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Word Deafness with Preserved Number Word Perception

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Abstract

We describe the performance of an aphasic individual, K.A., who showed a selective impairment affecting his ability to perceive spoken language, while largely sparing his ability to perceive written language and to produce spoken language. His spoken perception impairment left him unable to distinguish words or nonwords that differed on a single phoneme and he was no better than chance at auditory lexical decision or single spoken word and single picture matching with phonological foils. Strikingly, despite this profound impairment, K.A. showed a selective sparing in his ability to perceive number words, which he was able to repeat and comprehend largely without error. This case adds to a growing literature demonstrating modality-specific dissociations between number word and non-number word processing. Because of the locus of K.A.'s speech perception deficit for non-number words, we argue that this distinction between number word and non-number word processing arises at a sublexical level of representations in speech perception, in a parallel fashion to what has previously been argued for in the organization of the sublexical level of representation for speech production.

Keywords

Aphasia; numerosity; category-specific deficits; speech perception

1. Introduction

The human capacity for numerical cognition depends, at least in part, on nonlinguistic neural circuitry. Amalric and Dehaene (2016) show that expert mathematicians engage a largely distinct network of brain regions when engaging in high-level mathematical reasoning compared to reasoning about general-knowledge semantics. This high-level mathematical reasoning network corresponds closely with areas previously associated with a variety of number processing and calculation tasks (Nieder & Dehaene, 2009). Striking neuropsychological dissociations have been found between processing numerical concepts and number words as compared to other types of semantic processing. For example, Cipolotti and colleagues (1991) reported a patient who was unimpaired in semantic tasks involving non-numerical material, but was completely unable to perform numerical

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reasoning tasks with numbers greater than four, while Cappelletti and colleagues (2005) reported a patient who showed the opposite pattern – severe impairments across all semantic tasks except for those that required numerical processing. At least at levels of semantic and conceptual processing, dissociations between processing number and other types of meaning is clear.

A neural distinction between the processing of number concepts and semantic knowledge about other categories of words may not be particularly surprising. Conceptual knowledge has been argued to be organized categorically (e.g., Caramazza & Mahon, 2003; Huth et al., 2016). A variety of category-specific semantic deficits have been reported in the neuropsychology literature (see Capitani, Laiacona & Mahon, 2003 for review), with selective impairments in processing information about animals (e.g. Caramazza & Shelton, 1998; Hart & Gordon, 1992), fruits and vegetables (e.g., Farah & Wallace, 1992; Samson & Pillon, 2003; Crutch & Warrington, 2003) and tools and artifacts (e.g. Sacchett & Humphreys, 1992; Breedin, Saffran & Coslett, 1994). Under this framework, number concepts could simply be another category of semantic knowledge that has distinct neural substrates. The ability to reason about numbers has been argued to depend not on language, as this ability is observed in infants (Feigenson et al., 2004), primates (Brannon & Terrace, 1998) and cultures without linguistic number symbols (Gordon, 2004; McCrink et al., 2013). This suggests that our brains may have evolved a special system for processing numerical concepts (see Dehaene, 2011 for extended discussion).

However, the distinction between processing numbers and other types of words has not just been observed in semantics. As we will discuss below, there are several lines of evidence that suggest modality-specific differences between number and non-number word processing. Number/non-number word dissociations have been reported in individuals with selective impairments in either written or spoken language and in individuals with selective language comprehension or language production deficits, suggesting that the separation of number and non-number words processing occurs in systems peripheral to the central semantic processing system. Category-specific organization within modality is potentially more surprising, as it is clear that number words and non-number words share most peripheral processes, such as the visual system for recognizing the shapes of alphanumeric characters, or the articulatory system for producing the gestures of the lips and tongue necessary to produce both number and non-number words. Understanding the processing stages at which numbers and non-number words are separated can provide key insights into the organization of knowledge in the numerical and language processing systems.

Written letters and Arabic digits have similar visuospatial features and require similar motor-stroke planning in production. Yet, there is clear neuropsychological and neuroimaging evidence suggesting that at least partially separate mechanisms are involved in recognizing and producing letters and digits. Anderson, Damasio and Damasio (1990) and Starrfelt (2007) both report patients with a selective impairment in both reading and writing individual letters, but without difficulties in either reading or writing Arabic numerals. Delazer and colleagues (2002) also report a patient with impaired letter processing and intact digit processing, but for their case the deficit was selectively in written output, with no impairments for either type of symbol in written input. McCloskey and colleagues (2013)

report the opposite pattern, an individual with a neurodegenerative disorder that resulted in severely impaired perception and production of single digits, leaving the perception and production of letters largely spared. Strikingly, for all of these patients, deficits are limited to the written modality, with no impairments in processing either number or non-number words in the spoken modality, indicating that the deficits cannot be localized to an impairment at a semantic level. Furthermore, this dissociation between processing written letters and digits is consistent with recent neuroimaging investigations that have identified separable regions in the ventral occipitotemporal cortex for Arabic digit and letter processing (Shum et al., 2013; Grotheer et al., 2016).

Dissociations between number words and non-number words have also been reported within the spoken language system. Most of the dissociations that have been reported occur within the spoken production system. Patients have been reported with speech production deficits disproportionately affecting number words, while leaving other types of words largely intact (e.g., Marangolo, Piras & Fias, 2005). For example, the patient in Marangolo and colleagues had an impairment that could be localized to the spoken output modality, as he had no difficulty producing or comprehending written numbers, though he did have a mild impairment in spoken word comprehension that affected both number and non-number words. Cohen and colleagues (1997) report a patient who had a selective speech production impairment, but who produced different types of errors with number and non-number words, making semantic errors with numbers and phonological errors with other types of words, a pattern that has now been reported in a number of other cases (see Dotan & Friedmann, 2015 for discussion). Bencini and colleagues (2011) report a particularly clear dissociation in a single patient between producing number words, which were produced without error, and producing non-number words, which were produced with phonemic errors. This double dissociation within the spoken production modality between number and non-number words has been used to argue that, within the internal mechanisms of the speech production system, number words are processed by brain systems that are distinct from systems that process non-number words.

