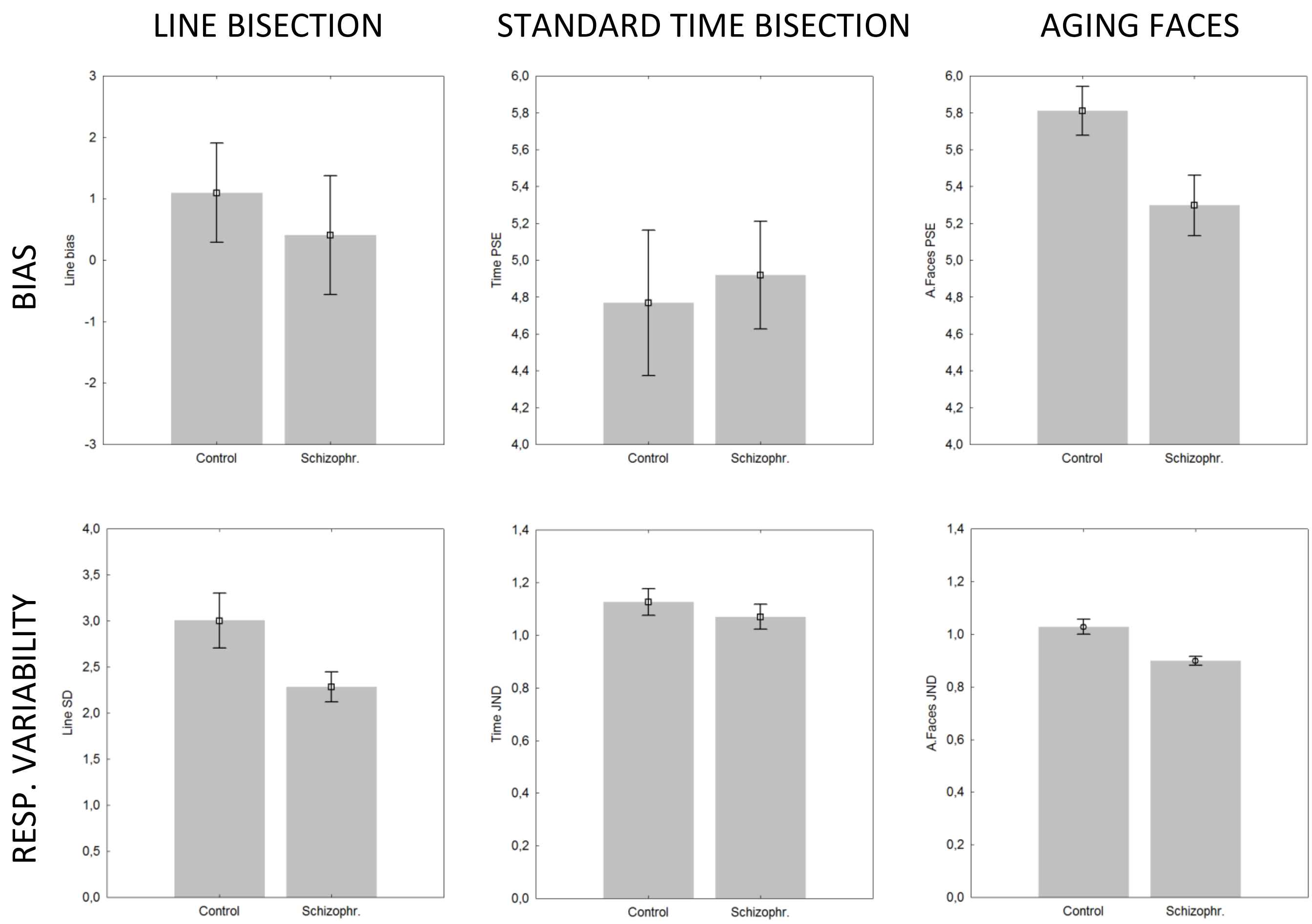

Figure 3. Bias and precision indexes in one spatial (Line Bisection) and two temporal (Standard Time Bisection and Aging Faces Bisection) tasks.

Bias (constant error) and precision (standard deviation) in Line Bisection are expressed in millimetres. Bias (PSE) and precision (JND) in both the Standard Time Bisection and the Aging Faces tasks are expressed in arbitrary units from 0 to 10 where 0 is the beginning and 10 the end of the stimulus. Error bars represent standard error of the mean.

As discussed in Experiment 1, one possible explanation for the end bias in the Aging Faces task is that participants are estimating a vital midpoint, that is, the midpoint of the life of the depicted person, instead of the midpoint of the duration of the video clip. Assuming that the estimation of someone’s vital mid-point is linked to the perceiver’s own estimated vital midpoint, and assuming that people tend to think that they are still in the first half of their lives (and thus that they are still young), a prediction from this account is that the subjective vital midpoint should be affected by the age of the participant: older participants should show a greater end bias. Put in other words, older participants should judge people of more advanced age as still closer to the beginning than to the end of their lives.

In order to test this prediction, we pooled together the healthy control group in Experiment 2 (mean age 33.5 years) and the younger healthy participants in Experiment 1 (mean age 23.8 years), and calculated the correlation between participants' age and their PSE in the Aging Faces task. We found no trace of significance between age and bias in Aging Faces (r_s = .112, *p* = .51, *B* = 0.23). Looking only at schizophrenic patients, the correlation between PSE and age was also close to null (r_s = 0.10, *p* = .77, *B* = 0.35). In other words, older participants did not estimate that the midpoint of an aging sequence is farther along the life. Therefore, the data do not support the suggestion that participants are estimating a vital midpoint in the Aging Faces task instead of the actual midpoint of the temporal interval comprised by the beginning and end of the video clip.

In any case, it must be emphasized that whatever is causing the bias toward the end of the clip in the healthy groups, the fact still remains of a smaller bias in the schizophrenic group when compared to a properly matched control group. In other words, schizophrenics are not affected by whatever factor is biasing the constant error of healthy controls.

Additionally, control and schizophrenic groups also differed in the precision of their performance, marginally in Line Bisection (*t*(22) = 0.52, *p* = .057, *B* = 1.52) and clearly in Aging Faces (*U* = 15, *p* = .001, *B* = 23.9). Surprisingly, schizophrenic patients were more precise than matched healthy controls in both tasks. In contrast, the Standard Time Bisection task did not reveal any difference between groups (*U* = 86.5, *p* = .42, *B* = 0.46; see Figure 3). Figure 4 compares the cumulative curve from each group in the Aging Faces task.

