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Non-Symbolic Exact Quantity Representation in a Language Impaired Population

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Abstract

English-speakers whose access to number language is artificially compromised by verbal interference and the Pirahã (an Amazonian tribe without exact number words) appear to rely on analog magnitude estimation for representing non-symbolic exact quantities greater than 3. Here, 16 participants with aphasia performed the 5 counting tasks from these previous studies. Performance was poorest when targets were not visible during response (70% correct, task 4; 71% correct, task 5) and best when targets were presented as subitizable groups of 2 and 3 (98% correct, task 2). Western Aphasia Battery-Revised subtest scores correlated with task performance, suggesting diverse forms of language impairment may contribute to errors. Coefficients of variation for tasks and significant correlations of target magnitude with error rate (r^2=.88) and error size (r^2=.87) across tasks suggest participant use of analog magnitude estimation. Experiments involving people with aphasia may further refine our understanding of how language and thought interact.

Keywords: aphasia, language, number

Introduction

"Linguistic relativity" occupies the broad theoretical middle ground where language and cognition interact, where the grammatical structures and lexicons of a language are believed to influence thought to a greater or lesser degree. While the idea that language can influence thought, perception, and action has a long history in Western philosophy, Whorf (1956) provided the first and clearest articulation of a strong version of this position. According to linguistic relativity, words aren't just names for pre-existing concepts; thought is influenced by the way particular languages are structured, what languages have words for, and what they don't. When a language is transmitted from one generation to the next, so are particular ways of "cutting up" the world that come with speaking that language.

Everett (2013) compiles a diverse array of recent research that explores domains like space, time, quantity, gender, and color and draws positive conclusions about the effects of language on thought. Similarly, Frank, Fedorenko, Lai, Saxe, and Gibson (2012), review several studies that find "meaningful cognitive differences" (p. 75) between speakers of languages that have words for particular concepts and those that don't. Such cognitive differences appear to exist both across cultures and across development. At the same time, experimentally manipulated verbal interference can temporarily remove differences otherwise present.

The domain of number is a good entry point for testing the linguistic relativity hypothesis. Numeracy develops alongside language in humans, and there are clear differences between the ways adult speakers of different languages perform number-related tasks. The Pirahã, an indigenous Amazonian tribe, are of particular interest here, as their language lacks words for exact number. Gordon (2004) engaged seven Pirahã tribe members in a series of nonverbal matching tasks where participants were asked to reproduce a visual array that matched a model. The Pirahã struggled to accurately reproduce any set of objects containing more than three items, even when the model was visible to copy. Gordon (2004) also noted Pirahã responses produced a coefficient of variation (CoV) of approximately 0.15, congruent with evidence that without access to number language and counting, people use less accurate but inborn abilities to estimate quantities larger than three[1].

Frank, Everett, Fedorenko, and Gibson (2008) replicated the tasks from Gordon (2004) with fourteen participants in a different Pirahã village. The authors found similar results for each task with the exception of the one-to-one matching task, where results were near ceiling. Consequently, Frank et al. (2008) concluded that some of the startling results of Gordon (2004) might be the product of participants not understanding the task or inconsistencies in the experiment.

Everett and Madora (2012) sought to resolve the conflicting results of Gordon (2004) and Frank et al. (2008). The authors recreated the three tasks from Frank et al.

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[1] CoV is the standard deviation of a data set divided by its mean. Studies of magnitude estimation in animals and humans have found that response variability correlates with target magnitude, producing a CoV of 0.15 (see Whalen, Gallistel, & Gelman, 1999).

(2008) with fourteen participants in a third Pirahã village. With one exception, Everett and Madora (2012) found no significant differences when making intra- or inter-study task comparisons. The exception was the one-to-one matching task from Frank et al. (2008), which was significantly different from control tasks and the Everett and Madora (2012) one-to-one matching task. The CoVs for all tasks in Everett and Madora (2012) were 0.15, consistent with Gordon (2004) and the hypothesis that the Pirahã were employing analog estimation strategies.