While a large number of cases have been reported with dissociations between number and non-number words in the spoken output modality, fewer cases have been reported in the auditory input modality. To our knowledge, there are only two relevant cases in the literature, both with a selective impairment in number processing in auditory input. Caño and colleagues (2008) report a patient with a selective impairment in the auditory processing of number words without a corresponding problem in processing non-number words, and without any deficit in processing written number words. Han, Shao and Bi (2011) report a similar case, an individual whose auditory perception of language is nearly perfect for words but severely impaired for numbers, with the additional caveat that the reverse pattern was observed in writing, with better performance writing numbers than writing words.

Taken together, these neuropsychological case studies suggest separate processing of number and non-number words within different modalities- written versus spoken language, language perception versus language production. One pattern that has not previously been reported in the literature is a sparing of number word processing in the auditory input modality, with an impairment in processing other types of spoken words. It is precisely this

pattern that we report in the current investigation. We present an individual (K.A.) with a profound impairment in comprehending spoken language following two strokes, who, despite this impairment, appears intact in comprehending spoken number words.

Modality-specific dissociations between number and non-number word processing provides some of the strongest evidence of the functional and neural segregation of word and number processing. The current case adds further evidence to this growing literature, reporting a novel pattern of impairment. In addition, careful analysis of where K.A.'s impairment with non-number words lies in the speech perception architecture provides novel evidence for where in the processing stream number and non-number words start to dissociate. Figure 1 depicts the cognitive architecture of speech perception we are assuming for the current study. According to this architecture, first, prelexical representations of the basic units of spoken words are extracted from the acoustic input. These prelexical representations serve as inputs into a lexical level, or a long term memory system that recognizes which sequences of sounds are familiar words. Lexical representations in turn activate semantic representations of the meaning of words. Bidirectional arrows are included between both the sublexical and lexical levels and the lexical and semantic levels because most theories of speech perception assume both bottom-up and top-down information contribute to the activation of representations at these levels. Assuming this architecture, we show that KA's difficulty in processing non-number words occurs because of a profound deficit at a prelexical level of representation. K.A.'s ability to perceive spoken number words in the face of this prelexical speech perception deficit suggests a division between how number and non-number words are processed, even at this early level of processing.

2. Case history

K.A. was a right-handed native English speaking male born in 1957 with twelve years of formal education who worked as an electrician. He suffered a right hemisphere stroke in 2002 that led to a minor deficit in speech perception, but he was able to return to work. He had a second, left hemisphere stroke in March 2013 that resulted in profound impairments in language processing. Behavioral testing for this study began in January 2015, 22 months following the stroke and continued until his death in April 2016, during which time his neuropsychological profile remained stable. Audiogram revealed moderate hearing loss in both ears, though his performance was not outside the range of normal controls and his performance was better with the hearing aids he wore during the course of testing. An MRI taken 27 months after the second stroke is shown in Figure 2. He had damage in both the left and right hemisphere in the superior and middle temporal gyri, Heschl's gyrus, temporal poles and insula. His left hemisphere lesion included inferior frontal damage, while his right hemisphere lesion included inferior temporal gyrus, parietal regions like the supramarginal gyrus and angular gyrus and the right middle and superior occipital gyri. It is worth noting that regions that have been argued to be involved in number processing (e.g. bilateral inferior parietal lobe, see Cantlon, 2012 for review) were spared by both strokes.

Initial assessment was carried out using the Western Aphasia Battery. His WAB Aphasia Quotient was 68.5 and he was classified as a Wernicke's patient. His spontaneous speech was largely fluent and correct, though he produced a substantial number of circumlocutions

and had mild word finding difficulties. More substantial testing of his residual language abilities revealed particular difficulty in tasks that required the perception of spoken language. He could repeat correctly only 60/120 of the single words in the Philadelphia Word Repetition task (Dell, Martin & Schwartz, 2007), and he showed no significant effects of either frequency (High: 32/60 vs. Low: 28/60, $\chi^2(1) = .3$, $p = .58$) or imageability (High: 35/60 vs. Low: 25/60, $\chi^2(1) = 2.7$, $p = .10$). The Peabody Picture Vocabulary task (Dunn & Dunn, 2007) was used to investigate his ability to comprehend spoken words. Performance with auditory input placed him in the <.1th percentile. A simpler task, in which he hears a single spoken word and is shown a single picture and has to decide whether the word and picture match, also was difficult for him (Martin, Lesch & Bartha, 1999). He had particular difficulty with mismatch trials in which the spoken word was phonologically similar to the picture (37/54, 69% vs. unrelated foils; 52/54, 96%, $\chi^2(1) = 12.5$, $p = .0004$), while he was marginally significantly worse on semantically related foils (45/54, 83%) than unrelated foils (52/54, 96%, $\chi^2(1) = 3.64$, $p = .056$). This severe impairment in the auditory input modality was in stark contrast to only a moderate impairment with written input. When he was administered the Peabody Picture Vocabulary task with written words, his performance placed him in the 13th percentile of age- and education-matched controls, with a raw score of 185. Similarly, his word repetition was much more impaired than his picture naming ability. While his picture naming was somewhat impaired, he was able to correctly name 83% of the pictures in the Philadelphia Picture Naming Test (Roach et al., 1996). While K.A. may have had mild impairments in written comprehension, semantics and speech production, his most striking deficit was in speech perception.