To sum up, schizophrenic patients showed a smaller bias in the Aging Faces task, in contrast to the significant end bias shown by controls. They also showed greater precision in both Line Bisection and Aging Faces, but not in the standard Time Bisection.

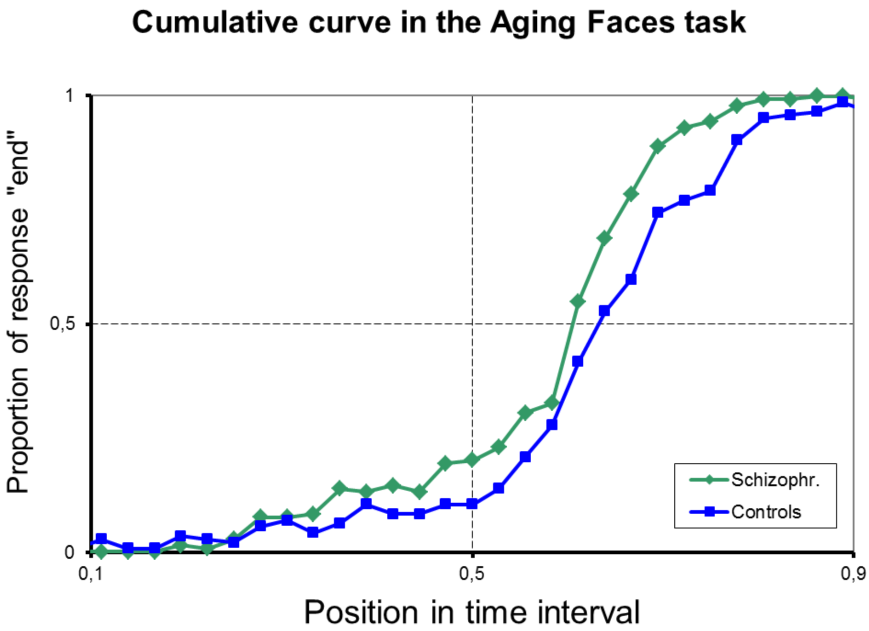

Figure 4. Proportion of trials with "end" response as a function of temporal position in the video clip in the Aging Faces task in Experiment 2 (healthy participants and schizophrenic patients).

Results from cross-group comparisons are further supported by correlation analyses with severity of schizophrenia. When data from the whole set of participants were used, three performance indexes correlated significantly to the Severity Ranking: precision in Line Bisection (r = −0.51, p = .01, B = 5.51), and both bias and precision in Aging Faces (bias: r = −0.56, p = .005, B = 11.09; precision: r = −0.42, p = .04, B = 1.91). The Chlorpromazine Index also correlated significantly with precision in Line Bisection (r = −0.50, p = .014, B = 4.43), and both bias and precision in Aging Faces (bias: r = −0.61, p = .002, B = 28.75; precision: r = −0.54, p = .007, B = 8.14). These results support the finding of greater precision in both space and one temporal task (Aging Faces) in the schizophrenic group that were revealed by cross-group comparisons. The GAF index of severity was less sensitive (as expected from its smaller variability within the schizophrenic group) and only correlated significantly to precision in Aging Faces (r = 0.62, p = .001, B = 31.8). When only data from the schizophrenic group were used, reducing sample size to half, the correlations between both the Severity Ranking (r = −0.74, p = .006, B = 9.74) and the Chlorpromazine Index (r = −0.68, p = .016, B = 4.85) to precision in Line Bisection remained significant. Moreover, the Chlorpromazine Index also correlated significantly with bias in the Aging Faces task (r = −0.61, p = .035, B = 2.58).

Correlations with severity of schizophrenia should be taken only as additional supportive evidence for the main results, revealed by cross-group comparisons. Their utility is limited, first, by the small sample size and the small variability in severity, as all cases were quite severe cases. Secondly, the two most sensitive indexes of severity (the Severity Ranking and the Chlorpromazine Index) suffer from potential problems. The Severity Ranking is based on the opinion of a single (though highly expert) judge. Because these ratings were made blind to the performance of the patients in the experimental tasks, the expectations of the judge are unlikely to have introduced any bias in the results, but ideally these ratings should have been obtained from at least two independent judges and their agreement computed. Unfortunately, it was not possible to have a second expert judge. In turn, the Chlorpromazine Index is based on a blend into a single scale of the affinities of different neuroleptic drugs for different receptors in the brain, which in turn mediate a variety of cognitive functions. With these cautions in mind, correlations of the performance indexes in one spatial and two temporal bisection tasks with the three indexes of severity (GAF, Severity Ranking, and Chlorpromazine Index) supported the main findings of the cross-group comparisons: Schizophrenic patients showed greater precision than matched controls in both Line Bisection and Aging Faces, as well as a smaller bias in Aging Faces.

In order to test whether there is a common system underlying the processing of different magnitudes, we analysed the correlations between the indexes in spatial and temporal tasks, first for bias and then for response variability. There were no significant correlations between the bias indexes in the three tasks. Regarding response variability, we found a possible correlation between Line Bisection and Aging Faces, indicated by the B Factor but not the p-value of the Spearman's rho (r_s = 0.32, p = .127, B = 3.98), but only pooling all participants together. When both groups were analysed separately we found no evidence of correlation between tasks neither in bias nor in response variability.

Pooling together the total set of participants in Experiments 1 and 2, we found only one significant correlation: again, response variability in Line Bisection covaried with response variability in Aging Faces (r_s = 0.36, p = .012, B = 5.82). All other correlations (both in bias and precision) were non-significant (in all cases, p > .14, B < 0.31). The B factors in all comparisons of bias measurements were below 0.25 (in all cases, B < 0.225), indicating a strong support against a covariation in bias between any two tasks. Regarding response variability, there lack of correlation between Line Bisection and Standard Time Bisection was also supported by the low B factor (r_s = -0.15, p = .29, B = 0.22).

To summarize, we found a positive correlation between the response variability in Line Bisection and Aging Faces grouping all participants together. This was not significant analysing both groups separately, but that may be due to the smaller sample sizes. This idea is supported by the finding that pooling together participants in experiments 1 and 2 the Bayes factor of this correlation increased from 3.98 to 5.82. In almost all other comparisons (all bias indexes and response variability in Line Bisection and Standard Time Bisection) we found support against a covariation between indexes. Thus, most of our results line against a common coding of magnitude. However, the correlation in response variability between Line Bisection and Aging Faces was consistent and needs to be considered.

