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Deafness for the meanings of number words

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Abstract

We describe the performance of an aphasic individual who showed a selective impairment affecting his comprehension of auditorily presented number words and not other word categories. His difficulty in number word comprehension was restricted to the auditory modality, given that with visual stimuli (written words, Arabic numerals and pictures) his comprehension of number and non-number words was intact. While there have been previous reports of selective difficulty or sparing of number words at the semantic and post-semantic levels, this is the first reported case of a pre-semantic deficit that is specific to the category of number words. This constitutes evidence that lexical semantic distinctions are respected by modality-specific neural mechanisms responsible for providing access to the meanings of words.

Keywords

aphasia; numerals; category-specific deficits

Introduction

A central question in cognitive psychology and cognitive neuroscience concerns how knowledge is represented and organized in the brain. Research with brain-damaged individuals has demonstrated that specific categories of concepts or words can be selectively impaired or spared. As a result, one of the most-studied phenomena in neuropsychology has been category-specific deficits. There have been reports of selective damage or sparing of a wide range of categories, including: animals (Warrington & Shallice, 1984; Warrington & McCarthy, 1983; Hart & Gordon, 1992; Caramazza & Shelton, 1998; for the reverse pattern, see Hillis & Caramazza, 1991), body parts (Dennis, 1976), proper names (Semenza & Zettin, 1989), fruits and vegetables (Farah & Wallace, 1992), artifacts (Moss & Tyler, 2000), numerals (Cipolotti, Butterworth & Denes, 1991 or Capelleti, Butterworth & Kopelman, 2001), abstract or concrete words (Warrington, 1975; Warrington & Shallice, 1984 or Breedin, Saffran, Coslett, 1994),

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It is worth noting that if the only difficulty were one of accessing meaning from the phonological input lexicon, we would expect good repetition of number words. In pure "word meaning deafness" the ability to repeat words is typically preserved, that is, individuals with this deficit can repeat words –albeit without understanding them- through sublexical acoustic to phonological conversion (Figure 1). However, as we indicated earlier, MMV had a deficit affecting this process, as indicated by his severe difficulties in repeating non-words –reported in Table 1 (11/104, 11% accuracy). Given this, MMV must primarily use the semantically mediated lexical route for repetition.

and specific grammatical categories, for example, the dissociation between open class words, nouns and verbs; and closed-class words, function words (e.g. Andreewsky & Seron, 1975; Caramazza, Berndt & Hart, 1981; Goodglass, 1993; Rapp & Caramazza, 1997).

The majorioty of the category-specific cases have been interpreted as showing impairment to semantic knowledge. There have only been a few cases of deficits restricted to a particular modality of input or output. These latter cases indicate a categorical organization of the pre or post semantic systems responsible for processing the phonological or orthographic forms of words or for object recognition. In this paper we document, for the first time, the case of an individual who shows a modality-specific comprehension deficit that is limited to number words presented in the auditory modality. These findings contribute to our understanding of the organization of human cognitive and neural systems by revealing a number of distinctions: between number words and non-number words, between number-word comprehension and production, and between the phonological and visual/orthographic processes responsible for accessing the meanings of number words.

In the following, we briefly discuss some of the category and modality-specific deficits and then go on to focus specifically on the literature regarding the organization of the number processing system.

Evidence concerning the category-specific organization of pre and post semantic processes

The categorical organization of the post-semantic word production systems has been supported by the finding of (a) category-specific deficits that are specific to an output modality, or (b) deficits that can, on the basis of other evidence, be determined to have a post-semantic locus. These findings have involved a number of categories, including: grammatical categories (nouns vs. verbs, Berndt, Haendiges, Burton & Mitchum, 2001; Laiacona & Caramazza, 2004; Shapiro & Caramazza, 2001, 2003b; see Rapp & Caramazza, 2002, for a review); abstract/concrete words (Franklin, Howard & Patterson, 1995), semantic categories (e.g., body parts, fruits and vegetables, colours, etc.; Beauvois, 1982; Dennis, 1976; Hart, Berndt & Caramazza, 1985), letter names (Goodglass, Wingfield, Hide & Theurkauf, 1986), number names (McCloskey, Sokol & Goodman, 1986; Anderson, Damasio & Damasio, 1990; Bachoud-Lévi & Dupoux, 2003, etc.), and proper nouns (Lucchelli & Renzi, 1992; Semenza et al., 1989; Cipolloti, 2000; etc.).

As an example, in cases of modality-specific, grammatical-category dissociations there is a selective deficit in producing words of one grammatical category and the deficit is restricted to either the spoken or written modality. Caramazza & Hillis (1991) reported two such cases; one exhibited selective difficulty in producing spoken verbs versus spoken nouns but had no particular difficulty with written verbs or nouns; the other case had difficulty producing written verbs versus nouns, with sparing of spoken verbs and nouns (see also Baxter & Warrington, 1985; Berndt & Haendiges, 2000; Hillis & Caramazza, 1995b; Rapp & Caramazza, 1998). In addition, there have also been cases of single individuals who exhibit a double dissociation of grammatical category by modality. A number of these have exhibited difficulty with open class vocabulary in spoken production and closed class vocabulary in written production (Assal, Buttet, & Jolivet, 1981; Bub & Kertesz, 1982; Coslett, Gonzales-Rothi & Heilman, 1984; Lecours & Rouillon, 1976; Lhermitte & Derouesne, 1974; Patterson & Shewell, 1987; Rapp, Benzing & Caramazza, 1997). In addition, Rapp et al. (2002) reported a single individual with a double dissociation of nouns/verbs by modality, such that he had better performance with nouns vs. verbs in the written modality and the reverse pattern in the spoken modality.

Although most of the evidence regarding modality-specific deficits has concerned post-semantic language production processes there has been some evidence of category-specific effects that can be localized to pre-semantic spoken and written word recognition systems or to the object recognition system (see Riddock & Humphreys, 1987, and Capitani, Laiacona, Mahon & Caramazza, 2003 for a discussion regarding the latter).

For example, regarding the orthographic input system used for reading, there is the report by Hillis et al. (1995) of a grammatical-category-specific deficit affecting written comprehension and lexical decision of verbs more than nouns. In addition, some research with neurologically intact subjects has provided some support for this notion of pre-semantic grammatical category representation within the orthographic system (see Folk & Morris, 2003; for evidence suggesting that syntactic-category information can mediate the semantic resolution process; also see, Boland, 1993; Gorrell, 1989; O'Seaghdha, 1989, 1997).

With regard to the pre-semantic phonological processing of words, evidence relevant to categorical organization has come from cases of what is sometimes referred to as *word meaning deafness*. Given the relevance of this evidence for the case described in this paper, we describe this literature in greater detail.

In certain individuals, auditory comprehension of words but not written comprehension is compromised (Bramwell, 1897; Franklin, Howard & Patterson, 1994; Kohn & Friedman, 1986; Hall & Riddoch, 1997). In at least some of these cases, pre-lexical processes as well as the phonological input lexicon are assumed to be intact because auditory lexical decision is preserved. Furthermore, the semantic store is assumed to be intact because written words are well understood. The difficulty in auditory word comprehension is, therefore, specifically claimed to involve a disconnection or disruption between an intact phonological input lexicon and an intact semantic store. Most individuals reported with this type of deficit have general problems in the auditory comprehension of words; however, there have been two reports of individuals whose auditory comprehension was affected by the abstractness of the words. One case was reported by Franklin et al. (1994). DRB had more difficulty with the comprehension of auditorily presented abstract words (low imageability words) than with concrete words. These problems occured only with auditory input, as he was highly accurate in his comprehension with written words. On the basis of DRB's good written word comprehension and his good performance in auditory lexical decision even with abstract words, the authors concluded that DRB's deficit originated in accessing semantic information for abstract words from the auditory modality. However, in a recent reanalysis of this case Franklin, Turner, Lambon Ralph, Morris & Bailey (1996) suggested that DRB might have had an early phonological impairment that was not detected by the tasks, such as minimal pair discrimination and lexical decision tests, employed by Franklin et al. (1994). Franklin et al. (1996) described another case similar to that of DRB. For DrO, performance was affected by the imageability and length of words, such that he had difficulty in the auditory comprehension of words that were short and abstract. The interpretation of this case is also in dispute. Does it reflect semantic access procedures that are specific to abstract words or do the deficits result from the fact that abstract words are more sparsely represented than concrete words at the semantic level? This representational difference could interact with a mild, general deficit in semantic access (reduction in activation, a rapid decay, or additional noise) to produce the apparent selective deficit to abstract words.

There have also been a small number of reports of selective sparing for categories of auditorily presented words. Jacquemot, Dupoux & Bachoud-Levy (2003) reported the case of an aphasic individual who seemed to have a selective sparing of animal names in the auditory modality. These authors described an individual with global aphasia who had comprehension difficulties only for words presented in the auditory modality. However, the category of animals was spared relative to all other categories of words. On this basis, the authors suggested that the phonological lexicon might be organized in terms of semantic categories.

In conclusion, finding patterns of modality-specific, category-specific impairment and sparing provides some indication that pre and post-semantic systems (or access to and from these systems) may be organized in such a way that neurological damage may affect specific semantic and/or grammatical categories.