Given this speech perception impairment, it was unsurprising that K.A. had difficulties with a number of short term memory tasks that relied on spoken input. His rhyme and category probe spans (Martin et al., 1999) were both less than one, indicating that he was unable to consistently say whether two auditorily presented words rhymed or were members of the same semantic category. His was only able to repeat both words in a two word sequence 5% (3/120) of the time, with similar performance for the first word (24/120, 20%) and the second word (18/120, 15%, $\chi^2(1) = .72$, $p = .40$) when scored separately. We were therefore surprised by K.A.'s performance on the digit span task with auditorily presented number words. He was given lists of digits to immediately recall, with two lists at each length, starting with length of two, and then increasing in length until he made errors on both of the lists. Over two administrations of this task, he was able to correctly recall all of the lists at length 2, 3 and 4 and in one administration he was able to correctly one of the two lists at length 5. This finding suggested that, despite his severe speech perception deficit, K.A. was able to perceive spoken digits, the focus of our current investigation. In the next section, we present a series of experimental tasks designed to probe where in the cognitive architecture of speech perception K.A.'s impairment with non-number word arises. Following that, we will report on a series of experimental studies designed to probe K.A.'s processing of number and non-number words.

3. Localizing the speech perception impairment for non-number words

In this section, we present a series of tasks designed to localize the level of impairment in K.A.'s speech perception stream. Figure 2 shows a cognitive architecture of speech

perception based on several prominent computational theories of how it is mapped from spoken words to meaning (e.g., McClelland & Elman, 1986; Luce and Pisoni, 1998; Norris, 1994; Dial & Martin, 2017). According to this theoretical framework, acoustic information activates language-specific sublexical representations. Activated sublexical representations are used to access a phonological lexicon, or the stored representation of the pronunciation of familiar words. These lexical representations in turn activate the semantic representations of the meaning of the spoken words. Sublexical representations can also directly map to the phonological level in the spoken production system, as in a task like nonword repetition.

We are interested in localizing K.A.'s deficit with non-number words within this theoretical framework. K.A. participated in a series of 5 carefully controlled experiments designed to probe different levels of representation within the speech perception stream (see Dial and Martin (2017) for a detailed description of these tasks). Tasks were matched on phonological difficulty as well as the need for working memory, avoiding confounds in commonly used material. K.A.'s ability to process sublexical units was probed by discrimination tasks with nonword stimuli, as well as an auditory-written syllable matching. His ability to access representations at a lexical processing level was probed by an auditory lexical decision, whereas his ability to access semantics from lexical representations was probed with a spoken word picture-matching task. These tasks are described in greater detail in the Materials section, below. Control data was collected from 11 self-reported neurally healthy older adults with normal or corrected to normal hearing, though only 10 controls participated in the picture-word matching and auditory-written syllable matching tasks. Based on the theory shown in Figure 2, we reasoned that if K.A. is only impaired with mapping from the phonological lexicon to semantic representation, he should perform well on all tasks except for the word-picture matching task. If his impairment is at the level of the phonological lexicon, he should be impaired at auditory lexical decision and word-picture matching, but not on the other three tasks. However, if his impairment was solely at a sublexical level, he should be roughly equally impaired on all of the tasks presented. By controlling for task demands, for example, by making the foils in the picture-word matching as phonologically distant from the target as the foils in the discrimination tasks, performance across the tasks should be directly comparable, which is not necessarily the case for comparing performance across standard neuropsychological tests (see Dial and Martin, 2017 for discussion).

3.1 Materials

3.1.1. Word discrimination.—Word stimuli consisted of 90 pairs of single syllable words two to four phonemes in length ($M=3.06$) that differed from each other by a single distinctive phonetic feature (i.e., manner, place or voicing) in either the initial or final consonant (e.g., pat-bat, bat-bad). Half of the items differed in the initial consonant and half differed in the final consonant. For the “different” stimulus pairs, roughly a third of the stimuli differed in manner ($n=32$), a third in place ($n=29$) and a third in voicing ($n=29$), and these were equally distributed between the initial and final consonant. The task consisted of 180 trials, half of which were the same and half of which were different. The 90 “same” trials were created by arbitrarily selecting one of the items from the 90 “different” stimulus pairs.

The stimuli were presented using natural speech tokens with one item spoken by a male and one item spoken by a female to avoid use of raw acoustic code in discrimination judgments. This manipulation was critical to ensure that participants were comparing abstract representations rather than raw acoustic information to make the discrimination judgments (i.e., making perceptual, rather than acoustic, judgments). There was an additional inter-stimulus interval (ISI) manipulation (50 vs. 1500ms). The long ISI was included because a previous study (Wolmetz & Rapp, 2011) suggested that some patients show refractory effects in speech perception, where processing of a stimulus leads to degraded or blocked access to a similar representation. Inclusion of the 1500ms condition reduces refractory effects but places a greater demand on short-term memory (STM) while the 50ms condition reduces STM demands while increasing refractory effects. Within each session there were 90 trials for each ISI condition, with trials blocked by ISI. In the first session, the 1500ms ISI block was presented first, and in the second session, the 50ms ISI block was presented first. Reported data collapses across these ISI conditions.