DISCUSSION

In this second experiment we did not find pseudoneglect in Line Bisection, neither in the control nor schizophrenic groups. This is a difference from Experiment 1. We did find, as in the previous experiment, a bias toward the "end" side of the time interval in the Aging Faces task, but only in controls. Schizophrenic patients showed no significant bias, but the B factor indicated that the evidence for a null bias was not conclusive enough, so we interpret the data as supporting that the bias in schizophrenic patients is smaller than in controls. Additionally, the end bias in the Aging Faces task in controls (Experiment 2) and the general population (Experiment 1) did not correlate with participants' age. It is possible that a sample with a greater age range may show a significant effect of age on this bias, but present data do not support this link, and therefore neither they support the possibility that participants are bisecting a life-long vital interval instead of the clip duration. Further research is necessary to clarify the source of this bias in the two healthy groups. Whatever the cause, there remains the fact that schizophrenic patients bisected temporal intervals in the Aging Faces task closer to the actual centre than properly matched controls.

Regarding response variability, we found marginally significant group differences in Line Bisection, leaning towards higher acuity in patients. We also found compelling evidence that schizophrenic patients showed greater precision than matched controls in the temporal Aging Faces task, suggesting an interaction between schizophrenia and time that was however not observed in Standard Time Bisection. In the Aging Faces task, test faces are chosen from the video clip and presented in random order to be judged regarding their proximity to the beginning or the end of the clip. The task is demanding and the fact that patients are performing with greater temporal acuity than controls, instead of showing a decrement in performance, argues against any deficit of a general nature that could affect cognitive processing across the board. They also argue against the possibility that patients' performance is a result of medication, as medication should theoretically produce deficits in performance. Moreover, the specific link between schizophrenia and space (Line Bisection) and schizophrenia and time (Aging Faces) was supported by correlation analyses, which showed that in patients with higher severity and dosage some of the indexes of performance improved. This contrasts with most prior reports regarding space and time bisection in schizophrenics, reviewed above (e.g., Barnett, 2006; Carroll et al., 2008, 2009a; Cavézian et al., 2007; Elvevåg et al., 2003; Michel et al., 2007). We have no ready explanation for this contrast. It is possible that some factor interacts with schizophrenia in a way that either harms (in some conditions) or favours (in other conditions) spatial and temporal processing. Such factor remains to be identified.

The superior performance of patients in Aging Faces seems to be genuinely not due to motivational factors, because if this were the case, then we would expect a similar trend in other tasks. However, we believe that more attention should be paid to the psychological state of patients while they are participating in an experiment. This is difficult to quantify, however the benefits to have such a record could help in the interpretation of results with psychiatric and neuropsychological patients in general.

We have found no previous reports of greater precision (reduced variable error) in bisection tasks in the literature on schizophrenia. Prior studies did not report variability in Line Bisection, so the present finding may have gone unnoticed. Regarding temporal tasks, prior studies most often showed worse precision (increased variable error) in schizophrenic patients (Allman & Meck, 2012). Moreover, extant evidence shows that schizophrenics do not always differ from controls in bias (constant error) in temporal tasks, but when they do, they usually show a stronger, instead of a reduced bias. Although the present findings are clear, the relatively small sample size in the patient and matched control groups suggest that they should be taken with caution and point to the need of additional research.

One limitation of the present study is the lack of an assessment of executive functions, as it has been shown that these functions are often deficitary in schizophrenia (see Orellana & Slachevsky, 2013, for a review). Moreover, there is independent evidence that the same brain structures that mediate executive functions play important roles in temporal cognition (Lewis & Miall, 2006). However, an executive deficit would predict worse performance in the schizophrenic group, contrary to present findings. Present results look more in line with published observations from a different clinical group, Tourette's syndrome. Patients with Tourette's syndrome are affected by uncontrollable tics, at least partially as a result of deranged activity in the dopamine-mediated circuit linking the basal ganglia and frontal lobes (McNaught & Mink, 2011). Paradoxically, Tourette's patients have shown better performance than healthy controls in cognitive control tasks (Jackson et al., 2007), and also in temporal reproduction tasks (Vicario et al., 2010). However, it would be premature to claim any clear relation between alterations in this neural substrate and improved temporal processing, as the evidence is still scant and the pattern complex (e.g., Vicario et al., 2010, reported better performance only in temporal reproduction task, but not in temporal discrimination, and only in intervals in the supra-second range).

Although present data are based on a relatively small sample size, they add to the evidence provided by Elvevåg et al. (2004), which is to our knowledge the only published study that has tested the processing of space and time in the same group of patients. These authors used absolute identification tasks, in which a series of stimuli (seven in their study) are presented and the participant learns to identify each one by means of a number corresponding to its location in the overall sequence (e.g., "this is tone number five"). Schizophrenic patients in their study showed a deficit in identifying the duration of tones (ranging from 333 to 2333 ms) and also in identifying letters within letter sequences (which is arguably a skill related to time processing). However, their discrimination of line lengths was unaffected, providing evidence for a dissociation between the magnitudes of space and time in schizophrenia. In the present study we found a somewhat different pattern of response between tasks: both groups performed very differently in the Aging Faces task, presented a marginally different acuity in Line Bisection but not a different bias, and we found no significant differences in the Standard Time Bisection. Related evidence not supporting a common coding of space and a different magnitude, number, in schizophrenia has been offered by Tian et al. (2011): their patient group showed a leftwards bias in line bisection but no bias in number bisection.

Finally, and centrally for the predictions of the common coding hypothesis, when all participants in Experiment 2 were pooled together, we found substantial evidence for correlation between response variability in Line Bisection and Aging Faces, as indexed by a B factor which approached 4 (however, the p-value was non-significant). When the sample was further expanded by including the participants in Experiment 1, this correlation increased both in terms of the B factor and the p-value, which reached significance. In all other cases (except the response variability between both temporal tasks, which was not conclusive) the B factor indicates a lack of correlation between tasks. Regarding the common coding hypothesis, these results provide a mixed picture. The correlations between spatial and temporal tasks may depend on the type of task used. So, we conclude, as well as in Experiment 1, that the evidence in support of a common coding of magnitude in the brain is weak at best. The overall implications of these findings are taken up in the general discussion, in Chapter IV.

Recruiting schizophrenic patients for a study in cognition poses some difficulties and thus our relatively small sample size. It does not seem likely that a larger sample in this second experiment would have produced markedly different results, since the B factors most relevant for our hypotheses are in most cases large enough to draw clear conclusions. However, undoubtedly the experiment would have benefited from a larger data set.

After the lack of substantial support for ATOM and the common coding hypothesis from Experiments 1 and 2, we looked for such evidence where it should arguably be easiest to find: in neglect patients.