The cognitive and neural categorically of numbers and number words

There is considerable evidence indicating that number concepts and number words may form specific categories of knowledge and/or lexical organization. As a backdrop to this discussion we first present the functional framework of number processing that we assume throughout and which is depicted in Figure 1. It is adapted from the language processing framework presented in Patterson et al. (1987) and incorporates features from McCloskey (1992) and Dehaene's triple code model (Dehaene, 1992;Dehaene & Cohen, 1995). From McCloskey (1992) we incorporate the idea of functionally independent script-specific modules for the comprehension of Arabic numerals and number words that are used to translate numerical input into an abstract semantic representation. From Dehaene's triple code model we incorporate the idea of the existence of a direct route linking the Arabic and verbal codes. This link appears in dotted lines because its existence is still highly debated (for proponents see: Blanken, Dorn & Sinn, 1997;Girelli, 1998;Dehaene, 1992;Dehaene et al., 1995;Cipolotti & Butterworth, 1995; but see McCloskey, Caramazza & Basili, 1985;McCloskey, 1992;Fias, 1998).

With regard to the semantic level, there is both neuropsychological and neuroimaging evidence for the independent neural representation of number concepts from other concepts, implicating the superior parietal lobe/s. With regard to the neuropsychological evidence, selective difficulties with numbers and number concepts have been associated with lesions of the left parietal lobe (McCarthy & Warrington, 1990; Benton, 1992; Gertsmann, 1957; Cipolotti, Butterworth & Denes, 1991; Dehaene & Cohen, 1997; Mayer, Martory, Pegna, Landis, Delavelle & Annoni, 1999). In addition, a number of neuroimaging studies with healthy individuals show the parietal regions activated in numerical tasks (Dehaene et al., 1995; Dehaene, Spelke, Pinel, Stanescu & Tsivkin, 1999; Pesenti, Thioux, Seron & De Volder, 2000; Pinel, Dehaene, Riviere & LeBihan, 2001; Pinel, Le Clec, van de Moortele, Le Bihan & Dehaene, 1999). Bilateral parietal activation is present when subjects are engaged in number comparison tasks (Le Clec'H, Dehaene, Cohen, Mehler, Dupoux, Poline, Lehéricy, van de Moortele & LeBihan, 2000; Chocchon, Cohen, van de Moortele & Dehaene, 1999). Recent studies implicate the intraparietal sulcus (IPS) in number processing (Cantlon, Brannon, Carter & Pelphrey, 2006; Cappelletti, Barth, Fregni, Spelke & Pascual-Leone, 2007) and in some numerical tasks such as manipulation of numerical quantities (Chocchon et al., 1999; Dehaene, 1996; Dehaene, Dehaene-Lambertz & Cohen, 1998; Simon, Mangin, Cohen, LeBihan & Dehaene, 2002); or mental arithmetic (Venkatraman, Ansari & Chee, 2005; Pesenti et al., 2000; Zago, Pesenti, Mellet, Crivello, Mazoyer & Tzourio-Mazoyer, 2001).

With regard to the organization of pre and post semantic processes there have been several reports indicating the number and non-number words are differentially represented in the written and spoken production systems. These reports are similar to the category-specific, modality-specific deficits described in previous sections. For example, similar to the finding reported by Geschwind (1965), more recently Cohen, Verstichel & Dehaene (1997) reported the case of an individual who had a severe neologistic jargon in spoken production, both naming and reading that resulted in a large number of phoneme substitutions. These difficulties were manifested for all categories of words and nonwords except for number words and letters. With number words, instead of phonological errors, he produced lexical errors that consisted of incorrect numbers words that were almost entirely free of phonological errors (see also Bachoud-Lévi et al., 2003). On this basis the authors concluded that during speech planning, different categories of words are processed by separable brain systems that are functionally and anatomically distinct.

Marangolo, Piras & Fias (2004) described the complementary pattern. They reported the case of an individual who exhibited a selective deficit in the spoken production of number compared to non-number words. The deficit could be localized to the phonological output system because number writing and the comprehension of written numbers (Arabic numerals and number words) were spared (see also Whalen, McCloskey, Lindemann & Bouton, 2002). The authors concluded that the locus of the deficit was at post-semantic, at the level of phonological lexical retrieval and, on this basis, argued for the existence of different modality-specific output lexicons for written and spoken production of numerals (see also, Marangolo, Nasti & Zorzi, 2004)

With regard to written output, Delazer, Lochy, Jenner, Domahs & Benke (2002) described an individual with a written production deficit that affected his ability to produce letters but spared his ability to write digits. It is worth noting that this deficit in letter writing occurred in the face of excellent oral spelling, excluding a central deficit in generating graphemes. The opposite dissociation was reported by Basso and Beschin (2000), who described an individual with difficulties producing digits and who made only very minimal errors in writing words and letters. In combination, these results are taken as evidence of post-lexical categorical organization of the representation of the written forms of letters and numbers – category-specificity at the periphery of the language processing system.

It should also be noted that cases describing selective sparing of number words at multiple levels of representation have also been reported (e.g., see Anderson et al., 1990; Domahs, Bartha, Lochy, Benke & Delazer, 2006 and Starrfelt, 2006).

In conclusion, among the clearest results in the literature on category-specific effects are findings regarding the selective impairment of number concepts, number words and digits. These findings are consistent with the notion that numbers form a distinct category of conceptual and word knowledge that is neurally instantiated in a manner that is independent from other knowledge categories. One pattern that has not been reported is that of category-specific deficit or sparing of numbers in the auditory input modality. It is precisely this pattern that we report in this investigation. We will report the case of an aphasic individual who exhibited impaired auditory comprehension of number words in the face of spared auditory comprehension of non-number words and spared written comprehension of both number and non-number words. We will show that the difficulty in the auditory comprehension of number words originates in the connections between an intact phonological input lexicon and an intact semantic system -a case of number-word meaning deafness.

CASE HISTORY

MMV is a right-handed Spanish-Catalan bilingual male born in 1937 with twelve years of formal education always in Spanish (technical high school level training in mechanics). In August 2000, he suffered a CVA and MR imaging revealed a left temporo-parietal lesion (Figure 2 and 3). At time of the CVA, MMV was working as a machine technician. After the stroke, he received speech therapy for 6 months and was diagnosed as a conduction aphasic. This investigation took place between May, 2002 and September, 2006, during which time his neuropsychological profile remained stable and no other deficits were present (paralysis, neglect, hemiparesis, visual or auditory problems, etc.). Audiometry testing indicated a mild bilateral neurosensorial hypoacusia within the normal range given his age.

Language comprehension and production in L1 and L2

MMV's first language was Spanish and this was the language that MMV used during his schooling and with his parents and siblings. However, he was highly competent in Catalan, because in his work he used the two languages. Furthermore, he principally used Catalan to speak with friends, his wife and children. In conclusion, in his current life MMV uses the two languages, Spanish and Catalan.

In both his L1 (Spanish) and in L2 (Catalan), MMV's language comprehension was good and his spontaneous speech was fluent and syntactically correct, though marked by a considerable number of phonological paraphasias and anomias. His language abilities were assessed formally with two different batteries (SPPB-CNL Language Screening Battery) and (EPLA-evaluación del procesamiento lingüístico de la afásia, Valle & Cuetos, 1995, and adapted Spanish version of PALPA, Kay, Lesser & Coltheart, 1992). The results reported in Table 1 indicated that the pattern of spared and impaired performance was extremely similar in the two languages. In both languages auditory and written language comprehension were excellent. He was similarly impaired in both languages in spelling and in the spoken production tasks of picture naming and repetition, while oral reading of words and nonwords was largely spared. Both accuracy and error types were similar across languages. Given the similarity of MMV's accuracy and error typology across a wide range of tasks in the two languages, the investigation focused on his L1 –Spanish (we refer to L2 findings in section 6).

Repetition, reading and naming of number and non-number words

The focus of this investigation is on comprehension, so we report on MMV's spoken production performance only briefly.

MMV was asked to repeat and read number and non-number words, as well as to orally name Arabic numerals, and line drawings of objects. Number stimuli consisted of a set of 135 Arabic numerals varying from 1 to 5 digits; non-number words consisted of the 260 items of the Snodgrass and Vanderwart (1980) set (see Table 2).

The contrast between intact reading (99%) and impaired picture naming (34%) for non-number words indicates a non-peripheral spoken production deficit, affecting either semantics, lexical retrieval or lexical phonological encoding. The fact that phonological and not semantic errors are produced in picture naming makes a semantic locus unlikely, implicating lexical retrieval or lexical phonological encoding. Furthermore, the fact that MMV's performance is intact for the oral naming of written numerals (100%) while oral picture naming of non-number words (34%) is severely impaired suggests a category-specific deficit in spoken production, affecting non-number words. His difficulties in oral naming of non-number words do not have to do with the complexity of the pictures as he was close to 100% correct on all tasks that involved picture comprehension (as indicated in Table 1), even including Pyramids and Palmtrees which only involves pictures. We refer the interested reader to Caño, Costa, Juncadella & Caramazza (in preparation) for further discussion of the spoken production deficit and its implications.