3.1.2. Syllable discrimination.—Consonant-vowel and vowel-consonant syllables were created using the stimuli from the single feature difference word discrimination task by removing either the initial or final phoneme (e.g., /pæ/-/bæ/), thus creating 90 stimulus pairs. Otherwise, the task was identical to the word discrimination task described above, including the ISI manipulation. Reported data collapses across these ISI conditions.

3.1.3. Auditory lexical decision.—Word stimuli for the auditory lexical decision task were created using 149 randomly selected stimuli from the word discrimination task. To create the non-word stimuli, we changed a single distinctive feature of a single phoneme of either the initial or final consonant of the word stimuli (e.g., bat → bap), thus totaling 298 trials, with half created by changing the initial consonant of a word stimulus and half created by changing the final consonant. Of the 149 word stimuli, there were 3 words that required the phoneme to be changed by two distinctive features in order to create a non-word, but the mean number of features changed within a word to create a non-word was essentially one ($M=1.02$). The word and non-word stimuli were presented using natural speech tokens spoken by a female.

3.1.4. Single picture-word matching (PWM).—Stimuli for the single PWM task were constructed from 28 pairs of spoken words that differed by a single distinctive feature in the initial or final phoneme. Half of the items differed in the initial phoneme and half in the final phoneme (e.g., pear-bear; log-lock). The corresponding picture stimuli were acquired using a Google Image search. Each picture was presented individually two times across the experiment, once with an auditorily presented word that matched the pictured item (e.g., a picture of a log presented with the word log) and once with an auditorily presented word that corresponded to the pair of the picture (e.g., a picture of a log presented with the word lock), thus totaling 112 experimental trials, along with 40 additional filler items. Picture and word stimuli were concurrently presented. The auditory stimuli were natural speech tokens recorded by a female speaker.

3.1.5. Auditory-written syllable matching (AWSM).—The six stop consonants paired with /ɒ/ (i.e., /pɒ/, /bɒ/, /dɒ/, /tɒ/, /gɒ/, /kɒ/) were used as the auditory stimuli for the AWSM task. The written stimuli were BA, PA, DA, TA, GA and KA, respectively. Each spoken syllable was presented individually twelve times across the experiment, six times with a written syllable that matched the spoken syllable and six times with a written syllable that did not match (twice for voicing, twice for manner, twice for place), thus totaling 72 experimental trials.

3.2. Procedure

All 5 tasks were administered on an iMac desktop computer running PsyScope (Cohen, MacWhinney, Flatt & Provost, 1993). Auditory stimuli were presented via speakers with volume adjusted to a comfortable level. Errors were coded using raw data output from Psyscope. Each experiment began with five practice trials, followed by the experimental trials. Tasks were presented over five or six experimental sessions separated by at least a week. In session 1 and 2, the word and nonword discrimination tasks were administered. Because there were two ISI conditions (i.e., 50ms and 1500ms) for the word and syllable discrimination tasks, the tasks were administered in two blocks across two separate sessions to avoid repetition of stimuli within a single session. In session 3, the auditory lexical decision task was presented. Session 4 was the spoken-word picture matching and session 5 was the AWSM task. For the AWSM a pre-test was administered to ensure that K.A. was able to read the written syllables. He was able to read the written syllables with 100% accuracy by the second attempt.

Fifteen trials into the first block of the first task (word discrimination), the experimenter was uncertain whether K.A. had understood the initial instructions. Additional instruction, including several spoken and written samples were provided by the experimenter, as well as additional written instructions and a diagram of the task. Trials preceding these additional instructions were excluded from analysis.

Since all tasks require a yes-no decision, data are reported as d' . Three statistical analyses were carried out. First, we determined whether K.A.'s d' was significantly worse than control performance, using the Crawford and Howell (1998) modified t -test. Second, using exact binomial probabilities, we evaluated whether K.A.'s performance was better than chance.

3.3. Results/Discussion

Table 1 reports discrimination scores for all the tasks presented above as well as the performance of the control participants. K.A.'s performance was quite poor on all of these tasks. He was correct on only 66% of the trials in the word discrimination task ($d' = .9$) and 60% of the trials in the syllable discrimination tasks ($d' = .5$) and was significantly worse than controls on both tasks ($t(10) = -4.66, p < .001$ and $t(10) = -4.23, p < .001$, respectively). However, an exact binomial test indicated that for both of these tasks, it was extremely unlikely that K.A.'s performance was simply due to chance guessing (Word Discrimination Task, $p < .001$; Syllable Discrimination Task, $p < .001$). Performance on Auditory Lexical Decision was also very poor (54% accuracy, $d' = .2$), significantly worse

than controls ($t(10) = -3.82$, $p < .001$), and not significantly better than would be expected by randomly guessing on each trial ($p > .1$). Picture word matching was also very inaccurate (54% accuracy, $d' = .3$), worse than controls ($t(9) = -6.17$, $p < .001$), and not different than would be expected by guessing ($p > .3$). Finally, his performance on auditory-written syllable matching task was poor (60% accuracy, $d' = .6$), worse than controls ($t(9) = -6.04$, $p < .001$), and no better than would be expected by guessing ($p > 1$).