3. Experiment 3: bisection with neglect patients

Experiments 1 and 2 allowed to characterize the bias and precision of the general population in various bisection tasks, and to compare schizophrenic patients with a control group in these tasks. Our main goal was to compare the performance between dimensions to assess whether there could be evidence of a common system behind concrete and abstract processing. Results in both experiments were not in line with the predictions of a common coding of magnitude, as only a few of the predicted correlations between tasks were found in response variability, and never in bias. However, it can be also argued that the effect of pseudoneglect, despite being known for decades and thoroughly described in several meta-analyses, is not strong enough to capture the covariation between magnitudes. In order to test this claim we decided to test neglect patients, a population where the spatial bias should be quite large, and compare their performance in different bisection tasks.

Hemispatial neglect produces a characteristic lack of awareness on one side of space. A typical case are patients who ignore stimuli on their left visual field after a severe stroke affecting the right parietal lobe. These patients are reported to exhibit a particularly large bias in the line bisection task (e.g., Harvey et al., 1995), as it could be expected if one tries to mark the middle of a line having no awareness of a large portion of it. In fact, line bisection is one of the diagnostic tools that can be used to identify this condition (e.g., Ferber & Karnath, 2001) and therefore in recent years there are practically no research efforts to prove that these patients differ from the general population in line bisection (see for example Harvey et al., 1995, for an earlier example). They are however a prime case to study the relations between magnitudes.

Oliveri et al. (2009) studied the performance of neglect patients and a control group in temporal tasks, including time bisection, finding that patients' temporal bisection supported the representation of time along a horizontal axis, a mental time line. They also observed wider response variability in patients than in controls. Saj et al. (2014), and later on Bonato, Saj and Vuilleumier (2016), tested neglect patients in temporal memory tasks, concluding in both cases that their results suggested a spatial representation of time, as the spatial bias of neglect patients seemed to permeate to the performance in the temporal task. On a similar trend, Calabria et al. (2011) found that neglect patients performed worse than a control group in a temporal comparison task, supporting the claim that their spatial impairment had also extended to temporal perception.

It is however the representation of numbers where the spatial bias in neglect patients has been more extensively studied. Several works have not only provided evidence that neglect patients differ from the general population in number bisection, but also offered compelling evidence that the behaviour of neglect patients in line bisection and number bisection supports a spatial representation of numbers or a common representational ground (Umiltà, Priftis & Zorzi, 2009; Zorzi et al., 2006, 2012; Zorzi, Priftis & Umiltà, 2002). In words by Umiltà et al. (2009),

> *"(...) neuropsychological studies have offered convincing evidence that humans indeed represent numbers on a mental number line oriented from left to right. Neglect patients systematically misplace the midpoint of a numerical interval they are asked to bisect (e.g., they say that <5> is halfway between <2> and <6>) and their mistakes closely resemble the typical pattern found in bisection of true visual lines."* (p. 561)

Evidence against this claim has also been provided though. According to van Dijck et al. (2011), referring to these patients, "consistent double dissociations between defective processing of the left side of physical and mental number space have called into question the universality of this interpretation" (p. 2570). From this perspective alternative explanations have been proposed, like the influence of defective memory functions or the decade to which a number interval belongs (Aiello, Merola & Doricchi, 2012; Doricci et al., 2005; Rossetti et al., 2011; van Dijck et al., 2011).

In conclusion, neglect patients offer a unique opportunity to test the relationship between magnitudes, in the sense that they exhibit a clear spatial bias. There is considerable evidence of similar biases in the domains of time and number, but there is also evidence of dissociations between magnitudes in these patients. As far as we know, however, there has not been a study measuring performance in spatial, temporal and numerical tasks in the same patients to test out these predictions.

Given the very characteristic features of neglect patients we decided to potentiate the assessment of spatial abilities by including yet another version of line bisection in this third experiment. In Experiments 1 and 2 participants had to mark the centre of the line, that is, they had to produce the middle point. In this experiment, we also used a task where the participant sees lines with a mark already on them and are asked to judge if the mark is closer to the left or the right end of the line. We decided to add this task since production and judgment may tap on the same spatial representations by means of different processes, so we would have a more sensitive test of spatial processing.

In this experiment we also added a number bisection task (described below) to explore the dimension of numerical magnitude and compare it with space and time. As previously mentioned, it is relatively well established that these patients clearly differ from the general population in this task. On the flip side, we did not use Aging Faces here. The high attentional demands of this task made it unadvisable to be used with our participants in this experiment: neuropsychological patients, most of which survivors of a severe stroke or other brain injuries, and older than the participants in the prior two experiments.

This third and last experiment of the series compared a population of neglect patients with a matched control group. We expected neglect patients to show a large bias in line bisection, and in general clear differences in bias between groups. If there is a common coding system for all magnitudes, then bisections of temporal and numerical intervals should also display a bias similar to line bisection in our patients. In the control group (neuropsychological patients without hemispatial neglect) we did not expect a bias comparable to neglect patients in line bisection, and consequently neither in temporal nor numerical bisection. Perceptual acuity should also have similarities across tasks within participants.

MATERIALS AND METHODS

Participants

Ten neglect patients with different degrees of severity and five control participants (neuropsychological patients without neglect symptoms) matched in age, handedness and experience with psychology experiments took part in this experiment. All of them were regular collaborators of the University of Birmingham (U.K.). One of the patients was removed from data analysis due to his highly erratic responses in different tasks, which suggested an insufficient understanding of the instructions or very low sustained attention. Testing took place in the School of Psychology of this university. Table 2 shows their demographic information and the lesion side and severity for neglect patients. Severity was measured with the Apples Test (Bickerton et al., 2011): participants are presented a sheet of paper with 50 apples drawn on it; some of them are full, others lack the left half and others the right half (Figure 5), and participants have to identify the incomplete apples. The severity index is given as percentage of incomplete apples missed.

Table 2. Demographic and neuropsychological information of participants in Experiment 3.

Group	Gender	Age	Handedness	Apples Test	Lesion side
Control	male	76	right	0	
Control	male	40	right	0	left
Control	male	60	right	2	
Control	male	68	right	0	
Control	male	40	right	0	
Neglect	female	63	right	6	left
Neglect	male	53	right	8	right
Neglect	male	77	right	6	left
Neglect	male	65	left	8	
Neglect	male	53	right	6	
Neglect	female	73	right	14	bilateral
Neglect	male	55	right	12	bilateral
Neglect	male	62	right	10	
Neglect	male	74	right	52	right

The score of the Apples Test provided is the percentage of apples missed, as described in the text.