In addition to the information these tasks provide regarding MMV's spoken production abilities, they also point to a modality and category-specific deficit in the auditory comprehension of number words that will be documented and investigated in detail in subsequent sections. With regard to comprehension, there is a striking difference in his production of number words according to the modality of the input —good performance with visual input –either written word (reading-100%) or Arabic numeral input (naming-100%), and poor performance with spoken input (repetition-24%). This suggests a deficit within the auditory comprehension system, at either the semantic level and/or in the processing of the auditory stimulus. Furthermore, the deficit appears to be category specific given that, in repetition, different types of errors were produced for number and non-number words, with number words giving rise almost exclusively (97%) to lexical substitutions of one number word for another (note, however, that the substitutions were not similar either in magnitude or phonology) and non-number words giving rise largely to phonological errors (84%). The detailed investigation of this apparent modality-specific, category-specific comprehension difficulty is the topic of the experimental investigation.

In subsequent sections, we examine the locus and nature of the impairment within the cognitive architecture of language comprehension depicted in Figure 1, investigating: 1) MMV's general auditory/phonological processing abilities, 2) his access to long term memory (LTM) phonological representations of number words, 3) his semantic knowledge and processing of number words, 4) the possibility that the difficulty in the auditory processing of number words can be reduced to a difficulty in the auditory processing of abstract words and 5) a number of factors that may influence his auditory comprehension of number words (e.g., frequency-complexity, memory load or response delay).

Evaluation 1: Auditory/phonological processing

Task 1.1: Sound categorization—We evaluated MMV's ability to categorize sounds into the following basic categories: speech (Catalan, Spanish and English), backward speech, non-speech (animal, artifacts music). Difficulties in this task would indicate a problem at the acoustic level of processing.

Stimuli from different categories were presented in random order for trials of 10 seconds in duration. MMV was asked to categorize each stimulus into the following categories: speech (and in this category the individual was asked to indicate the language of the stimulus), backward speech and non-speech (to be categorized as animal, artifact or musical sounds). Performance on these tasks was flawless (see table 3).

The next tasks were directed at evaluating pre-lexical phonological processing and recognition. A deficit specifically affecting this stage is sometimes referred to as "word sound deafness" (Ziehl, 1896; Franklin, 1989), indicating a specific difficulty in the processing of word sounds. Five age and education matched control subjects were also tested and the mean and range of their results are also presented in Table 4.

Task 1.2: Phoneme monitoring in number and non-number words—A list of number and non-number words (20 numerals and 60 words) was presented auditorally and MMV was asked to raise his hand when he heard a word with a particular letter sound (e.g., "t"). Five different letters were used. MMV's accuracy with both number and non-number words was good and within normal range (57/60, 95% for words and 19/20, 95%, for numerals).

Task 1.3: Discrimination of minimal pairs (words and non words)—MMV was asked to indicate if two orally presented stimuli were the same or different (the two stimuli differed only in one phoneme). The experimenter's mouth was covered to prevent lip-reading. MMV's performance with both words and nonwords was outside the normal range (81/96, 84% for words and 41/56, 73% for non-words).

Task 1.4: Rhyme verification—MMV was asked to indicate if two orally presented words rhymed. MMV's performance was good, just slightly outside the normal range (38/40, 95%).

Task 1.5: Embedded word detection—We auditorally presented 200 words, 25% of which contained an embedded number word; the rest of the stimuli did not contain embedded words. For example, the words "bizc**ocho**" (sponge cake) and "derr**ocho**na" (person who wastes money) contain the sound sequence corresponding to the number eight ("ocho"). The number word was never related to the meaning of the word. A total of 3 different number word targets were used (“ocho (8), “uno” (1) and “tres” (3)) and presented in 3 different blocks, one block for each numeral. In each block, MMV was asked to raise his hand when he heard the sequence of sounds “ocho” in the word structure (or the other sounds, “uno” or “tres” in the other two blocks). Although less accurate than normal controls, MMV’s overall accuracy was very good at 93% (140/150), with 99% correct detections of the numbers in number-embedded and 6% (9/150) false alarms to stimuli that did not contain number words.

To summarize: the results indicate good performance on all phonological decoding tasks except for minimal pair discrimination task. This may be a consequence of his mild hearing loss which may affect fine-grained discrimination such as that required for this task. The other tasks largely depend on a coarser grain of phonological analysis –detecting rhyme or an embedded word. Thus, a mild deficit in acoustic/phonemic processing cannot be ruled out. However, it would not explain the level of difficulty or the types of errors that MMV has demonstrated in the repetition of number words (Table 2) or in the auditory comprehension of number words that will be documented in subsequent sections. That is, a mild deficit in phonological processing would certainly not be expected to result in errors such as the the repetition of “veintitres” (23) as “cuarenta y cinco” (45).

Evaluation 2: Accessing the phonological (input) lexicon

The next major processing stage involves using phonological representations to search long-term memory for comparable representations —accessing the phonological (input) lexicon. A deficit in this stage is often referred to as “word-form deafness” (Kohn et al., 1986; Howard & Franklin, 1988; Franklin, 1989). The hallmark characteristic of such a deficit would be the inability to recognize that a phonological string corresponds to a word of the language.

Task 2.1: Lexical decision—We administered both auditory and visual lexical decision tasks in which the word stimuli were number (n=50) and non-number words (n=100) and non-words (n= 110). Number words consisted of 10 single digit numbers, 30 two-digit numbers, and 10 three-digit numbers. Seventy-five of the non-words were derived from non-number words, 35 were derived from number words, and all were derived by changing one or two phonemes (or letters). Words from all categories were presented in a pseudo-random fashion.

As indicated in Table 5, although MMV’s performance with auditory presentation is quite good, it is outside the normal range, while with visual presentation his performance is well within the normal range. Thus, for MMV there was a significant difference between overall performance with auditory vs. visual ($X^2 = 8.790$, $P = .0005$) that was not observed for control subjects ($X^2 = 3.071$, $P = .141$). What is most important, however, is that within either modality, MMV’s performance with number and non-number words was comparable. In neither auditory nor visual presentation was there a significant difference between number and non-number stimuli for either words or non-words (auditory words: $X^2 = .785$, $P = .507$, auditory non-words: $X^2 = .017$, $P = 1$; visual words: $X^2 = .0$, $P = 1$; visual non-words: $X^2 = .672$, $P = .662$).

Task 2.2: Number plausibility judgment—As a further test of MMV’s ability to discriminate familiar versus unfamiliar auditorally presented sequences, we presented number word combinations that corresponded to plausible numbers such as “cuarenta y tres” (43) or “trescientos setenta” “370” as well as implausible number word combinations such as “tres cuarenta” (3-40) or “setenta trescientos” (70-300). MMV was asked to indicate which numbers were plausible. MMV’s accuracy was excellent, within the normal range and comparable across modalities (auditory: 96% (94/100); visual: 95% (93/100); $X^2 = .082$, $P = 1$).

To summarize, the mild phonological processing deficit reported earlier could be expected to result in mildly impaired performance in auditory vs. visual lexical decision. Importantly, such a deficit should affect number and non-number words comparably. This indeed is the pattern observed for MMV (Table 5). What is striking is MMV's overall very high accuracy in auditory lexical decision across all word categories and in number plausibility judgments. This indicates that access to the phonological lexicon is largely spared for both number and non-number words and that this stage of processing cannot be the source of MMV's difficulties in auditory number word comprehension and repetition.

Evaluation 3: Semantic processing of number and non-number words

Having ruled out deficits in auditory pre-lexical and lexical processing, we are left with the possibility of deficit at the semantic level or in access to this level from the phonological input lexicon. The evidence presented thus far documenting MMV's excellent performance with visual presentation of numbers - oral reading or naming of Arabic numerals (Table 2)- would suggest an intact semantic and conceptual processing of numbers. However, one might entertain the possibility that a mild semantic deficit could interact with a mild phonological deficit to create an apparent modality-specific, category-specific deficit. To evaluate this possibility, it is critical to extensively evaluate semantic processing. In this section we report on six number-comprehension tasks carried out with visually presented stimuli only and an additional eight tasks carried out with both auditory and visual modalities. We additionally present four tasks to provide additional evidence regarding comprehension of non-number words. These tasks represent a very thorough evaluation of MMV's number and non-number word comprehension abilities. They show that with visual presentation, MMV's performance with numbers is flawless, while with auditory presentation, the modality-specific comprehension deficit is striking, severe and limited to number words.

Number comprehension: Visual presentation

- *Task 3.1: Visual magnitude judgment.* Two number words (from 1 to 3 digits in length) were presented visually and MMV was asked to say if the pair of numerals that the number words corresponded to had the same digit length (e.g., twenty and fifty-seven). MMV's performance was perfect (20/20, 100%).
- *Task 3.2: Visual parity judgment*. Arabic numerals and number words (from 1 to 3 digits in length) were presented visually and MMV was asked to say if the number presented was odd or even. MMV's performance was perfect (10/10, 100%).
- *Task 3.3: Transcoding Arabic numerals to number words*. A list of Arabic numerals (from 1 to 3 digits in length) was presented and MMV was asked to write the corresponding number words. He made only one error in which he misordered the digits (24/25, 96%).
- *Task 3.4: Transcoding number words to Arabic numerals*. A list of written number words (from 1 to 3 digits in length) was presented and MMV was asked to write the corresponding Arabic numerals. He made no errors (25/25, 100%).
- *Task 3.5: Ordering Arabic numerals or word numbers by magnitude*. We visually presented 3 Arabic numbers or number words and asked MMV to reorder them from the lowest to the highest according to their magnitude. In the two conditions, MMV's performance was without error (25/25, 100% each condition).
- *Task 3.6: Personal and non personal number facts*. This task consisted of a series of oral questions concerning personal or general information that required a numeric response. For example, questions about famous historical dates such as "in what year did the Spanish civil war begin?" autobiographical dates (e.g., year of birth), general knowledge (e.g., number of players in a soccer game, cardinal facts, numbers with

special significance, etc.). The individual was asked to respond orally. MMV made no errors (36/36, 100%).