K.A. was extremely impaired in all of these measures of speech perception, suggesting that his impairment includes a deficit at the sublexical level during speech perception. His speech perception deficit cannot simply be explained by his moderate hearing loss. Matched controls were screened for hearing loss with the same procedure, and K.A.'s hearing loss fell well within the range of the control participants, all of whom had significantly better speech perception than he did. However, his performance appears to be slightly better for sublexical tasks (word and syllable discrimination, auditory-written syllable matching) than for tasks that included additional lexical and semantic processing components (auditory lexical decision, picture word matching). Better performance on the discrimination tasks cannot be attributed simply to those tasks being easier, as these discrimination tasks had an additional working memory load, requiring participants to remember one spoken stimulus and compare it to a second token, and controls performed worse on the discrimination tasks than on the picture word matching task. In order to examine relative levels of impairment, his performance on each of these tasks was converted to a z -score relative to the control group. For syllable and word discrimination tasks, z -scores were roughly equivalent. Although z -scores indicated slightly better performance for auditory lexical decision vs. syllable discrimination and picture word matching vs. auditory-written syllable matching tasks, the 95% confidence interval of the difference between the tasks, calculated using a bootstrapping procedure, contained 0. Therefore, we conclude that K.A. has a primary deficit in sublexical processing of spoken input, with a small secondary deficit in lexical-semantic processing of spoken words.

Despite this sublexical impairment with non-number words, K.A. was remarkably good at perceiving spoken number words. In the next section, we discuss a series of experiments carried out with K.A. showing that his perception of number words was spared relative to other types of spoken stimuli.

4. Comprehension of number words

As discussed above, the first indication that K.A. had a selective sparing of number words was in his remarkable performance on the digit span task relative to his poor performance on similar tasks with non-number words. The ability to correctly repeat 4 or 5 auditorily presented digits but essentially never being able to repeat two non-digit words was certainly striking.

However, even within unimpaired populations, span scores tend to be higher with number words than with tasks that use non-number words (Crannell & Parish, 1957; Jones & Macken, 2015). This phenomenon could be due to a variety of factors. Number words are a small, closed set of stimuli and each item in the set is phonologically distinct from all other

items. With the convergence of these factors, it is possible that less phonological information is needed for a participant to correctly identify the spoken stimuli in a digit span task than in an open-class word repetition task, which could explain K.A.'s better performance on that task.

Therefore, we devised a series of short experiments designed to probe K.A.'s perception of number words compared to other similar types of words. When possible, we compared auditory presentation of these number word and non-number word stimuli with visual presentation, to show that (1) the impairment with non-number words was selective to the auditory input modality and (2) number words were spared with both auditory and written input. The experiments, described below, involved the following tasks: matching, writing-to-dictation, and magnitude comparison.

Ideally, we would have been able to identify other categories of closed-set stimuli in which the members were matched on other variables, like length and lexical neighborhood. However, the number of other closed set categories are quite limited (our experiments used letters of the alphabet, days of the week, months of the year) and therefore we cannot match conditions on all relevant psycholinguistic variables. However, in addition to the other closed set categories, we devised an experiment with open-class words that were roughly the same length as the number words, high in imageability, and with even sparser phonological neighborhoods, and presented the same set of words to him over the course multiple session to try to mimic some of the properties of digits as a stimulus set.

4.1. Methods and Procedures

4.1.1. Matching Tasks.

4.1.1.1. Auditory-Visual Matching.: We compared K.A.'s auditory comprehension of number words to performance on conditions consisting of either closed sets of stimuli or imageable words. The three closed set conditions included letters, days of the week, and months of the year. The imageable word condition consisted of nine words (plane, coffee, school, night, fire, church, hotel, spider, hand). These stimuli were slightly longer than the digits in terms of number of phonemes (Imageable Words: mean = 4.0, standard deviation = .71, Digits: mean = 3.1, standard deviation = .93) and had fewer phonological neighbors (Imageable Words: mean = 10.8, standard deviation = 9.4, Digits: mean = 18.7, standard deviation = 10.2). The number word condition consisted of numbers zero through twelve as these are numbers represented by a single word. The letter condition consisted of nine letters (A, C, F, H, I, L, M, O, R) that are non-rhyming to increase phonological distinctiveness. The days condition consisted of all seven days of the week and the months condition of all twelve months of the year. In separate blocks, K.A. was presented with a piece of paper that included numbers written in Arabic numerals, uppercase letters, or the days, months, or imageable words in written form. The experimenter read each stimulus aloud, covering her mouth from K.A.'s view, and instructed K.A. to point to the correct written stimulus. K.A. completed 149 trials for numbers, 45 trials for letters, 45 trials for imageable nouns, 98 trials for days, and 96 trials for months.

4.1.1.2. Visual-Visual Matching Tasks.: We assessed K.A.'s comprehension of written stimuli through a visual-visual matching task. K.A. completed this task for three conditions: numbers, letters, and imageable words. Only one condition was assessed at a time. In the numbers condition, K.A. was presented with numbers one through nine in written word form on a computer screen and asked to point to the corresponding Arabic numeral. In the letter condition, K.A. was presented with lowercase letters and asked to point to the corresponding uppercase letter. Only letters that are not identical in uppercase and lowercase forms (A, B, D, E, F, G, H, J, K, M, N, P, Q, R, T, U, Y) were included. The imageable word condition consisted of the nine words described in the auditory-visual matching task presented in written form on the computer screen while K.A. pointed to the appropriate picture. K.A. completed 90 trials for each condition.

4.1.1.3. Imageable Word Training Task.: Number words are unique in that they are a phonologically distinct closed set. To try to replicate these conditions with non-number words, an additional study was designed in which the same set of phonologically distinct spoken word stimuli was repeated across sessions. The logic was that repeating the same set of stimuli across sessions should lead to these stimuli being treated more as a closed set as training goes on. If K.A.'s intact number processing reflected the fact that numbers are phonologically distinct and in a closed set, then we predicted that K.A.'s performance on this task would at least improve across training sessions, if not reach a level of performance comparable to his number word performance. We selected the set of nine imageable words used in the previous tasks. Using the experimental procedure from the auditory-visual matching task, we presented each word 10 times per session in random order. We conducted 5 total sessions, each separated by approximately one week.