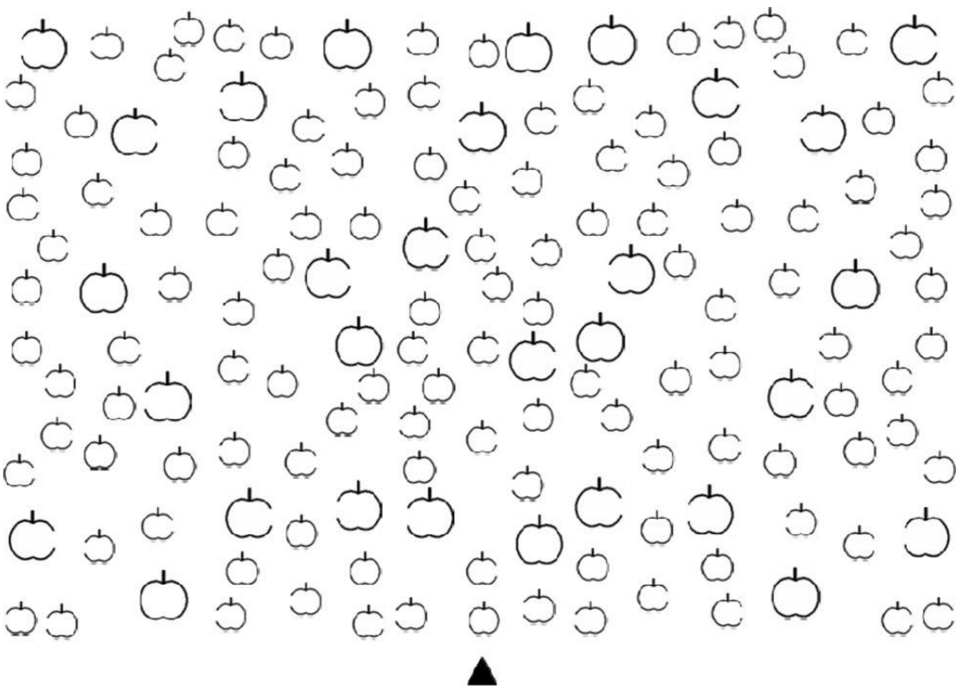

Figure 5. The Apple Cancellation sheet (Apples Test) (Bickerton et al., 2011; Figure 1)

Tasks

- Line Bisection

The standard line bisection was administered as in Experiments 1 and 2. Twenty four sheets with a line printed in the middle were provided one by one, and participants had to mark the estimated centre with a pen.

- Landmarks

The new spatial bisection task, that we will refer to as the Landmarks task, was a computer based exercise that consisted on the presentation of a line centred in the middle of a 15 inch screen (length 25.6 degrees of visual angle (dva), width 0.2 dva) with a mark near the centre. There were 12 possible locations for this mark, six on each side of the middle, following a logarithmic scale (see Figure 6). We used a logarithmic scale in order to be able to capture the whole range of potential responses without having an excessive amount of experimental conditions. The mark locations were 0.05, 0.25, 0.55, 0.9, 1.4 and 2.05 degrees of visual angle to the left and to the right of the centre of the line. Each of these locations appeared 10 times, totalling 120 stimuli that were randomly presented using Eprime 2.0 software. Responses were given orally and registered by the experimenter out of the participant's sight in order to prevent any spatial activation generated by the action of responding.

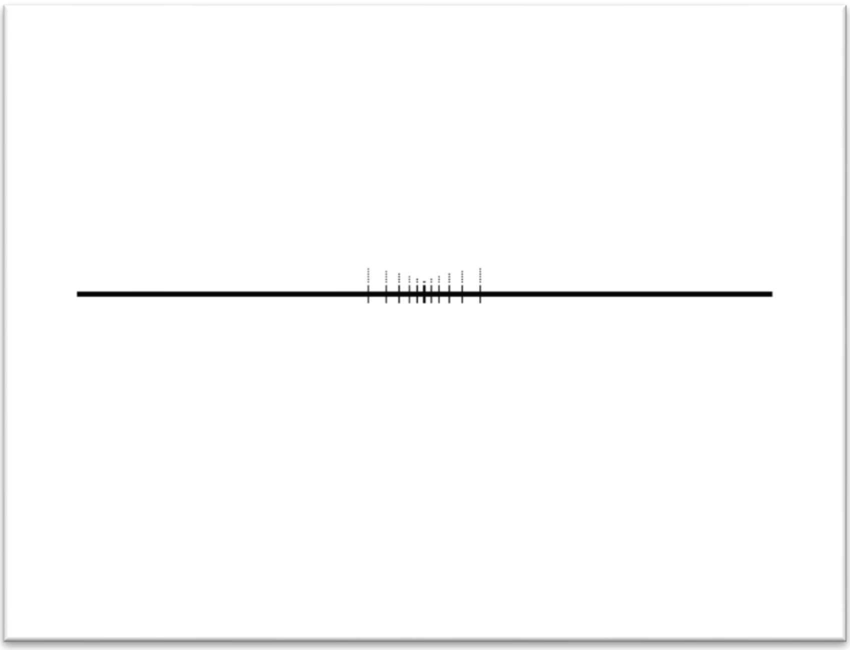

Figure 6. Possible locations of the probe mark in the Landmarks task.

- Standard Time Bisection

The standard temporal bisection task was almost identical to that described in Experiment 2. The only modification was that we reduced the number of practice trials from 20 to 12 to adapt to the higher tiredness experienced by many of these patients. A minimum of 90% accuracy in these trials was required to start the experiment.

- Number Bisection

The numerical bisection consisted on the presentation of three numbers in the screen (font Times New Roman, size 46, approx. 3 dva). Two of them were situated on the left and right side of the screen, representing the two ends of a numerical interval. The third number was centred in the screen, equidistant from the other two. The distance between numbers was around 3.9 dva. Participants had to estimate to which end of the interval the central number was closer in value. For example, if the number on the left was 21, the one on the right was 48 and the middle one was 29, the correct answer would be "it is closer to 21".

This task was therefore in essence similar to the landmarks task, but instead of having a mark in a line that had to be judged we presented a number whose position in a numerical interval had to be judged. Three independent variables were manipulated. One was the size of the interval (the difference between the upper and lower limit), which could be either 27 or 53. A second variable was the location of the upper and lower limits of the interval: in half of the trials the lower limit was on the left and in the other half it was on the right. And third, the number in the centre could be in one of 6 possible numerical positions relative to the centre of the interval, following again a log scale: [-8,5], [-2,5], [-0,5], [0,5], [2,5] and [8,5]. Each of the resulting four conditions included 30 trials, totalling 120 trials that were presented randomly. Once again, responses were given orally and registered by the experimenter out of the participant's sight in order to prevent any spatial activation generated by the action of responding.