Number comprehension: Visual and auditory presentation

- *Task 3.7: Arithmetic facts:* Single digit addition, multiplication, subtraction and division problems were presented (e.g., 3+4; 2×5; 8-4; 6÷3). With visual presentation, performance was almost flawless for each problem type (addition: 100% (24/24), subtraction, division and multiplication: 96% (23/24)). However, when the same arithmetic facts were auditorally presented, MMV made errors with all operations (addition: 46% (11/24), subtraction: 71% (17/24), division: 25% (6/24) and multiplication: 62% (15/24)). The difference in accuracy between written and auditory presentation is highly significant (X^2 = 52.35, $P < .01$).
- *Task 3.8: Magnitude comparison*. Pairs of Arabic numerals (from 2 to 3 digits in length) were presented and MMV was asked to indicate the larger of the two numbers. Accuracy was 100% (48/48) with visual presentation, but with auditory presentation performance was significantly worse (33/48, 69%; X^2 = 17.77, $P<.01$).
- *Task 3.9: Same/different judgment*. Pairs of numerals (from 2-5 digits in length) for same or different judgments. MMV only made errors with auditory presentation (24/40, 60%; X^2 = 20.00, $P<.01$).
- *Task 3.10: Number matching-3 options*. In the auditory modality a number word (2 or 3 digits in length) was spoken and MMV was asked to point to the corresponding number among three Arabic numerals written on a page. In the written modality, a written Arabic numeral was presented for 3 seconds, removed from sight and then, as in the auditory modality, he was asked to point to the corresponding number among 3 Arabic numerals written on a page. Performance in the visual modality was perfect (340/340, 100%), while with performance in the auditory modality was significantly worse (244/340, 72%; X^2 = 111.78, $P<.01$).
- *Task 3.11: Number matching-5 options*. This task was the same as the previous one except that the written options were 5 number words. Again, with visual presentation MMV's performance was perfect, but with auditory presentation performance was significantly worse (53%, 180/340; X^2 = 209.23, $P<.01$).
- *Task 3.12: Date verification*. MMV was asked to make a true/false judgment in response to questions which included a date. For example, "Is the 25th of December Christmas day?" "Is the 18th of December Christmas day?". When the questions were presented in a written manner, the performance was 100% (33/33) and with auditory presentation performance was significantly worse (73% 24/33; X^2 = 10.42, $P=.02$).
- *Task 3.13: Series.* A series of 3 numbers (e.g., 4-6-8) were presented and MMV was asked to say the next number in the series (5 series were made up of single-digit numbers and 19 of two-digit numbers). His accuracy with visual presentation was 93% (28/30), while with auditory presentation accuracy was 43% (13/30; X^2 = 17.33, $P<.01$).
- *Task 3.14:* What comes next? Sixty numbers were presented (1 to 5 digits in length) and MMV was asked to say the next number. With visual presentation he made no errors (100%, 60/60) but in auditory presentation his performance was 34% (21/60; X^2 = 57.77, $P<.01$).

Non-number word comprehension: Visual and auditory presentation—The following tasks were designed to evaluate comprehension of non-number words beyond the results reported in Table 1. Visual and auditory presentations were carried out for all tasks in the following manner: In the auditory modality a non-number word was presented auditorially and MMV was asked to point to the corresponding non-number word among 5 non-number alternatives written on a page. In the written modality, a non-number word was presented for 3 seconds, removed from sight and then, as in the auditory modality, MMV was asked to point to the corresponding non-number word number among 5 non-number words written on a page. Results are reported in Table 8.

- *Task 3.15: Word-picture matching*. Stimuli consisted of items from different semantic categories that were presented blocked by semantic category (animals, colors, pieces of clothes, parts of body and fruits). Performance was 100% with both visual and auditory presentation.
- *Task 3.16: Compound word-written word matching-semantic distractors*. The stimuli consisted of 50 compound words (e.g., "pez espada"- "***swordfish***") presented auditorily and the written choices included words semantically related to the target (e.g., "caballito de mar"- "***seahorse***"). Compound words are potentially more similar in their morphological structure to complex number words (e.g., cepillo de dientes (toothbrush) / cuarenta y cinco (45)). Performance was 100% with both visual and auditory presentation.
- *Task 3.17: Compound word-written word matching-phonological distractors*. Identical to task 3.16, the stimuli consisted of 50 compound words presented auditorily (e.g., "cepillo de dientes"- "***toothbrush***") and the written choices included words were phonologically related to the target (e.g.,"pasta de dientes"- "***toothpaste***"). Performance was 100% with both visual and auditory presentation.
- *Task 3.18: Auditory word-picture matching-Verbs*. MMV was auditorily presented with a verb and was asked to choose between two pictures - the correct picture that represented this verb. The distractors were semantically related or visually related to the target. Performance was 100% with both visual and auditory presentation.

Summary of semantic evaluation of number and non-number words—The evidence clearly indicates intact semantic representations for number words when the stimuli are presented visually. In contrast, MMV has significant difficulties in processing auditorily presented number words across a wide range of tasks (whether or not a spoken response is required). Given the evidence from Tasks 2.1 and 2.2 that MMV is typically hearing number words correctly and recognizing them as words, and that his semantic knowledge of numbers is intact, why should he have such grave difficulties in understanding auditorally presented number words? This can be understood if we posit a deficit in accessing the meanings of number words after the stage at which contact is made with the long-term memory representations of familiar word forms-the phonological lexicon.

A specific deficit in accessing the meanings of words presented auditorally has been referred to as "word meaning deafness" (Franklin et al. 1994; Bramwell, 1897; Hall et al., 1997; Franklin et al., 1996). In MMV's case it would seem that the word meaning deafness is restricted to the category of numbers. As already indicated in Table 1, he exhibited excellent written and auditory comprehension of non-number words across a wide range of tasks, in both Spanish and Catalan (Auditory word-picture matching I and II) . The additional tasks carried out to evaluate non-number word and reported in Table 8 provide further, strong support this conclusion. Furthermore, the tasks that will be presented in the next section will also reveal excellent comprehension of concrete and abstract non-number words. Clearly therefore, MMV's comprehension difficulties are restricted to number words presented auditorally. The occurrence of a modality-specific, category specific deficit affecting the auditory comprehension of number words is highly significant as it implies a distinction in the neural substrates that support access to the semantics for number versus non-number words. Before settling on such a conclusion however, it is important to consider an alternative characterization of the number/non-number word dissociation; namely that it could be an artifact of an underlying deficit affecting the auditory processing of abstract words.

Evaluation 4: Abstractness/concreteness

As indicated in the Introduction, cases of "word meaning deafness" have been reported where the auditory comprehension difficulties specifically target abstract vs. concrete words. One might be concerned, therefore, that the category specificity of MMV's deficit does not involve number vs. non-number words but rather abstract vs. concrete words. Consistent with this possibility is the observation by Dehaene et al. (1998) that numerals are a more abstract semantic category than animals or objects. To investigate this hypothesis we carried out four tasks (also administered to normal control subjects) that allowed us to evaluate the effect of abstractness/concreteness on MMV's word comprehension (Table 9).

Task 4.1: Spoken word-picture matching—Using pictures from the Peabody Vocabulary Test (Spanish adapted version) we created two sets of pictures (each set with 30 items)—one corresponding to more concrete (e.g., a palm tree) and less concrete (e.g., a picture that represented "terror") words. The mean concreteness values for these sets were 5, 44 and 3, 66 respectively concreteness values from Lexesp corpus, Léxico informatizado del español, Sebastián, Martí, Carreiras & Cuetos; 2000). Furthermore, the two sets were matched for phoneme length and lexical frequency. A word was orally presented and MMV was asked to point to the correct picture among 4 options. In this task MMV's performance was excellent with no significant difference in accuracy between concrete and abstract words (30/30, 100% for concrete words and 29/30, 97% for abstract words).

Task 4.2: Visual and auditory synonym judgment—This task consisted of 60 pairs of words, half were synonyms and half were not. Furthermore, 30 pairs had high imageability values and the other 30 pairs had low imageability values (subtest EPLA Test). This task was presented in both written and auditory modalities. MMV had to indicate if the pair corresponded to synonyms or not. MMV's performance was close to perfect in auditory and written versions (57/60, 95% and 58/60, 97% respectively) and well within normal range.

Task 4.3: Auditory-written word matching—We created two sets of words, 25 words with low imageability values and 25 words with high imageability values (the mean values for these sets were 3, 23 and 5, 99 respectively). Furthermore, the two sets were matched for phoneme length and lexical frequency. Each word was presented auditorally and the participant was asked to point to the target word among 5 written foils. The foils consisted of either abstract or concrete words that were unrelated to the target. Stimuli were presented blocked by imageability. MMV's performance with concrete words was flawless and performance with abstract words, while good (88%), was outside the normal range.