Frank et al. (2012) extends the experimental tasks performed with the Pirahã to a numerate population by using verbal interference in an attempt to force participants to resort to analog magnitude estimation (Whalen et al., 1999). The authors hypothesized that if language is not crucial to establishing exact number, then participants should successfully perform non-verbal number tasks under verbal interference. Should language be necessary for exact numeracy, however, these same participants should fall back on analog magnitude estimation under verbal interference revealing a constant CoV, as seen in other studies. To test this, Frank et al. (2012) had thirty-five MIT students attempt the matching tasks performed with the Pirahã while simultaneously repeating radio news broadcasts aloud. The results of these experiments were then compared to each other and to the results of the same experiments with the Pirahã from Frank et al. (2008).

While the English-speakers were found to be more accurate than the Pirahã, both groups made "significant and systematic errors" (p. 79) on the "nuts-in-a-can" task (see Figure 1 below), where participants have no access to a direct or remembered visual representation of the array. Here, college students under verbal interference, like the Pirahã, produced a flat CoV of 0.15 across targets, suggesting the use of analog magnitude estimation. Frank et al. (2012) drew the conclusion that the concept of "exact match" does not require language, but that language is crucial to storing and manipulating exact quantities greater than three. This conclusion is in line with the language as a technology or tool-kit version of the linguistic relativity hypothesis, wherein language allows us to transcend our pre-linguistic cognitive capacities (Gentner & Goldin-Meadow, 2003).

The evidence to date strongly suggests that language for number has a significant influence on how quickly and accurately we comprehend and process quantities larger than three. At the same time, there is room for debate as to how fundamental number language is to the correct apprehension of exact quantity. One largely unexplored route to an understanding of the relationship between language and counting (and more generally, questions regarding linguistic relativity) involves studying people with organic language impairments. People with focal brain lesions—either as a result of infarcts, tumor resections or other restricted lesions—may acquire *aphasia*, an impairment of a person's ability to comprehend and formulate language across multiple modalities, including speaking, reading, writing, and listening (Rosenbek, LaPointe, & Wertz, 1989). Consequently, people with aphasia may experience difficulty in the use of language for number and calculation (Dragoy, Akinina, & Dronkers, 2016). McNeil and Pratt (2001) specify that aphasia is a processing or performance disorder—that is, a problem in using language for a known concept. By this reasoning, if aphasia were to affect a person's ability to represent exact quantity on a non-symbolic task such as the one employed in the current study, it may work in a similar fashion to verbal interference—by disrupting access to a number concept and consequently impairing comprehension or speech in relation to that concept. However, it is conceivable that aphasia may impair some individuals' ability to represent exact quantity in a manner more like the Pirahã, who have no exact number language to employ. In such a scenario, a person with aphasia may be impaired because they have no stored verbal label for exact quantity available for access. While the current study cannot adjudicate between these possibilities, we hope the diversity of impairment within the present aphasia population may provide a window into qualitative differences that account for errors across the kinds of tasks used with the Pirahã. We also hope to suggest ways that aphasia populations may generally contribute to investigations of the linguistic relativity hypothesis.

While several case studies have examined the impact of aphasia on calculation—e.g., Dragoy et al. (2016), where 7 of 10 participants with aphasia struggled with basic arithmetic and when comparing Arabic representations of quantities—little research to date has examined the impact of language impairment on non-symbolic representation of quantity. Lemer, Dehaene, Spelke, and Cohen (2003) examined a person with acalculia due to a focal lesion of the left parietal lobe and another person with semantic dementia from predominantly left temporal hypometabolism to demonstrate dissociations between tasks associated with counting and those associated with innate quantity systems of number processing. As predicted by a lesion in the parietal lobe, the patient with acalculia showed a severe slowness in approximation, and exhibited impairments in subitizing and numerical comparison tasks. Meanwhile, the patient with semantic dementia had intact approximation abilities and showed preserved processing of non-symbolic small numbers—that is, her "quantity processing" systems were functioning as expected—but struggled with tasks that required intact verbal processing and counting. Given these findings and related results with other populations, language impairment in the form of aphasia may be predicted to negatively affect the individual's ability to produce *non-verbal and non-symbolic representations of exact quantity*.