4.1.2. Repetition Tasks—A second series of experiments looked at K.A.'s ability to repeat the same types of stimuli as used in the matching tasks. The experimenter read each stimulus aloud, covering her mouth from K.A.'s view, and instructed K.A. to repeat the word. K.A. completed 187 trials for numbers, 135 trials for letters, 135 trials for imageable nouns, 142 trials for days, and 144 trials for months.

4.1.3. Writing to Dictation Tasks—In addition to matching and repetition tasks, spoken word comprehension was assessed through a writing-to-dictation task. K.A. was instructed to write the number or letter spoken by the experimenter. Stimulus presentation was blocked by condition and K.A. was informed of the condition prior to starting. The number condition consisted of numbers zero through twelve and the letter condition consisted of all 26 letters of the English alphabet. In all, K.A. completed 52 trials in each condition.

4.1.4. Magnitude Comparison Task—A magnitude comparison task was administered to compare auditory and written comprehension as well as semantic knowledge of numbers and days of the week. In this task, K.A. was asked to identify which of two digits was larger or which of two days of the week comes first. Stimuli were presented either verbally by the experimenter or visually on a computer screen. Each condition was presented separately and K.A. was informed of which condition was being assessed. K.A. completed

50 trials in the auditory number condition, 48 trials in the written number condition, 56 trials in the auditory days condition, and 55 trials in the written days condition. Two trials in the written number condition and one trial in the written days condition were excluded because K.A. was not looking at the computer screen during stimuli presentation.

4.3. Results

Accuracy data for auditory and visual matching, repetition, writing to dictation, and magnitude comparison tasks, excluding the training task, are presented in Table 2. Performance across different tasks was analyzed using a 2-by-2 chi-square analysis, with the Yate's correction for continuity. Within the set of auditory matching tasks, his performance was perfect for number words (149/149), and significantly better than his performance with letters (38/45; $\chi^2(1) = 19.8$, $p < .0001$), days of the week (85/98; $\chi^2(1) = 18.3$, $p < .0001$), months of the year (76/98; $\chi^2(1) = 34.0$, $p < .0001$) and imageable words (38/45; $\chi^2(1) = 19.8$, $p < .0001$). For three tasks, a comparison could be made across the auditory and visual modality. For number words, K.A.'s performance was perfect for both auditory and visual input. For both letters and imageable words, he was significantly worse with the auditory modality than the visual modality (letters: 88/90; $\chi^2(1) = 6.6$, $p = .01$; imageable words: 90/90; $\chi^2(1) = 11.7$, $p = .0006$).

This pattern of a selective impairment in spoken non-number word processing with sparing of number word processing was also observed in tasks that relied on other output modalities. In the repetition task, K.A. was significantly better at repeating number words (183/187) than letters (119/135; $\chi^2(1) = 11.1$, $p = .0009$), imageable words (109/135; $\chi^2(1) = 25.2$, $p < .0001$) and months of the year (111/144; $\chi^2(1) = 33.3$, $p < .0001$), though not significantly better than repeating days of the week (136/142; $\chi^2(1) = .5$, $p = .44$). In the writing-to-dictation tasks, he was significantly better at writing digits (50/52, 96%) than letters (40/52, 77%; $\chi^2(1) = 6.7$, $p = .01$). In the magnitude comparison task, K.A.'s performance was nearly perfect, and no different, between the auditory (48/50; 96%) and written presentation of numbers (48/48, $\chi^2(1) = .5$, $p = .49$), but was significantly different between auditory (40/56) and written presentation of days of the week (53/55, $\chi^2(1) = 10.9$, $p = .0009$). Within the auditory domain, his magnitude comparison was significantly better for number words than for days of the week ($\chi^2(1) = 9.6$, $p = .002$).

For the training task, K.A.'s performance on the auditory-visual matching task with the same set of imageable words stayed remarkably constant across the 5 sessions (Session 1: 73/90, 81%; Session 2: 83/90, 92%; Session 3: 77/90, 86%; Session 4: 77/90, 86%; Session 5: 75/90, 83%). Using a Cochran's Q-test, we found no significant difference in performance on this task across sessions ($\chi^2(4) = 6.29$, $p = .18$). A McNemar test was used to compare performance on the first and last session, with no significant difference in performance between the two sessions ($\chi^2(1) = .05$, $p = .83$). Moreover, performance on each of the 5 sessions was significantly worse than performance at the comparable auditory-visual digit matching experiment ($\chi^2_s = 9.4$, $p_s < .002$).

4.4. Discussion

Across a range of tasks, we demonstrated that K.A. made a significant number of errors with auditory presentation, but was perfect, or near perfect with visual presentation. This pattern of performance was observed for letter names, days of the month, weeks of the year, and a set of imageable words and was observed regardless of the type of response that had to be produced, whether it was matching the spoken word to an array of visual stimuli, producing a written response for the spoken stimulus, making a semantic judgment about the spoken word, or repeating a word. For one type of stimuli, number words, his performance showed a different pattern. He was perfect or near perfect on all tasks, both with the auditory and written presentation, regardless of how he had to respond¹. This pattern matches what was observed in the initial case report – better performance with written than spoken stimuli paired with surprisingly good performance at repeating auditorily-presented sequences of digits compared with repeating auditorily presented non-number words. However, these experiments confirm this observation in a more carefully matched set of experiments in which number words are compared to other sets of stimuli that have similar properties (i.e. drawn from a closed set of phonologically distinct items). Additionally, there were no improvements observed when the same set of words was repeated across multiple testing sessions, as might be expected if the preserved number word processing ability was simply due to familiarity with the stimuli set. Taken together, these series of experiments lead us to conclude that while K.A. has a selective impairment in processing auditorily presented linguistic stimuli, his ability to comprehend auditorily presented number words is spared.