Task 4.4: Written semantic comprehension—Stimuli consisted of 15 high imageability words and 15 low imageability words. A written word was presented and the participant was asked to point to the word that had the closest semantic relation to the target in 4 written words. The distracter foils consisted of one semantic distracter and 2 unrelated semantic words (subtest EPLA Test). MMV made no errors with the concrete words (30/30, 100%) and was within normal range (12/15, 80%) with the abstract words.

In summary, MMV's performance with abstract and concrete words is comparable to that of normal control subjects, who show (depending on the task) somewhat inferior performance with abstract words. On this basis, we can conclude that he does not suffer from any particular difficulty in processing abstract words –in either the auditory or visual modality- allowing us to rule out the possibility that his severe auditory number comprehension deficit is simply a reflection of a broader deficit affecting the comprehension of abstract words.

Evaluation 5: Variables affecting number word comprehension

There are a wide range of variables that could be examined with regard to their contribution to MMV's auditory number comprehension deficit. We specifically considered: the frequency-complexity of the numbers, memory load (set size), response delay and presentation rate.

Task 5.1: Auditory-visual matching: Memory load and number complexity/ frequency—The task was a word-picture matching task in which MMV was presented with a piece of paper showing nine pictures of items from the same category: common objects (e.g., house, car, knife) or animals (e.g., dog, cat, horse), single-digit numbers (1-9) or two-digit, single-word, monomorphemic numbers (11, 12, 13, 14, 15, 20, 30, 40, 60). Objects, animals and single-digit numbers were matched for phonological length; objects and single-digit numbers were matched in frequency.

The two number sets differed in complexity (1 vs. 2 digits; which we will refer to as low vs. moderate complexity numbers). Unfortunately however, number complexity is confounded by frequency as the less complex numbers are also more frequent, and so it will not be possible to disentangle these factors in this and subsequent tasks.

Target set size (the number of stimuli to be identified on each trial) was one ("house"), two ("house-car") or three items ("dog-cat-fish"). Stimuli were presented either auditorally or visually. In the visual presentation, sets of 1, 2 or 3 stimuli were visually presented in a horizontal series across a page for 3 seconds, removed from view and MMV was asked to point to targets among the set of 9 choices. In the auditory presentation, he responded after hearing the entire set. MMV was asked to point to the targets in the order in which they were presented, for example, "*dog- cat- fish*" or "*3-6-5*". Presentation was blocked by stimulus category, modality and set size; with each block consisting of 50 trials. Therefore this experiment allowed us to examine: stimulus category, modality, set size and number complexity.

It is important to not that in this and subsequent tasks (unless otherwise indicated) accuracy was calculated as the number of items correct out of the total of number of items attempted (only substitution errors were considered).

As indicated in Table 10, MMV was highly accurate with objects and animals, regardless of modality or set size and there was also no difference between objects or animals.

In contrast, his performance with numbers varied according to modality, with excellent performance in the visual modality (100%) and poor performance in the auditory modality. The differences between the two modalities were highly significant for both simple and complex numbers (single digits: $X^2 = 118.563$, $P<.01$; and two digits, $X^2 = 145.042$, $P<.01$).

The two modalities also differed with regard to the effect of set size, such that within the auditory modality, there was a significant effect of set size for both single and two-digit stimuli (comparing set size 1 and set size 3, *single digits:* $X^2 = 35.115$, $P<.01$; *two digits:* $X^2 = 19.829$, $P<.01$), while there was no effect size for visual presentation (single digits:$X^2 = .0$, $P=1$; *two digits:* $X^2 = .335$, $P=1$). Finally, although overall performance in the auditory modality was better with the less vs. more complex numbers, this difference did not reach statistical significance ($X^2 = 2.882$, $P=.107$). It is also worth noting that there was no clear tendency to make more errors on specific positions within a sequence nor to consistently substitute one number for another.

The results replicate the category and modality specificity of the deficit that was already well-documented in previous tasks. They indicate that both working memory demands (set size) and number complexity/frequency affect only auditory number comprehension. Single digits, which are very frequent and low in complexity, can be identified correctly (100% accuracy) from a list of 9 written stimuli if presented one at time, while the 2-digit numbers of only moderate complexity are problematic (84% accuracy) even under those relatively ideal presentation circumstances. Performance with both simple and complex numbers rapidly deteriorates as memory demands increase. However, it is important to note that memory demands do not affect performance in general as they have no effect on visual presentation even with number words and that, furthermore, in the auditory modality, object and animal identification is unaffected by set size. That is, memory load is relevant only for numbers in the auditory modality.

Task 5.2: Auditory-visual matching with latency manipulation—This task was identical to the previous one, except that MMV was required to wait either 0.5 second or 2 seconds after the stimuli were presented before he pointed to them on the page in front of him. Only auditory stimuli were presented, and set size varied from 1-3. Number stimuli consisted only of the 2 digit, medium complexity stimuli (11-15, 20, 30, 40, 60) used in the previous task. This allows us to determine if latency demands interact with memory load. In addition, animal and object names were presented at set size 3.

Importantly, as in the previous task accuracy for number stimuli decreased significantly with set size (set size 1 to set size 2, X^2 = 7.049, *P=.009;* set size 2 to set size 3, X^2 = 9.740, *P=.002*), however it was not significantly affected by response latency (set size 1, X^2 = .758, *P=.667;* set size 2, X^2 = .0, *P=1;* set size 3, X^2 = .427, *P=.624*).

Furthermore, the selective difficulty with number words was again evidenced by the lower accuracy with numbers versus objects and animals for set size 3 at both 0.5 and 2 second latencies (Objects: X^2 = 39.409, *P<.01* and X^2 = 46.441, *P<.01*; animals: X^2 = 36.552, *P<.01* and X^2 = 52.910, *P<.01*). Moreover, response latency did not affect performance with the categories of objects or animals (objects: X^2 = .0, *P=1*; animals: X^2 = 1.862, *P=.367*).

Task 5.3: Repetition: Number complexity/frequency and latency manipulation— MMV was asked simply to repeat number stimuli which were either of moderate complexity (2 digit, mono-morphemic numbers words such as “eleven”) or “high” complexity (high=2 digit, multi-morphemic number words such as “seventy-three”). We note that, again, complexity is confounded with frequency. The stimuli were presented one at a time and latency was manipulated such that MMV was required to wait 0.5, 2 or 5 seconds before responding.

The results (Table 12) reveal a significant effect of number complexity, comparing moderate and high complexity stimuli at all latencies (at 0.5 seconds, X^2 = 8.934, *P=.003;* at 2 seconds, X^2 = 5.507, *P=.029;* at 5 seconds, X^2 = 8.246, *P=.006*), such that while MMV’s ability to repeat single 2 digit numbers of only moderate complexity was good (95-100%), his performance with two-digit, complex numbers was extremely poor (55%-67% accuracy). There was no effect of response latency for either number category (moderate complexity: X^2 = 1.026, *P=1* and high complexity: X^2 = .667, *P=.587*).

5.4 Yes/no verification of complex numbers—MMV’s difficulty in understanding complex two-digit numbers even with a minimal delay of half a second was explored further in this task that involved no delay, a set size of only one and a simple yes/no verification response. Stimuli consisted of 280 auditorily presented two-digit, complex (e.g., “thirty-two”) numbers. In each trial MMV was both told and shown a written two-digit, complex number (e.g., 78) and was asked to simply report if the auditory and visual numbers presented in the trial were the same or different. MMV's accuracy on this task was 86% (241/280) with 25 false positives and 14 incorrect rejections. This is a very clear indication of the depth of his auditory number comprehension difficulties.

5.5 Refractory access?—Given the evidence that MMV's deficit originated in the processes involved in going from the phonological lexicon to the semantic system, MMV can be considered -by definition- to be suffering from a semantic access deficit limited to number words in the auditory modality. Warrington and colleagues have argued that there is a type of access difficulty that is characterized by the refractoriness of the access procedures (Warrington et al., 1983; Warrington & Cipolotti, 1996; Warrington & Shallice, 1979; Warrington & Leff, 2000; see also Rapp and Caramazza, 1993 for critical discussion). According to these authors, one key characteristic of refractoriness is sensitivity of performance to the rate at which stimuli are processed, or more specifically, the response-stimulus interval. The idea is that there is "a reduction in the ability to utilize the system for a period of time following activation" (Warrington et al., 1983, p. 874). In addition, Warrington and colleagues have shown that when multiple items from the same semantic category are presented in succession, there is increasing processing difficulty—a probe position effect. In order to evaluate whether MMV's comprehension was affected by either presentation rate or probe position, we administered a task that is closely modeled after the task reported by Warrington & Crutch (2004) and Crutch & Warrington (2004).