In the current study, participants with aphasia performed the same set of five, increasingly complex matching tasks used with the Pirahã and English-speakers whose access to language was artificially compromised by verbal interference (Frank et al., 2012). It bears noting that unlike the previously studied groups, a clinical aphasia population consists of individuals with a diversity of verbal and nonverbal impairments. Regardless, we hypothesize that participants will make more frequent and larger errors (1) in proportion to target size; (2) on each subsequent, more difficult, task; and (3) produce a flat coefficient of variation (CoV) on each task and across target quantities, suggesting reliance on the analog magnitude system to estimate quantity. Such results would lend further support to the hypothesis that access to language for exact number is necessary for the recognition and representation of exact quantities. While general severity of language impairment is predicted to correlate with performance across tasks, we are also interested in whether particular aspects of language impairment point to specific qualities of language involved in counting and exact quantity representation.

Results suggesting that aphasia limits a person's ability to represent non-symbolic exact quantities would complement the body of evidence demonstrating a relationship between exact number language and the ability to perform non-symbolic exact quantity tasks. When taken alongside similar evidence from previous studies with different human populations—i.e. children raised in numerate cultures but who have yet to develop number-language skills (e.g., Condry & Spelke, 2008), adults in numerate cultures under verbal interference, and adults in an anumeric culture—it would seem difficult not to conclude that access to exact number language has an effect on the way that humans think about numbers. More broadly, these findings may refine hypotheses generated by linguistic relativity with regard to the necessity and/or effective use of language in representing basic number concepts. The linguistic diversity present *within* the present clinical aphasia population may provide deeper insight into relations between particular aspects of language function and the representation of exact quantity.

Methods

Sixteen participants (3 female) completed aphasia assessments and the set of five non-verbal and non-symbolic exact quantity representation tasks from Everett and Madora (2012) and Frank et al. (2012). Thirteen participants also completed a numeral elicitation task, confrontation naming task, and free counting task. Eight completed tests of nonverbal semantic processing and short-term memory—the Semantic Category Probe (Freedman & Martin, 2001), and Pyramids and Palm Trees tests (Howard & Patterson, 1992). All participants had aphasia resulting from a left-hemisphere stroke as determined by their score on the Aphasia Quotient (AQ) portion of the Western Aphasia Battery-Revised (WAB-R) (Kertesz, 2006) and a speech-language pathologist. Within this framework, 5 participants are considered to have Broca's aphasia, 6 Anomic aphasia, 2 Wernicke's aphasia, 2 conduction aphasia, and 1 global aphasia. Eligible participants were a minimum of six months post onset of aphasia (M=73 months, R=9–159 months), between the ages of eighteen and eighty-five years (M=61, R=43–75) and native English speakers.

Aphasia assessment. Participants completed the AQ portion of the WAB-R (Kertesz, 2006). This formal assessment includes tasks such as answering simple questions, describing pictures, manipulating and naming common objects, following directions, repeating words, and matching pictures to printed words and sentences.

Matching tasks (Everett & Madora, 2012; Frank et al., 2012). Participants completed five non-verbal and non-symbolic exact quantity representation tasks in the following order: a one-to-one matching task, an uneven matching task, an orthogonal matching task, a hidden matching task, and a "nuts-in-a-can" task (see Figure 1). In every task, the experimenter presented a quantity of spools of thread (approximately 1" tall, ¾" in diameter) and asked the participant to construct a row of un-inflated balloons (approximately 4" long and 2" wide) that matches the number of spools of thread. In the one-to-one task, the experimenter placed the spools one at a time in an evenly spaced line from left to right. In the uneven task, the spools were presented in the same manner as in the one-to-one task, but broken randomly into smaller groups of two and three. The orthogonal task is identical to the one-to-one task except that the row of spools is presented in a line perpendicular to the participant. The hidden matching task is identical to the one-to-one task except that the row of spools is hidden from the participant after being presented. In the "nuts-in-a-can" task, the experimenter places spools one by one into an opaque cup. Participants were tested once per task on each quantity from four to twelve in one of two random orders, totaling forty-five trials per participant.