Procedure

Participants were tested individually. They required between one and three sessions to complete all four tasks. Line bisection tasks were always administered last in a session in order to avoid any spatial preactivation that could affect other dimensions. When time and number bisection were administered in the same session, time was first since stimuli in this task are centred and symmetrical in the screen and therefore should not produce any lateral bias that could affect other tasks.

RESULTS

Given the relatively low number of participants, which is often the case in studies with neuropsychological patients, it would not be surprising that some variables would not follow a normal distribution. Deviations from normality were checked with the Shapiro-Wilk test. In the group of neglect patients, only response variability in Number Bisection deviated from normality (W = 0.81, p = .026). In the control group this was the case for variability in Line Bisection (W = 0.77, p = .047). Taking both groups together we should expect a higher deviation from normality since both groups presumably perform differently in bisection tasks. In this case three variables were not normally distributed, but none of them was a bias index: response variability in Line Bisection, Standard Time Bisection and Number Bisection (overall, $W \leq 0.839$, $p \leq .016$). Non parametrical alternatives were used to analyse our results when needed. T-tests were replaced with the Mann-Whitney U when comparing groups, and the Sign Test when comparing against a fixed value. Pearson's r was replaced with Spearman's rho (r_s) for correlations.

The next step in the analysis was to confirm that neglect patients do exhibit the expected biases in spatial perception and production. Against our expectations, we did not find a significant deviation from the midpoint in any of the tasks. This was the case also for the control group (in all cases, $p > .13$, $0.32 < B < 0.9$). A possible confound of this test can be that the bias in neglect patients can be either leftwards or rightwards (depending in part on the side of the lesion), and large values on both sides could make the test inconclusive. Using the absolute value of the bias could be a way to bypass this. However, it would be problematic as it could introduce a new confound, namely an inflation of the bias when considering the measure at the group level. In the control group participants may perform with leftwards, rightwards or no bias, and the group average would indicate whether they exhibit pseudoneglect as a whole. Using absolute values would make positive and negative biases to be added, artificially inflating the group bias. In order to avoid these problems, we compared the bias in absolute value between both groups. We found no significant differences in bias between both groups neither in Line Bisection nor in Landmarks (overall, $p > .41$, $0.5 < B < 0.6$). Note however that our data do not allow suggesting that both groups performed with a similar bias. The small sample size in this experiment may be the reason for this result. Figure 7 shows the performance of each group (patients and controls) in all bisection tasks.

We found a similar scenario regarding the Standard Time bisection and Number Bisection tasks: no conclusive evidence of bias in any group or grouping all participants. This was true also for each of the conditions of the Number Bisection task: all data, only when the small anchor was on the left, only when it was on the right, only with small interval, only big interval, and the four conditions that result from combining the position of the anchors and interval size (overall, $p > .21$, $0.27 < B < 0.9$). Comparing the absolute value of the bias in temporal and numerical bisection (and all conditions within Number Bisection) also did not produce a conclusive result (in all cases, $p > .31$, $0.46 < B < 0.98$). In the Number Bisection task we found a marginally significant effect of anchor position, but only grouping all participants together ($p = .054$, $B = 1.48$). We found no effect of interval size (overall, $p > .24$, $0.3 < B < 0.61$). Regarding response variability, the only significant difference between both groups was found in the measure of precision in the Landmarks task, where controls exhibited a higher level of accuracy in their estimations ($t(12) = -2.63$, $p = .022$, $B = 3.02$; in all other variables, $p > .1$, $0.46 < B < 1.2$).

Thus, in Experiment 3 we did not find a significant deviation from the midpoint in any of the tasks, neither in controls nor in neglect patients. The same was found grouping all participants together. Also the bias exhibited by neglect patients in all four bisection tasks was not statistically different from controls. However, as the B factors just reported indicate, we cannot suggest that both groups performed similarly either. As we can observe in Figure 7, the average bias in the temporal and numerical bisection was more rightwards for neglect patients. There is a possibility that actual differences were masked by the dispersion of data, and with more participants or people more similar in damage within groups significant differences in bias could have been found.

Only one variable correlated with the severity of symptoms in the neglect group, the standard deviation in the Line Bisection task ($r = 0.79$, $p = 0.012$, $B = 6.1$). Obviously no correlations of this kind were found in the control group, as their severity was insignificant. However, pooling together both groups, and therefore with a wider variety of severity-related information, a trend was apparent in both the bias and response variability in the Landmarks task. As severity increases, the bias tends to go leftwards ($r = -0.54$, $p = 0.045$, $B = 2.06$) and response variability increases ($r = 0.56$, $p = 0.038$, $B = 2.34$). This leftwards tendency contradicts the generally expected directionality of the bias. A meticulous observation of our data revealed that the patients exhibiting the largest severity of neglect also showed the largest bias, bisecting to the left of the midpoint. This finding is not surprising as the direction of the bias is not a homogeneous trait in neglect patients. Using the absolute value of the bias did not increase the reported significance. Although the correlations are sizeable and significant, the evidence for them in the data amounts to only weak evidence by established standards.