In this auditory word-visual matching task, stimuli consisted of one set of 20 2-digit, complex numbers and 20 animal names. For each category, five response sheets with 4 written stimuli from each category were prepared. The number words were represented as Arabic numerals, the animal names were printed. For each response sheet one word at a time was presented auditorily and MMV was asked to point to the item on the answer sheet. The four items on each sheet were repeated four times in pseudorandom order before moving on to another answer sheet. Number words and animal names were presented in a blocked manner. The task was presented twice, once at a fast (1 stimulus/second) and once at a slow (1 stimulus/10 seconds) presentation rate.[2]

The results (Table 13) indicate a significant overall difference in accuracy between number words and animals, with perfect performance with animal words and 85%-88% accuracy for numbers. The difference between the two categories was significant at each presentation rate (X^2 = 12.973, *P<.01* for the fast condition and X^2 = 10.667, *P<0.001* for the slow condition). However, for numbers there was no effect of presentation rate (X^2 = .211, *P=.819*) nor for probe position (X^2 = 8.643, *P=.034*, the difference beetwen correct and incorrect responses was significant at each probe position). Finally, although the data in Table13 are collapsed four repetitions of the stimuli, an analysis indicates that there was also no effect of repetition (X^2 = 2.883, *P=.201*).

In summary, with regard to MMV's auditory comprehension of numbers, the results of the tasks reported in this section reveal: (1) no effect of response delay, presentation rate, or probe position, indicating that MMV's deficit is not sensitive to the temporal demands of the comprehension task (or at least not within the range of values we have examined). The absence of effects of presentation rate and probe position indicate that MMV's deficit differs from those of other individuals who have been described as having semantic access impairments (McCarthy & Kartsounis, 2000; Crutch & Warrington, 2001, 2005; (Forde & Humphreys, 1995). (2) A significant effect of both number complexity/frequency and working memory demands. The data show that MMV's auditory number comprehension is good only when a

[2]Because MMV responded promptly after each stimulus presentation, in his case presentation rate is essentially comparable to response-stimulus interval.

single, high-frequency digit must be identified. However, the fragility of even this comprehension is revealed when memory demands are increased simply by increasing set size from 1 to 2. Despite the effects of working memory load, it is important to note that the auditory comprehension deficit is not limited to conditions that stress working memory, as, MMV's comprehension is seriously compromised (84%-86% accuracy) for two-digit numbers even when no memory demands (delay or set size) are placed on the system (Tasks 5.1 and 5.4).

Evaluation 6: The organization of the bilingual language system

As was stated at the outset, this study has focused on MMV's first language -Spanish, which was also the language in which he was educated. However, it is important to note that MMV was a very balanced bilingual and in his everyday life he spoke the two languages regularly; in fact, with his wife and children he spoke his L2 -Catalan- more than his L1. Given this situation it was interesting to evaluate the extent to which the same deficit is present in his L2, and to consider the implications this may have for our understanding of the cognitive and neural organization of the bilingual language system.

Subsets of the tasks presented in the body of the paper were administered to MMV in his L2 and the results (for the two languages) are reported in Tables 1 and 14. Although only a small amount of testing was done in his L2, the results indicate that MMV demonstrated the same modality and category specific difficulties with number words in Catalan as he did in Spanish. Specifically, in Table 13 we observe that performance in his two languages was practically the same in many tasks and highly similar in others. Only the subtraction task is significantly worse in Catalan than in Spanish (71% vs 33%; $X^2 = 6.76$, $P=.02$). With regard to our understanding of bilingual language systems this suggests that the two languages either share procedures for accessing the meanings of number words from the auditory modality, or that these procedures are sufficiently proximal in the brain that they were both affected by MMV's lesion (see De Diego Balaguer, Costa, Sebastián-Gallés, Juncadella, & Caramazza, 2004;Hernandez, Costa, Sebastián-Gallés, Juncadella & Reñé, 2006; and Hernandez, Caño, Costa, Juncadella, Gascón, submitted, for a similar argument regarding category-specific gramamtical deficits and regular and irregular verb morphology).

Summary

In the course of the six evaluations reported above, we have shown that MMV's severe difficulties in comprehending number words –including even single-digit numbers- cannot be the result of a deficit in pre-lexical phonological processing, accessing the phonological lexicon or at the level of number-word semantics. The evidence indicates that MMV activates the correct phonological representations of number words in the phonological input lexicon, but that subsequently there is a failure to activate the semantics corresponding to the number word. This occurs despite the fact that the semantic representations of number words have been shown to be intact for stimuli presented in the visual modality. Thus, this pattern of performance corresponds to a deficit in accessing the meaning of number words in the auditory modality —number word meaning deafness. To the best of our knowledge this is the first well-documented report of this type of deficit and indicates that there is modality and category specificity in the processes and neural substrates involved in accessing number word meanings from modality-specific lexical representations.

General Discussion

We have reported on the case of an individual who, subsequent to damage to the temporo-parietal region of the left hemisphere, suffered a language comprehension deficit that was restricted to understanding number words presented in the auditory modality. Auditory comprehension of non-number words was intact, as was visual comprehension of both number and non-number words. Within the auditory modality, MMV was able to identify number words as words of the language, but was not able to reliably understand them. Temporal factors affecting presentation rate and response latency did not have an effect on auditory number comprehension, although increasing set-size and/or number complexity (or frequency) decreased comprehension accuracy. These results reveal category and modality specificity in the neural substrates supporting access to meaning. The specificity must be such that neural damage can affect the substrates involved in access to the meaning of number but not non-number words in the auditory but not the visual modality.

While considerable neuropsychological, cognitive and neuroimaging literature has supported the claim of cognitive and neural distinctions between the categories of number and non-number words at a semantic level, there has been relatively little evidence regarding whether or not this distinction is maintained in the lexical systems involved in word comprehension and production (for example, see Jefferies, Bateman & Lambon Ralph, 2005). Furthermore, while there has been some evidence supporting distinctions in the retrieval and/or storage of number words in spoken and written production, there has been no evidence to date that the word comprehension system is sensitive to this distinction. This report, therefore, fills a significant gap in our understanding of the categorical organization of the modality-specific lexical processes that interface with semantic systems.

The results from this study indicate severe difficulty in the recovery of number word meaning from the auditory modality. These difficulties are apparent even when MMV is asked to comprehend a single two-digit, monomorphemic number word such as “eleven”. The fact that these difficulties are exacerbated by increasing set size would sem to suggest a working memory component to the deficit. However, the findings that a) there is no effect of increasing temporal demands and b) that comprehension is impaired for single two-digit numbers even under optimal conditions with no temporal load, argue against a significant working memory component. Given this, what seems most likely is that access to the meaning of numbers from the auditory modality is severely disrupted and, even when apprently intact (high frequency single-digit numbers), it is quite fragile and unstable so that increasing task demands have severe consequences for comprehension.

With regard to neuroanatomy, it is worth noting that the MMV’s lesion largely spares the IPS (intra-parietal sulcus) the area most consistently implicated in number meaning representation and processing (for a review see Piazza & Dehaene, 2003), as well anterior temporal areas that have been linked to the representation of semantic knowledge for non-number words (Hodges & Patterson, 1996; Mummery, Patterson, Wise, Vandenbergh, Price & Hodges, 1999). Therefore, MMV’s lesion, primarily affecting the middle temporal gyrus, the posterior portion of the superior temporal gyrus and sulcus and very inferior parietal cortex may have preserved general auditory and phonological processing abilities as well as access to the anterior temporal representation of word meaning for non-number words, while specifically disrupting access to the semantics of numbers in the IPS region from the auditory modality.

The special status of numbers?

The question underlying all reports of category-specific effects is if it is the category per se that is the determining factor or if, alternatively, there is a correlated variable that is actually responsible for the effect. For the category of numbers one correlated variable that has been of concern is the semantic variable of abstractness (e.g., Dehaene et al., 1998). We were able to show that MMV did not have any particular difficulty with abstract words in the auditory modality. Concerns regarding other correlated variables have been raised and we consider these here. Specifically we consider the possibility that the selective difficulty with number words arises because number words are (1) automatised sequences, or (2) a small semantic category.

One concern is that it may not be the category of numbers that is selectively impaired or spared (and therefore specifically distinguished either cognitively or neurally) but rather that numbers are affected by virtue of the fact that they form a part of the "automatic speech" vocabulary (Lum & Ellis, 1994; Cummings, Benson, Walsh & Levine, 1979; Cohen, Dehaene & Verstichel, 1994). Other categories of words within this set would be highly automatised sequences such as the letters of the alphabet, days of the week, months of the year. In fact the individuals described by Cohen et al. (1997), Bachoud-Levi et al. (2003), Cipolotti et al. (1991), and Thioux, Pillon, Samson, De Partz, Noel & Seron (1998) had poor performance with words from ordered sequences as well as with numerals (letters, days of week, names of month). However, MMV was able to repeat days of the week and months of the year without making the lexical errors he made in number word repetition (Table 2) and his auditory comprehension of words from these categories (as assessed by auditory-written word matching was close to perfect; 95% for days of week and 98% for months). This stands in contrast to his poor performance on a similar task reported earlier (Task 3.10 and 3.11) that involved auditorily presented number words. It is clear, therefore, the fact that number words may fall into the category of automatised, sequential vocabulary does not account for the dissociation we have reported.

Number words form a relatively small limited vocabulary set, similar perhaps to sets such as colors or parts of the body. MMV, in a task of auditory word matching with pictures using these categories, did not have any problem in his phonological input processing (249/250, 99.9%). This allows us to exclude category size as a cause of MMV's selective deficit with numbers. These results are similar to those obtained by other individuals (Thioux et al., 1998; Domahs et al., 2006).