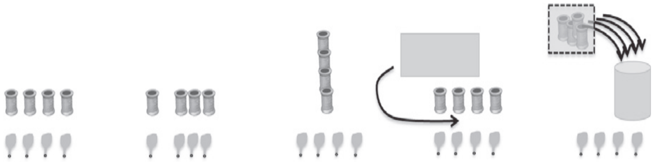

Figure 1: Schematic of each matching task. From left to right: one-to-one match (task 1), uneven match (task 2), orthogonal match (task 3), hidden match (task 4), "nuts-in-a-can" (task 5). Image is from Frank et al. (2012).

Numeral elicitation task. Participants were asked to name the number of spools of thread presented, increasing from one to twelve and then decreasing from twelve to one. In each case, participants were asked, "How many spools of thread are there?" by the researcher. Divergence between performance on this task and on the matching tasks might illuminate whether the participant is having difficulty recognizing, articulating, or representing the target quantity.

Confrontation naming task. Participants were asked to name the Arabic numerals one through twenty as presented individually on flashcards. In each case, participants were asked, "What number is this?" This task assessed the participant's ability to recognize and name Arabic numerals. Confluent or divergent performance on this task when compared to the matching and counting tasks might help differentiate the participant's ability to recognize and name symbolic and non-symbolic numbers.

Free counting task. Participants were asked to count up from one to twenty and down from twenty to one. The researcher says, "Please count from one up to twenty" and "Please count from twenty down to one." Participants were allowed five minutes to recite each count list. Performance on this task indicates the participant's capacity to access and articulate counting numbers in order, a factor in the participant's performance on the matching tasks.

Semantic Category Probe Test (Freedman & Martin, 2001). Participants listened to a list of three or more words and determined whether the final word is from the same category as any of the preceding words by saying or pointing to "Yes" or "No." This task assesses the participant's capacity to retain semantic information in their short-term memory, where impairment might be a potential reason for poorer performance on the matching tasks.

Pyramids and Palm Trees Test (Howard & Patterson, 1992). Participants matched a pictured item to the closest associate among a set of two pictured choices (e.g., fish matched to: cat, table). This task assessed the participant's capacity to process non-verbal semantic information. Distinguishing between semantic and verbal impairments may help explain performance on the matching tasks.

Results

There was notable variation across participants and tasks. Percent correct scores for all tasks ranged from 53% to 98% (Table 1). Participants responded correctly on 83% of task 1 trials, 98% of task 2 trials, 90% of task 3 trials, 70% of task 4 trials, and 71% of task 5 trials (Fig. 2, far left).

Participants' accuracy descreased as the target quantity increased across all tasks ($r^2 = 0.87$) (Fig. 2, center left) and for each individual task (Fig. 3, top row). Similarly, error magnitude increased as target quantity increased ($r^2 = 0.88$) (Fig. 2, center right). CoV was similar across target quantities and tasks (Fig. 2, far right), but higher on task 4 (0.10) and task 5 (0.11) (Fig. 3, bottom row). Across analyses, aphasia participants' performance was remarkably similar to the performance of English speakers under verbal interference from Frank et al. (2012) (Figs. 2 and 3). Compared to the Pirahã (Figs. 2 and 3, aggregated from Everett & Madora, 2012; Frank et al., 2008; and Gordon, 2004), participants with aphasia and English speakers under verbal interference were generally more accurate and made smaller errors, but all three groups showed similar patterns of responding across tasks.