5. General Discussion

We have reported the case of an individual who, subsequent to two strokes that damaged the superior temporal lobe bilaterally, suffered a severe spoken language comprehension deficit, with written language comprehension and spoken language production largely spared. In one series of experiments, we localized his spoken language impairment to a sublexical level of processing in the speech perception stream. In another series of experiments, we demonstrated that this speech perception deficit spared the category of number words.

The conclusion that K.A. has a speech perception deficit that spares number word perception fills a gap in the broader literature on the relationship between number and non-number processing. The demonstration that number and non-number word processing can be selectively damaged following stroke provides some of the strongest evidence that these types of stimuli are instantiated in separate neural substrates. Double dissociations between number word and non-number word processing have been reported in semantics (e.g., Cipolotti et al., 1991; Cappelletti et al., 2005), spoken language production (e.g., Marangolo, Piras & Fias, 2005; Bencini et al., 2011) and within the written language system (e.g. Anderson, Damasio & Damasio, 1990; McCloskey et al., 2013). These dissociations suggest that even within modality specific systems – written vs. spoken language, the processes involved in producing language vs. the processes involved in perceiving language – this

¹The one exception to this pattern is that he showed no noticeable impairment in repeating days of the week. However, given his repetition performance with the other stimuli types, and his difficulties with days of the week in the other tasks, we interpret this null result as a Type 2 error, rather than a selective sparing of only days of the week only in repetition.

distinction between number and non-number processing holds. Caño and colleagues (2008) report a single dissociation showing a selective impairment in number word processing in the speech perception domain with spared processing of other types of auditorily presented stimuli (see also Han, Shao and Bi, 2011). K.A. provides the complementary case to complete the double dissociation, with impaired non-number word speech perception and spared number word speech perception. Therefore, this case adds to a growing literature supporting a special status for number words within specific modalities of input and output.

However, there are clear differences between K.A. and M.M.V., the case reported by Caño and colleagues (2008), in terms of the locus of impairment within the speech perception system. M.M.V. had slight impairments in sublexical and lexical auditory processing that affected both number and non-number words. For example, M.M.V. made errors in repeating both number words and non-number words, though the repetition problem was more pronounced with number words. The selective and severe deficit for number words arises only in auditory comprehension processes that map modality-specific lexical representations to amodal semantic representations, in tasks like the auditory-visual matching tasks in which M.M.V. was perfect with non-number words but impaired with number words.

Our results suggest that K.A.'s impairment with non-number words arises at a level of sublexical phonological representations. If his speech perception deficit for these stimuli were due to either lexical/semantic representations or a disconnection between the sublexical level and the lexical level, we would not expect him to have difficulties in repetition tasks or in syllable and word discrimination tasks (see Slevc and Shell, 2015 for discussion). The fact that K.A. made essentially no errors with number words, including in the repetition task, suggests that these sublexical phonological representations are intact for number words. Therefore, within the speech perception system, number and non-number words divide into separate processing streams at an earlier point than what Caño and colleagues (2008) argue. Specifically, number words and non-number words activate representations at a pre-lexical phonological level of processing that are sufficiently distinct that they can be separately impaired by brain damage.²

On the surface this claim seems farfetched. Standard cognitive theories assume that the same set of sublexical features (here represented as phonemes, though they could be syllables, features, allophones, or something else) is used to activate lexical representations corresponding to familiar words comprised of those sublexical units, with, presumably, the same processing stream used to process number and non-number words. That is, the same /t/ phoneme is needed to recognize the word "two" and the word "tin". In this basic architecture, this step necessarily precedes knowledge about what these words mean, including information about the semantic category of the word. According to this model, there is no mechanism for a category-based distinction at this early stage of processing.

²While K.A. had a severe prelexical phonological processing deficit, a comparison between syllable and word discrimination and auditory single word picture matching suggest that K.A. had an additional lexical-semantic deficit at least for non-number words. This raises the possibility that K.A.'s problems with non-number words could be caused by the interaction of multiple deficits. Under this account, the difference between number and non-number word processing is that K.A. does not have a lexical-semantic deficit for number words. To make this account work, we would have to assume that his impaired prelexical phonological processing is good enough to support performance on all of these tasks, in the absence of an additional lexical-semantic deficit. However, given the severity of his problems with repetition and discrimination tasks, we think that this possibility is unlikely.

An alternative view is that this sublexical level of processing includes both phoneme detectors and detectors for more complex phonological sequences, like number words. This proposal matches a recent proposal in the spoken output modality, that posits a similar type of organization in the sublexical representations involved in speech production to account for number and non-number word dissociations in speech production (Cohen et al., 1997; Dotan & Friedmann, 2015). A number of cases have been reported who make phonological errors with non-number word production (e.g. naming a picture of a CAT as “cag”) that could be isolated to a sublexical level of phonological representation but also make primarily semantic errors when producing number words (e.g. reading the digit 6 as “five”).