Finally, we might consider whether it is number words per se that are affected or any words that refer to quantity—words such as many, few, enough, etc. In order to explore this issue, MMV was asked to perform an auditory word-written word matching task and a repetition task with words denoting quantity. In the first task, MMV was asked to point to the corresponding word among four quantity words written in a page. MMV's performace was perfect, 100%. In the second task, MMV was asked to repeat a list of number words that refer to quantity ("muchos"- *many*; "bastantes"- enough; etc.). MMA's accuracy in this task were 70% correct. However, his errors consisted largely of phonological errors, as was the case with non-number words (Table 2); importantly, he produced no lexical substitutions-his hallmark error in number word repetition.

Modality-specific comprehension: An argument against phonological recoding

A persistent question in language research is the extent to which written language is dependent on spoken language. Given the fact that written language is evolutionarily recent and typically acquired in the individual well after spoken language is firmly established, it would not be surprising if written language comprehension relied on the mediation of spoken language even in the literate adult. Specifically, much attention has been paid to the question of whether or not the comprehension of written forms requires prior conversion to phonological form. In other words, are there orthography-specific processes for gaining access to meaning? Or are the meanings of words only accessible via links from spoken language representations to meaning?

The cognitive neuropsychological evidence for orthographic autonomy in reading most typically takes the form of individuals who cannot produce the correct phonological forms of written words that they can, nonetheless, understand. Such cases have been reported not only in English but in more transparent orthographies such as Italian and Spanish (for a review and discussion see Rapp, et al., 2000). The other relevant pattern is that of individuals with "word meaning deafness" who can understand written words despite failing to understand the meanings of words they hear. It is critical, however, in these cases that a pre-lexical locus of the auditory comprehension problem has been ruled out. As indicated in the Introduction, there are a very small number of reported cases in which this has been clearly established.

The case of MMV provides clear evidence for the independence of access to meaning from print, at least with regard to number words. MMV is able to easily and accurately understand the meaning of written number words (see Tasks 3.1 to 3.14), under conditions in which he cannot understand auditorily presented number words. Furthermore, his success in auditory lexical decision and related tasks (Tasks 2.1, 2.2) indicates that his failure to understand auditorily presented number words is not due to pre-lexical difficulties or even to a lexical level failure in recognizing them as familiar words. Therefore, if written number words would necessarily be converted to phonological form for comprehension, he should have failed in comprehending them. In addition to showing that written number word comprehension can occur in the absence of phonological recoding, MMV's performance very clearly reveals that Arabic numeral comprehension can also occur in the absence of phonological recoding (Tasks 3.1, 3.2, 3.4, 3.5 among others). Simply stated, he does not have to look at the digit 18 or the letters EIGHTEEN, and recover the phonological form "eighteen" in order to access the meaning.

On this basis, one can argue that, at least in the numerically-literate adult, the cognitive and neural organization of the language system allows for direct access to meaning from orthographic and Arabic number representations.

Conclusion

An individual with a deficit that affects his ability to understand the meaning of numbers presented in the auditory modality provides a wealth of information regarding the cognitive and neural organization of the language system. His performance reveals the categorical status of numbers as well as the independence of the auditory and visual language processes that allow us to determine the meanings of the words and symbols we hear and see.

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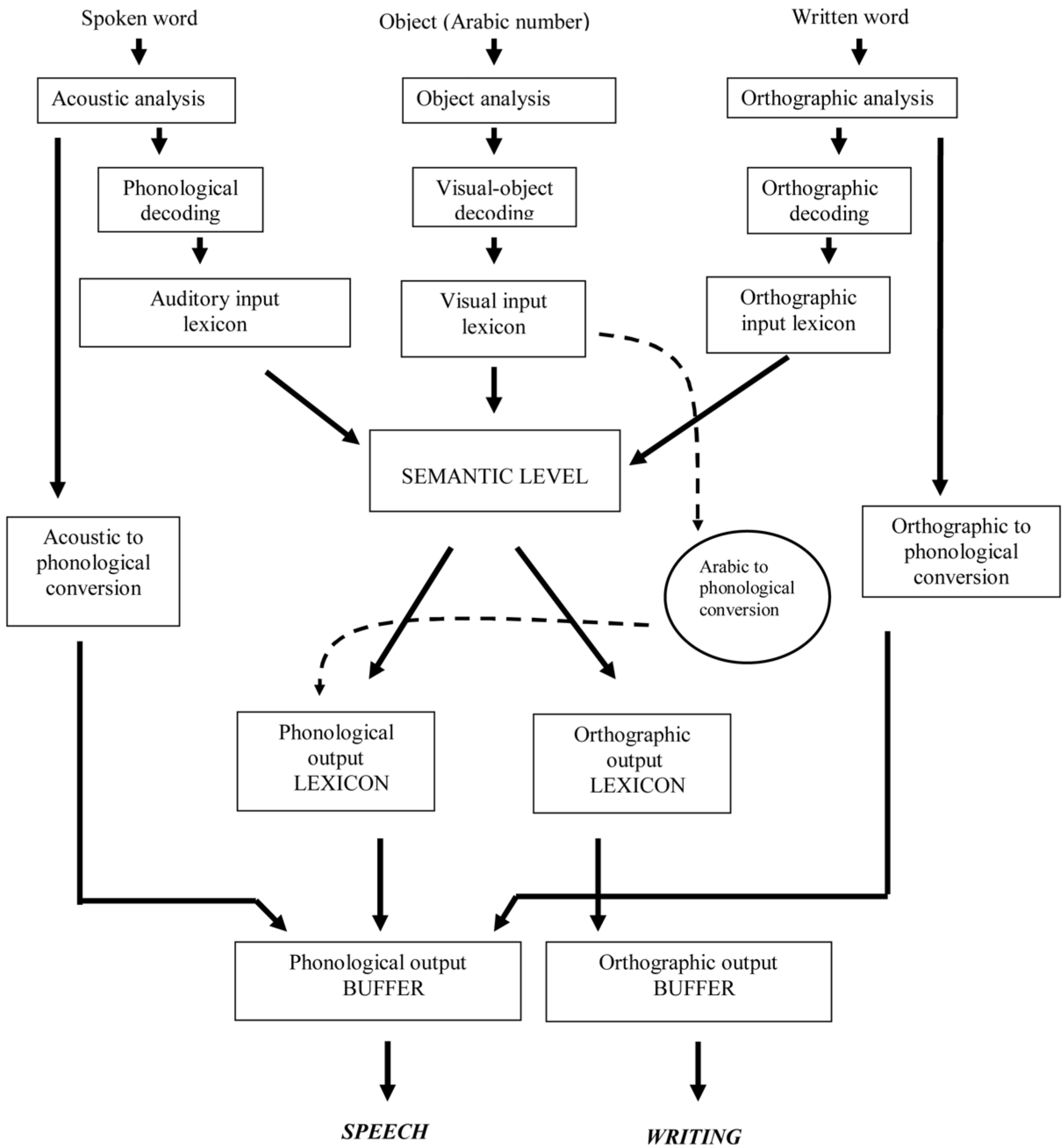

Figure 1.
Archictecture of processing of numbers and other class of words.

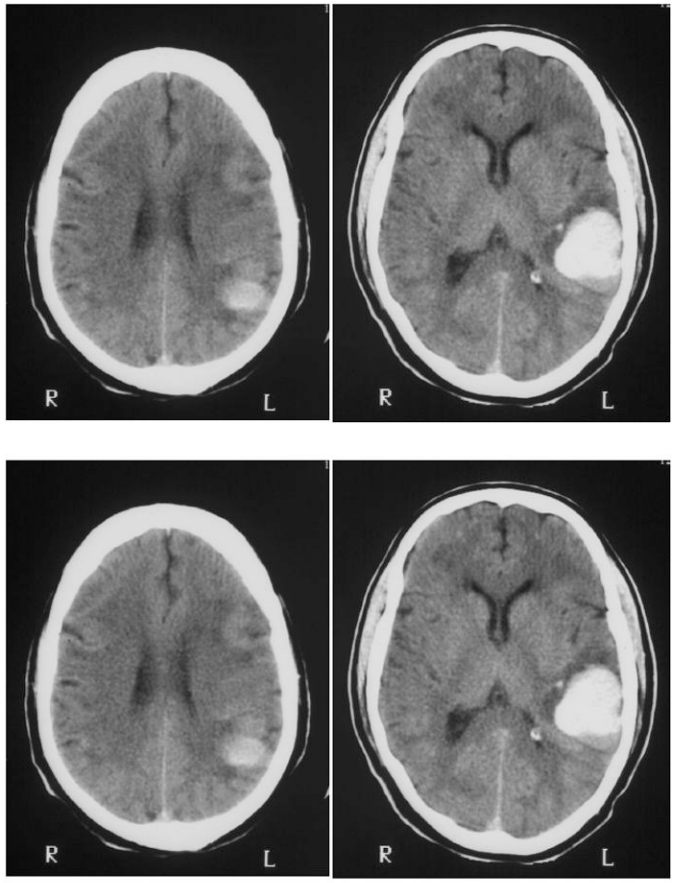

Figure 2.
2 Scan image showing MMV’s left temporo parietal lesion (2000).