Participant	Task 1	Task 2	Task 3	Task 4	Task 5	Total	% Correct
2	0	0	0	1	0	1	97.8
16	0	0	0	1	1	2	95.6
7	0	0	0	1	1	2	95.6
1	0	0	0	1	1	2	95.6
10	0	0	0	1	1	2	95.6
12	1	0	0	1	1	3	93.3
13	0	1	3	1	2	7	84.4
11	0	0	0	5	2	7	84.4
15	0	0	0	4	5	9	80.0
3	2	0	1	3	4	10	77.8
9	1	0	2	2	5	10	77.8
6	4	0	2	2	2	10	77.8
14	2	0	2	4	4	12	73.3
4	5	1	0	3	4	13	71.1
8	5	0	2	6	3	16	64.4
5	4	1	3	7	6	21	53.3

Table 1: Participant errors across tasks. The maximum number of errors on each task is nine. Darker colors indicate more errors.

WAB-R AQ and subtest scores were reliably correlated with task performance on tasks 4 and 5. AQ and subtest scores were most predictive of performance on task 5, the "nuts-in-a-can" task (Table 2).

Thirteen participants completed additional number tasks. While, generally speaking, participants with higher AQ scores who had made fewer errors on the nonverbal matching tasks also performed better on the additional

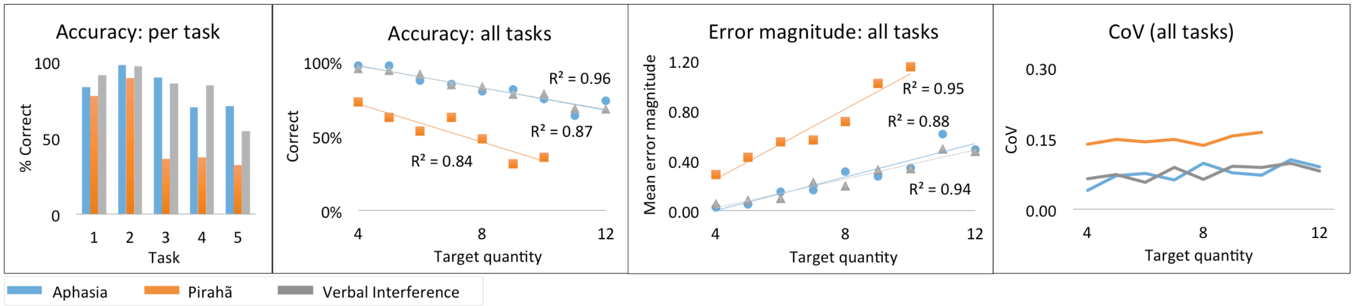

Figure 2: Matching task summary data for participants with aphasia, Pirahã, and adults under verbal interference. Far left: For participants with aphasia, performance was poorest when targets were not visible during response (70% correct, task 4; 71% correct, task 5) and best when targets were presented as subitizable groups of 2 and 3 (98% correct, task 2). Center left: Significant correlations were found between target magnitude with both error rate (r^2=.87) and error size (r^2=.88) (Center right) across tasks. Far right: Coefficients of variation for participants with aphasia mirrored those of adults under verbal interference. "Pirahã" data is from Everett and Madora (2012); Frank et al. (2008); and Gordon (2004). "Verbal Interference" data is from Frank et al. (2012).

counting tasks, there were exceptions. Participant 13, who has a high AQ score and made no errors on the additional number tasks made seven errors across matching tasks. Participant 11 made as many matching task errors as Participant 13 (refer to Table 1), but scored only 4 of 12 on the numeral elicitation task. Additionally, Participant 11, despite correctly reciting 18 of 20 numbers on the ascending free counting task, could not count backwards from 20 to 1, receiving a score of zero on the descending free counting task. Across all 8 participants who completed the nonverbal semantic processing and short-term memory tasks, higher AQ scores predicted better performance on the Pyramids and Palm Trees and Semantic Category Probe tests.