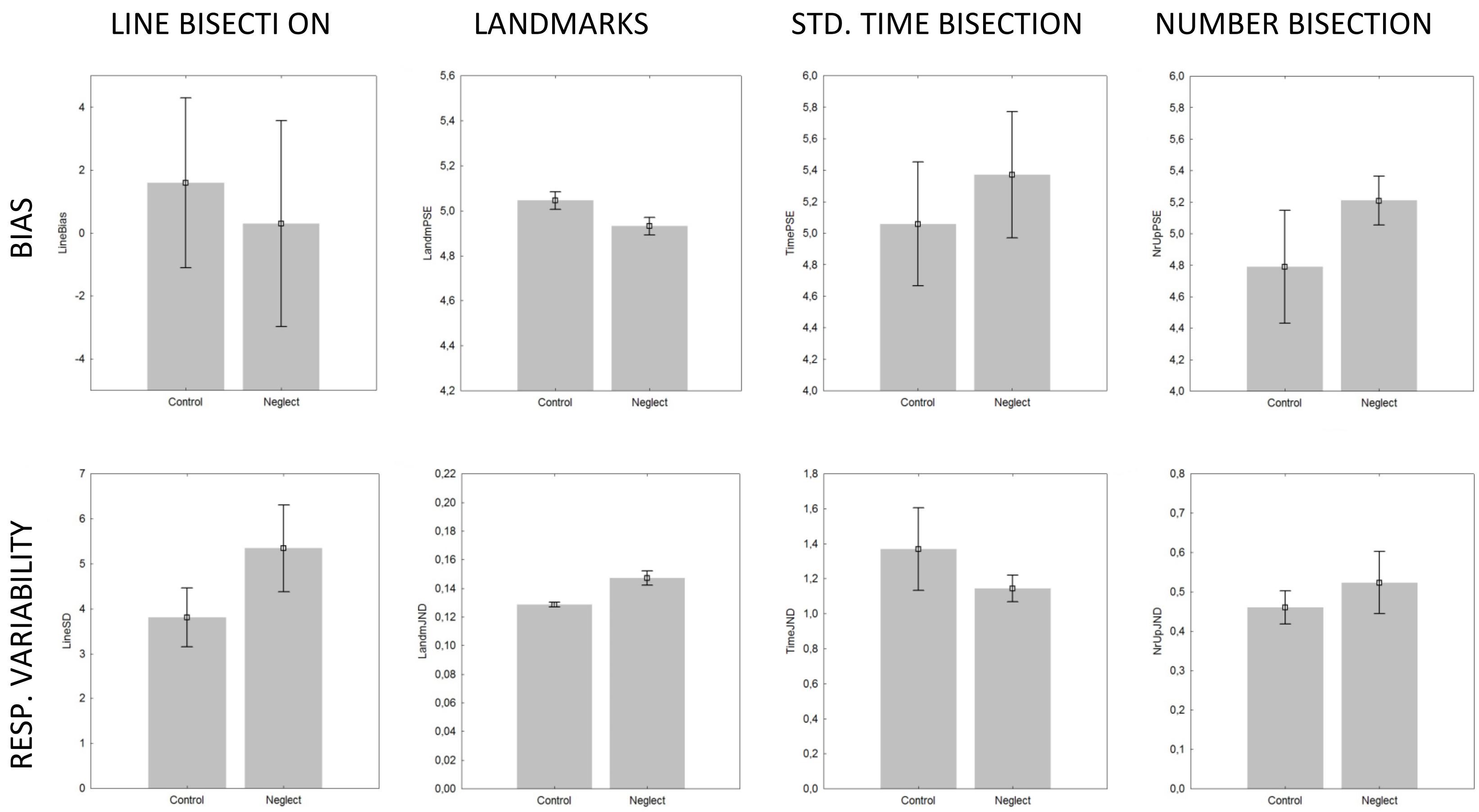

Figure 7. Bias and precision indexes in the bisection tasks of Experiment 3.

Bias (constant error) and precision (standard deviation) in Line Bisection are expressed in millimetres. Bias (PSE) and precision (JND) in the Landmarks task, the Standard Time Bisection and Number Bisection are expressed in arbitrary units from 0 to 10 where 0 is the beginning and 10 the end of the stimulus. Error bars represent standard error of the mean.

Briefly recapitulating, neglect patients were expected to exhibit a considerable bias in spatial tasks, and we hypothesized that this bias should also be observed in temporal and numerical bisection, according to the predictions of the common coding of magnitude. Even though in the Landmarks task there was a correlation between bias and severity of neglect, our results did not reveal a clearly larger spatial bias in neglect patients, and overall both groups did only differ in the precision index of the Landmarks task, being controls more precise than patients.

Up till now in this section we have described the analyses carried out to check whether participants exhibited a significant bias on the different bisection tasks, and also if there were group differences in bias or response variability in any of the tasks. This is certainly relevant information to interpret our results, but the crucial question to test the predictions of the common coding of magnitude is whether individuals perform similarly across dimensions. Group differences in spatial bias were certainly expected, but they were not required to test whether people with a larger bias or response variability in one task also exhibits it in the other tasks. Next in the analysis we checked the correlations between tasks within participants, the most relevant test for our hypotheses.

Within-group correlations are not advisable due to the small sample size (in the case of patients, n = 5). Taking all participants together, bias in Landmarks correlated with bias in Standard Time Bisection (r = -0.56, p = .036, B = 2.46), and response variability in Line Bisection correlated with variability in the Landmarks task (r_s = 0.64, p = .018, B = 3.03). All other correlations were non-significant (p > .1, 0.33 < B < 1.13).

All in all, we found only partial evidence for an internal link between the processing of prothetic dimensions. A particularly interesting finding was a correlation between the bias in the Landmarks task and bias in the Standard Time bisection, even with the relatively small sample size of this experiment. Importantly, the B factors on the non-significant comparisons are not low enough to suggest that the respective indexes are indeed uncorrelated.

DISCUSSION

In this experiment we tested some of the predictions of the common coding hypothesis with a population where they should be very easy to observe were they accurate: a group of neglect patients and a matched control group of neuropsychological patients without neglect symptoms. Rather than a large bias in spatial perception, neglect patients displayed a small bias in both spatial bisections. In fact, neither controls nor patients exhibited a significant deviation from the actual midpoint in any of the tasks, or differed in bias from each other. This finding is not by itself a critical caveat to test our hypotheses but it obviously hinders the rationale of the experiment.

A possible reason for this lack of statistical differences in spatial bias between controls and neglect patients could be the variability in severity within the neglect group, as revealed by the Apple test (Table 2). In other words, it could be the case that there are clear differences between neglect patients and controls in spatial bias, but due to the wide range of severity in our patients, statistical analyses did not reach significance. This possibility can be tested calculating the correlation between severity and performance in bisection tasks. As reported above, in most tasks we did not find such correlation (it was only significant in response variability of the Landmarks task). Therefore, the variability of symptoms of neglect patients seems not to be the cause of the lack of statistical differences with controls.

Another plausible explanation for this would be that patients are very trained in these kinds of tasks, and may have learnt over time to use strategies to adjust their estimations. Two potential avenues can follow from this. One would be that if patients are less trained in temporal and numerical bisection, then correlations between severity and performance in these two tasks could suggest a relationship in processing between different magnitudes. Second, if patients have learnt to bypass their bias in perception by some sort of conscious correction or recalibration of their attention, then there should still be a correlation between the performance in the different bisection tasks. None of them is supported by our data.

Finally, it is possible that some of the non-significant relationships described here could reach significance and a stronger evidential base with a higher amount of participants. This is true especially for the comparison of bias and acuity between groups, or to the assessment of neglect and pseudoneglect in the different tasks. However, the crucial test for our hypotheses was the individual variation in performance across the different tasks. We did find partial evidence of correlation between tasks, and the non-significant correlations were not conclusive enough to support the absence of a common coding of magnitude.