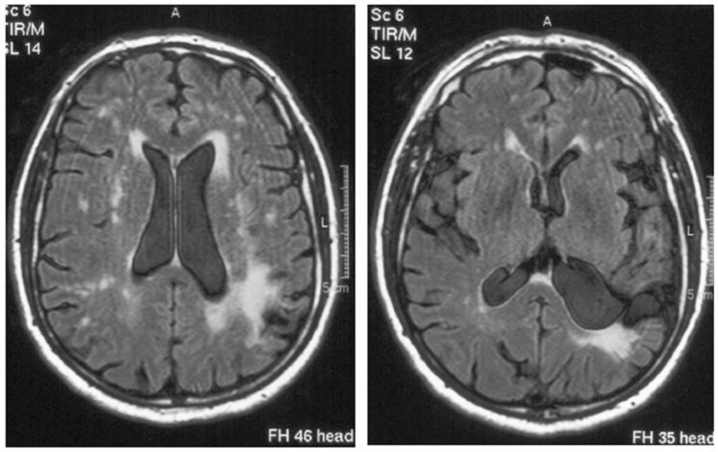

Figure 3.
MR image showing MMV's left temporo parietal lesion (2004, four years after the stroke).

Table 1

MMV's accuracy in language comprehension and production tasks in L1 (Spanish) and L2 (Catalan).

Comprehension		L1	L2
	Auditory word-picture matching I	75/75 (100%)	75/75 (100%)
	Visual word-picture matching I	75/75 (100%)	75/75 (100%)
	Auditory word-picture matching II	60/60 (100%)	60/60 (100%)
	Visual word-picture matching II	60/60 (100%)	60/60 (100%)
	Semantic comprehension	12/12 (100%)	12/12 (100%)
	Oral Synonym judgment	57/60 (95%)	55/60 (92%)
	Written Synonym judgment	58/60 (97%)	55/60 (92%)
	Sentence completion	19/21 (90%)	20/21 (95%)
	Comprehension of definitions	75/78 (96%)	71/78 (91%)
	Test Pyramids and Palmtrees (visual modality with pictures)	50/52 (96%)	-----
Repetition	Words	16/35 (46%)	19/35 (54%)
	Non words	11/104 (11%)	20/104 (20%)
Picture Naming	Nouns	19/40 (47%)	19/40 (47%)
	Verbs	8/20 (40%)	8/20 (40%)
	Snodgrass-Vandewart picture set – oral	89/260 (34%)	89/260 (34%)
	Snodgrass-Vandewart picture set – written	142/260 (55%)	-----
Writing to dictation	Words	20/40 (50%)	16/40 (40%)
	Non words	2/24 (8%)	1/24 (4%)
Reading	Words	71/75 (95%)	71/75 (95%)
	Non words	24/24 (100%)	23/24 (96%)

Table 2

MMV's accuracy and errors in oral naming, repetition, and oral reading of number and non-number words.

	Oral Naming	Repetition	Reading
Number words (N=135)	100%	24%	100%
Errors	-	n=102	-
% lexical errors	-	97%	-
% phonological errors	-	-	-
% other errors	-	3%	-
Non-number words (N=260)	34%	62%	99%
Errors	n=171	n=99	n=2
% lexical errors	9%	10%	-
% phonological errors	31%	84%	50%
% other errors	57%	6%	50%

Table 3

MMV's percentage of correct responses in sound categorization.

Category	Stimulus	% correct Categorization	N
Speech	Catalan, Spanish, English	100%	30
Backward speech	Backward speech	100%	10
Non-speech	Animals, artifacts, music	100%	40

Table 4

Percentage of correct responses for MMV and five age and education-matched control subjects.

	MMV	**Control subjects**	
		Mean	**Range**
Discrimination of minimal pairs			
Words	84%	99%	(96-100)
Non words	73%	99%	(95-100)
Rhyming task	95%	98%	(97-100)
Phoneme monitoring			
Words	95%	97%	(92-100)
Numerals	95%	99%	(95-100)
Embedded number word detection	93%	100%	(99-100)

Table 5

Percentages of correct responses for MMV and control subjects in lexical decision task and number plausibility judgment.

	MMV		Control
Lexical decision		**Mean**	**Range**
Auditory presentation			
Non-number words	94%	99%	(97-100)
Numerals	90%	100%	(99-100)
Non words derived from words	91%	97%	(95-100)
Non words derived from numerals	91%	99%	(97-100)
Visual presentation			
Non-number words	100%	100%	(99-100)
Numerals	100%	100%	(99-100)
Non words derived from words	93%	97%	(95-100)
Non words derived from numerals	97%	96%	(86-100%)
Number plausibility judgment			
Auditory	96%	98%	(95-100)
Visual	95%	98%	(95-100)

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Table 6

Accuracy on tests evaluating conceptual understanding of numerals in the visual modality.

Tests	% correct
Visual magnitude comparison	
Arabic numerals	100%
Written number words	100%
Visual parity judgment	
Arabic numerals	100%
Written number words	100%
Transcoding Arabic numerals to number words	96%
Transcoding number words to Arabic numbers	100%
Ordering Arabic numerals or number words by magnitude	100%
Personal and non personal number facts	100%

Table 7

MMV's accuracy on tasks of number comprehension with auditory vs. visual presentation.

Tests	Auditory Presentation	Visual Presentation
Arithmetic facts		
Addition	46%	100%
Multiplication	62%	96%
Subtraction	71%	96%
Division	25%	96%
Magnitude comparison	69%	100%
Same/different	60%	100%
Number matching -3 options	72%	100%
Number matching -5 options	53%	100%
Date verification	73%	100%
Series	43%	93%
What comes next?	34%	100%

Table 8

MMV's accuracy on tasks of non-number comprehension with auditory vs. visual presentation.

Tests	Auditory Presentation	Visual Presentation
Word-picture matching (Closed categories: colors, parts of body, animals, fruits, clothes)	249/250 (99%)	250/250 (100%)
Word-written word matching –Compound words (semantically related distractors)	50/50 (100%)	50/50 (100%)
Word-written word matching –Compound words phonologically related distractors)	50/50 (100%)	50/50 (100%)
Word-picture matching (verbs)	25/25 (100%)	25/25 (100%)

Table 9

Percentages of correct responses of MMV and control subjects in set of tasks.

	MMV		Control subjects
		mean	**Range**
Peabody Vocabulary test (auditory)			
Concrete words	100%	100%	(100-100)
Abstract words	97%	100%	(100-100)
Synonym judgment			
Auditory			
High imageability	100%	100%	(100-100)
Low imageability	90%	93%	(87-100)
Visual			
High imageability	100%	99%	(93-100)
Low imageability	93%	93%	(90-100)
Auditory-written word matching			
Concrete words	100%	100%	(100-100)
Abstract words	88%	99%	(96-100)
Written semantic comprehension			
Concrete words	100%	99%	(93-100)
Abstract words	80%	83%	(67-100)

Table 10

MMV's accuracy in word-picture matching, varying stimulus type, number complexity, set size and modality.

	Auditory Presentation	**Visual Presentation**
Set size 1 *(N=50, each condition)*		
Objects	100%	100%
Animals	100%	100%
Arabic numerals-single digit	100%	100%
Arabic numerals-two digit	84%	100%
Set size 2 *(N=50, each condition)*		
Objects	100%	100%
Animals	97%	100%
Arabic numerals-single digit	70%	100%
Arabic numerals-two-digit	67%	100%
Set size 3*(N=50, each condition)*		
Objects	99%	100%
Animals	97%	100%
Arabic numerals-single digit	54%	100%
Arabic numerals-two digit	48%	99%

Table 11

Auditory-visual matching varying response latency with objects, animals, 2-digit numbers of medium complexity.

	.5 secs.	2 secs.
Set size 1 *(N=25 sets)*		
Numbers	92%	84%
Set size 2 *(N=25 sets)*		
Numbers	68%	68%
Set size 3*(N=25 sets, each condition)*		
Numbers	51%	45%
Animals	95%	99%
Objects	96%	96%

Table 12

Accuracy in repetition at three different latencies, of single numbers of either moderate or high complexity.

	.5 secs.	2 secs.	5 secs.
Numbers-moderate complexity (20 stimuli/latency)	95%	95%	100%
Numbers-high complexity (27 stimuli/latency)	55%	67%	67%

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Table 13

Accuracy between numerals and animals collapsed across presentation and repetition.

	Probe 1	Probe 2	Probe 3	Probe 4	Total
Numbers					
Fast	90%	90%	65%	95%	85%
Slow	85%	80%	85%	100%	88%
Animals					
Fast	100%	100%	100%	100%	100%
Slow	100%	100%	100%	100%	100%

Table 14

MMV's accuracy on oral tasks with numbers in his two languages Spanish (L1) and Catalan (L2).

	N	Spanish	N	Catalan	description
Oral naming	135/135	100%	135/135	100%	see table 2
Reading (numbers words)	135/135	100%	135/135	100%	see table 2
Repetition	33/135	24%	21/135	16%	see table 2
Oral arithmetic facts					see task 3.7
Addition	11/24	46%	11/24	46%	
Multiplication	15/24	62%	13/24	54%	
Subtraction	17/24	71%	8/24	33%*	
Division	6/24	25%	10/24	42%	
Number matching -3 options	244/340	72%	249/340	73%	see task 3.10
Number matching -5 options	180/340	53%	189/340	55%	see task 3.11
Same/different	24/40	60%	23/40	57%	see task 3.9
Series	13/24	43%	7/24	29%	see task 3.13
What comes next?	21/60	34%	12/60	20%	see task 3.14

* significant difference