		Task				
		1	2	3	4	5
WAB-R subtest	**AQ**	0.41	-0.02	0.23	0.61	0.77
	Speech	0.30	-0.04	0.18	0.62	0.74
	Comprehension	0.42	0.04	0.10	0.38	0.69
	Repetition	0.38	-0.01	0.16	0.50	0.68
	Naming	0.49	-0.10	0.33	0.66	0.72

Table 2: Correlations between task performance and WAB-R subtest scores. AQ = Aphasia Quotient, Speech = Spontaneous Speech, Comprehension = Auditory Comprehension, Naming = Naming and Word Finding. Darker colors indicate larger *r*-values.

Discussion

Generally, participants (1) made more errors for larger target quantities, (2) made errors of greater magnitude for larger target quantities, and (3) had more difficulty with tasks where targets were not visible during response. There was consistency among those participants with the greatest overall task impairments. Participants who made ten or more incorrect responses also made errors across tasks 1, 3, 4, and 5. Eight different participants responded incorrectly to at least one trial of task 1, where the target remained visible and did not require conservation in space or time, nor, presumably, counting: correct responding only required participants to match one object to another. The results of task 1 stand in stark contrast to near-ceiling results on task 2. In task 2, targets were presented in groups of 2 and 3. This is the only difference between tasks 1 and 2, suggesting that many participants were able to subitize the visible targets on task 2 in order to answer accurately, but were unable to do so consistently on task 1. Near-ceiling performance on task 2 also suggests that perceptual and/or attentional impairments (e.g., field cuts, neglect) do not explain poor performance on tasks 1, 3, 4, and 5; this represents an important control condition in a stroke population with expected neurological and behavioral heterogeneity. Surprisingly, performance on task 3 was superior to performance on task 1, despite the required spatial translation between the perpendicular target array and horizontal response. Participants responded incorrectly on 10% of task 1, 2, and 3 trials, where the target remained visible for comparison, matching, and recounting. Performance on tasks 4 and 5 was poorer, as expected: both involve responding without the target array still visible.

These results mirror those of previous studies with the Pirahã and adults under verbal interference, although the Pirahã made more frequent and larger errors, more clearly suggesting a reliance on analog magnitude estimation in attempting to represent target quantities. Of all the research of this kind conducted with the Pirahã, only the one-to-one matching task in Frank et al. (2008) produced a CoV markedly different from 0.15. Everett and Madora (2012) offered a speculative explanation: unlike the others, the village tested in Frank et al. (2008) had been exposed to math tutoring that included neologisms for number words. It is the neologisms for number words that are exceptional—all the villages had been exposed to the one-to-one matching