IV. General discussion

1. Conclusions and discussion of the experimental series

The experiments described above pursue the goal of testing the prediction that concrete and abstract dimensions are associated in terms of the mental processes involved. These are specific predictions of A Theory of Magnitude (Walsh, 2003), and the common coding view. Stemming from the line bisection task, we have applied that principle also to temporal and numerical intervals, and compared performance of our participants across tasks, both in perceptual bias and acuity. The expected results were straightforward: a high degree of correlation between the individual performance in different dimensions would argue in favour of a common coding of magnitude. Lack of that correlation would instead be compatible with an independent processing for the different dimensions. The results obtained with this approach, have provided only partial support for the predictions of the common coding hypothesis.

In the first experiment of the series we tested a sample of undergraduate students, who could be considered as representative of the general population: reasonably healthy persons with well-functioning brains. We reproduced the pseudoneglect effect described in the literature in line bisection, but we found no evidence of covariation between bisection tasks and therefore no substantial support for our hypotheses. In the second experiment we tried to provide a better testbed for the predictions by adding a population that has been reported to exhibit a distinctive pattern of spatial pseudoneglect, consistently different from the general population, and also to differ from healthy people in the acuity of their temporal perception. In this case, we did not find evidence of pseudoneglect in Line Bisection, neither in schizophrenic patients nor in controls. However, these two groups clearly differed in one of the temporal bisections, the Aging Faces tasks, where schizophrenics surprisingly outperformed controls both in bias (which was smaller for these patients) and precision in their responses. In line with their performance in Aging Faces, patients also exhibited a higher average precision in Line Bisection, which was marginally significant. In this experiment response variability in Line Bisection and Aging Faces were positively correlated. No further evidence of correlation between tasks was found. This experiment therefore provided partial support for the common coding hypothesis.

The lack of conclusive evidence in experiments 1 and 2 prompted us to test neglect patients, a population known for their bias in spatial perception. If all magnitudes share a common system, such bias should also be observable in other domains such as time and numerical value. The Aging Faces task, which had provided the most interesting results so far (experiments 1 and 2), could not be used with the participants of the third experiment. Instead, we added the Landmarks task, which involved judgement rather than production, and in this sense it would be more comparable to the other tasks. Together with the Number Bisection task, that added the domain of numerical magnitude to our exploration of common coding.

Performance in the Landmarks task correlated with severity of symptoms and we found significant differences between groups, but only in the response variability in Landmarks. To our surprise, we did not find the characteristic spatial bias described for neglect patients, who did not statistically differ from a matched control group in this or the other tasks. Both groups only differed in response variability in the Landmarks task. It is possible however that with more participants, more significant results in this regard could be found. However, the critical contrast for our purposes was the correlation between tasks within participants. We found significant correlations between the bias in the Landmarks task and Standard Time bisection. Most comparisons between tasks were however inconclusive. Overall, the third experiment of the series provides only partial evidence for the common coding hypothesis. Also the finding of a different pattern of performance between groups in the Landmarks task compared to the rest further warns against a complete support for common coding according to our data. It must be noted that this experiment probably would have benefited considerably from a larger sample size.

Present data and available related evidence thus support the conclusion that the common coding hypothesis may be stated in too general terms and it may need further qualification and development. Not all prothetic magnitudes are the same. Moreover, even single magnitudes such as space and time are not monolithical entities. There are different spaces and different times in the mind/brain. Spatial maps abound all over the brain (Silver & Kastner, 2009). Evidence suggests that the representation and processing of space differs depending on a variety of reference frames, including retinotopic (Silver & Kastner, 2009), object-centred (Olson, 2003), and peri-personal vs. extra-personal (Holmes & Spence, 2004). There may also be processing differences between the three spatial axes: lateral, vertical, and sagittal (Franklin & Tversky, 1990).

Regarding time, there is convincing evidence that temporal intervals at sub-second and supra-second ranges may be processed by different mechanisms: in particular, short intervals up to the range of 1 s may be perceived directly, whereas longer intervals ranging from several seconds to minutes or longer units may require the implication of attentional and inferential mechanisms (Block, 1990; Zakay & Block, 1996). Moreover, it is well-established that temporal processing is the result of a brain-wide network including the cerebellum and basal ganglia (see Grondin, 2010; Allman & Meck, 2012, for reviews). Magnitude processing in the parietal cortex is also part of a network that includes prefrontal regions, among others (Bueti et al., 2008). Lewis and Miall (2003) proposed a role for the parietal cortex only in the sub-second range. The processing of numerical value has also been reported to be influenced by factors that are not likely to be shared with other dimensions, like the position in a decade (Aiello et al., 2012) or memory functions (van Dijck et al., 2011), which are not likely to exert a considerable influence for example in the bisection of lines.

Future progress on the question of the representation of prothetic dimensions will sure benefit from a more nuanced view that will specify which aspects of which dimensions are likely candidates to be represented and served by a common mechanism, and where and how is such mechanism implemented in the brain.

2. Final remarks

I would like to end this work with a consideration with respect to the future of common coding and in general embodied and grounded cognition. Some theories are set to explain narrow aspects of brain functions, others seem distant from our subjective experience, others ignore seemingly solid data against them and focus only on proving their postulates, and many also seem quite difficult to implement in a neuron-based system like our brain. We regularly use different models to explain different data, but those models are sometimes incompatible with each other. Still, we keep assuming that our view is probably appropriate and thus research keeps growing in every direction. The conclusions and implications of each particular view are defended with data (there is data to defend almost anything), and we keep spending generous resources in researching ideas that cannot be simultaneously true. My wondering is, where is that leading?

We are nevertheless adding knowledge, but perhaps when we find an explanation that is compatible with a wide variety of results we may find out that much of our theorizing was out of place. Would it not be more reasonable to try to start with views that have the potential to be compatible with what today are alternative or even opposing proposals?

We can find points of view that are not only contradictory but even mutually unintelligible but each of them is supported empirically (i.e., publications that pass the requirements for scientific knowledge on each side). However, because they are contradictory, not all of them can be true. And therefore it may be wise also to look for explanations that are not only empirically supported but also that satisfy the -somewhat subjective but crucial in my opinion- criterion of plausibility. In other words, a proposal should make sense by itself, not only based on the necessary acceptance of previously published knowledge. This way we may save ourselves from some of what Barsalou (2016) called "Quixotic dead ends". It is my hope that the future of our discipline does not only come with more data, but also with an increasing appreciation of the value of wisdom in science.

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