Because of this pattern, Cohen and colleagues (1997) proposed the *building blocks hypothesis* (see also Dotan & Friedmann, 2015). According to this hypothesis, the basic units in the speech production system are not only phonemes, but also include larger, pre-assembled phonological units, such as numbers, morphological affixes and function words. Each of these sets of units comprise the basic building blocks of different types of stimuli, with digits being the building blocks for number words and phonemes being the building blocks for non-number words. These sets of units are sufficiently distinct cognitively, such that the substitution of phonological units stays within category of building block. “Cat” is produced as “cag” because the /g/ phoneme is substituted for the /t/ phoneme. By the same process, “six” is produced as “five”, because the pre-assembled phonological unit “five” is substituted for the pre-assembled phonological unit “six”. These sets of units also have sufficiently distinct neural substrate that occasionally brain damage will effect one type of unit but not the other. While the most common pattern with patients is a combination of semantic errors with numbers and phonological errors with non-number words, assuming separable neural substrates can account for patients who make phonological errors with non-number words and no errors with number words (e.g. Bencini et al., 2011).

Our proposal is simply that the *building blocks hypothesis* applies not only to the phonological units of speech production, but also to the phonological units of speech perception. This type of organization could account for the pattern of impairment observed with K.A., assuming that the phonemes and number word representations at this sublexical level are sufficiently distinct neural that they can be separately damaged, with K.A.’s damage impacting phonemes but not number word representations. These different neural substrates may occur because of differences in the locations these prelexical phonological representations project to, with digit units projecting to regions associated with numerical processing and phoneme units projecting to regions associated with other types of semantic processing.

This extension of the building blocks hypothesis to speech perception requires some additional specification. In speech production, these units are activated by lexical-semantic representations, but in speech perception, these units need to be activated by the speech signal. Because of this, some ambiguity needs to be resolved. Consider the phonology input [ert]. Since it corresponds to the number word “eight”, we assume that it activates the corresponding digit building block, but since it also corresponds to the non-number word “ate,” it must also activate its corresponding phoneme representations as well, or else the non-number word meaning could not be recognized. Indeed, many number of words are

homophonous with non-number words (e.g., one, won, two, too, to, four, for, fore), indicating that the same phonological input must be able to activate both the number word building blocks and the phoneme building blocks.. A further consideration are non-number words that contain embedded number words, like “forest”, which contains the embedded number word “four.” Until the end of the first syllable, the speech perception system has no way of knowing whether the stimulus will be a number word or a non-number word, so it seems feasible that the stimulus would activate the “four” unit along with the /f/ /ɔ/ /ɹ/ /ɛ/ /s/ and /t/ phonemes. This would predict that K.A. would be particularly good at perceiving words that had number words embedded in them. While this was not tested systematically prior to his unexpected death, this prediction is not borne out by the available evidence. His errors in repeating words with embedded number words (e.g. forest, contents) did not appear to be better than repeating other words, and the errors he made with those forms included phoneme substitutions that disrupted the number word (e.g. repeating “contents” as “kæntæns”). Therefore, we additionally assume some type of parsing within this prelexical system such that, if the entire word cannot be parsed into a set of digit building blocks, then the activation of all of the digit building blocks is suppressed.

A full extension of the *building blocks hypothesis* to speech perception would also predict that functors and morphological affixes have detectors at this sublexical level. This proposal fits within a larger debate about the grain size of the units of representation at a sublexical level, whether these units are phonological features, phonemes, syllables or something else (see Goldinger & Azuma, 2003 for review). Grain size has been argued to be dependent on the phonological structure of the spoken language, with some languages, for example, relying more on syllabic units of representation at the sublexical level (e.g. Cutler et al., 1986). In light of this literature, our proposal is that grain size may vary both as a function of the general language being spoken and as a function of the type of word being perceived.

In general, cognitive neuropsychological case studies have revealed impressive dissociations between numerical and linguistic processing, both in the central conceptual processing system and in the modality specific representations of written and spoken words for perception or production. Careful investigations of the patterns of deficits in these individual case studies have provided a rich source of evidence not just for our understanding of the categorical status of numbers in cognition, but also for our understanding of how the brain processes language more generally.

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Figure 1.
Cognitive architecture of speech perception.

Figure 2.
MR image showing K.A.'s lesions.

Table 1.

Accuracy data for syllable discrimination, word discrimination, auditory lexical decision, PWM and AWSM tasks.

Task	K.A. d' score	Control Mean d' score (Range)	< Controls?	> Guessing?
Word discrimination	0.9	2.4 (1.6–2.8)	*	*
Syllable discrimination	0.5	2.7 (1.9–3.5)	*	*
Auditory lexical decision	0.2	2.4 (1.5–3.2)	*	n.s.
PWM	0.3	3.4 (2.6–4.2)	*	n.s.
AWSM	0.6	3.8 (2.6–4.4)	*	n.s.

*
p < .001, n.s. = not statistically significant

Table 2.

Results of the number vs. Non-number Comparison Tasks

Task	Auditory Modality	Visual Modality
Matching Tasks		
<i>Numbers</i>	149/149 (100%)	90/90 (100%)
<i>Letters</i>	38/45 (84%)	88/90 (98%)
<i>Days of the Week</i>	85/98 (87%)	-
<i>Months of the Year</i>	76/98 (79%)	-
<i>Imageable Words</i>	38/45 (84%)	90/90 (100%)
Repetition Tasks		
<i>Numbers</i>	183/187 (98%)	-
<i>Letters</i>	119/135 (88%)	-
<i>Days of the Week</i>	136/142 (96%)	-
<i>Months of the Year</i>	111/144 (77%)	-
<i>Imageable Words</i>	109/135 (81%)	-
Writing to Dictation		
<i>Numbers</i>	50/52 (96%)	-
<i>Letters</i>	40/52 (77%)	-
Magnitude Comparison		
<i>Numbers</i>	48/50 (96%)	48/48 (100%)
<i>Days of the Week</i>	40/56 (71%)	53/55 (96%)