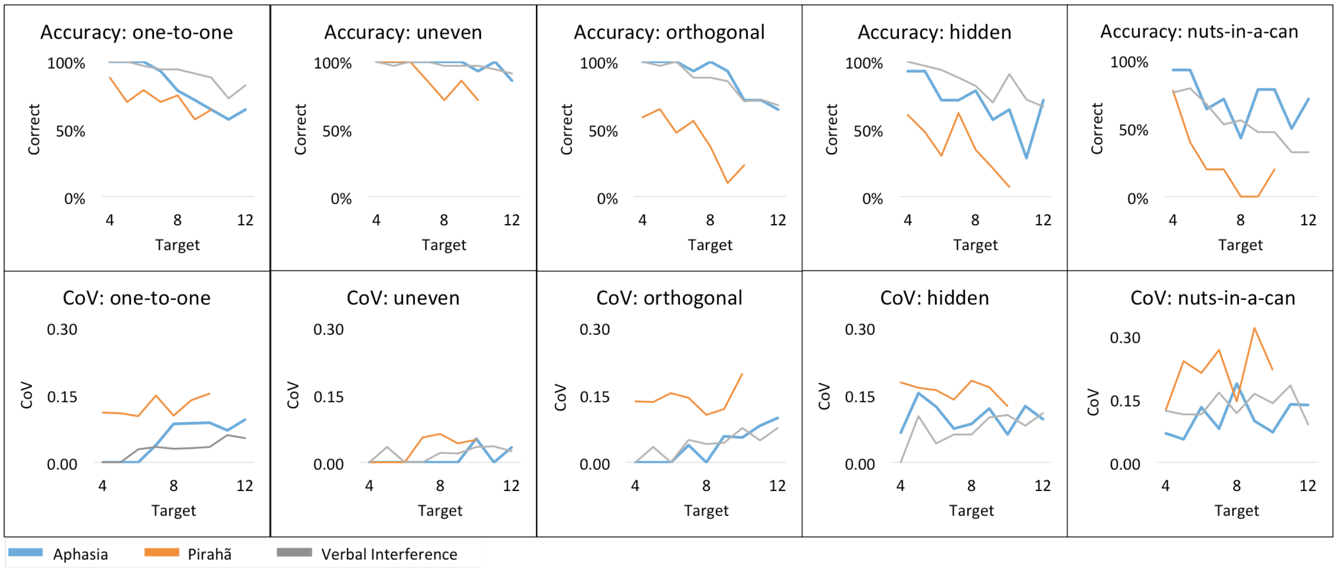

Figure 3: Task accuracy and CoV for participants with aphasia, Pirahã, and adults under verbal interference. Accuracy (Top row) and CoV (Bottom row) for participants with aphasia mirrored those of adults under verbal interference. "Pirahã" data is from Everett and Madora (2012); Frank et al. (2008); and Gordon (2004). "Verbal Interference" data is from Frank et al. (2012).

task and other attempts at basic math training by the Brazilian government, but only the site of Frank et al. (2008) had been exposed to number word neologisms. The authors are clear that this is speculation on their part, but it dovetails with a possible explanation as to the task performance differences between the Pirahã on the one hand and the verbal interference and aphasia participants on the other. In attempting to account for the lower CoVs and greater accuracy of the verbal interference participants, Frank et al. (2012) suggests that participants' "differential cultural experience with mathematics and other uses of exact numerosity led to their relatively more precise representation of analog magnitude" (p. 82). The same could be suggested of the aphasia participants in this study.

Certainly there are differences between the current population of people with aphasia, people of an anumeric culture, and English-speakers under verbal interference. What separates the Pirahã from other populations under discussion here is that they exist in a world without exact-quantity language and may not have a concept of number to access. English speakers under verbal interference, meanwhile, are members of a numeric culture who have had their ability to use language temporarily disrupted, and people who have aphasia are members of the same culture with a more permanent disruption. Also, an aphasia population consists of individuals with distinct lesions, resulting in a range of verbal and nonverbal impairments and significant heterogeneity is to be expected, compared to a population of English speakers undergoing experimental manipulation via verbal interference. While diversity within the current aphasia population is viewed as a potentially rich source for identifying particular aspects of language (e.g., comprehension, speech) that may uniquely affect particular aspects of number use (e.g., mental representation of exact quantity, counting), it also suggests caution before drawing definitive conclusions based on group performance.

That several studies have repeatedly found similar results despite population differences lends support to established ways of thinking about number, thought, and language. According to the model put forth by Feigenson, Dehaene, and Spelke (2004), we are born with two systems for the cognitive representation of number—a parallel-individuation system that can track up to three or four discrete objects and an analog magnitude estimation system we use to approximate large quantities. While these cognitive systems are also found in other animals, humans appear to use exact number words as tools that enhance our capacity to do things with quantities by bridging these systems. The results of the present and previous studies fit this model: language impairment, like verbal interference and living in a culture without exact number words, makes it difficult, if not impossible, for individuals to bridge the two systems for cognitively representing quantities. The present study also suggests that experiments involving people with aphasia may serve to further refine our understanding of how language and thought interact.

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