APPLYING DIVERSITY MEASURES TO THE ANALYSIS OF VERBAL BEHAVIOR

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This study explored the use of diversity indices, typically employed in ecological studies, to measure verbal behavior in children with autism spectrum disorder. By drawing comparisons between species richness and abundance, we applied beta diversity and Shannon diversity measures to assess the diversity and distribution of a verbal repertoire over time. This analysis utilized the outcomes of three verbal operant experimental analyses that use a multi-element design to test for the occurrence of four elementary verbal operants. Using archival data, diversity measures were then used to conduct a detailed analysis of the richness and evenness of verbal responses. The results demonstrate that beta diversity and Shannon diversity effectively capture the richness and distribution of the verbal repertoire over time. These findings suggest that diversity indices can provide a robust framework for assessing language development and the effectiveness of interventions. This research underscores the importance of integrating ecological diversity models into behavioral science to better understand complex human behaviors like language. Future applications of this method may allow for more complex analysis of verbal behavior within and across individuals and interventions.

Keywords: verbal behavior, beta diversity, Shannon entropy, biodiversity, quantitative analysis

Diversity indices have been used by various fields (e.g., ecology, biology, zoology, environmental sciences, urban planning, agriculture, and forestry) to quantify the variety of species sampled along an environmental gradient. At a basic level, the richness of an ecological community is defined by the number of unique species it supports. To the extent that an environmental gradient supports a greater variety of lifeforms (i.e., richness), and the distribution of unique lifeforms is relatively proportional (i.e., abundance), it has greater biological diversity (biodiversity). The measurement of biodiversity was first described by Whittaker (1960), who proposed three key variables for quantifying the biodiversity of a region: diversity of species sampled within an individual site (α-diversity), rate and extent of change across species along an environmental gradient (β-diversity), and richness of species sampled across a range of sites (γ-diversity).

Behavioral diversity indices are commonly used in animal research to evaluate variables contributing to animal welfare (Miller et al., 2020). Borrowing the same diversity indices from the field of ecology, zoologists studying animal welfare have applied these measures to compare the natural frequencies of species-specific behavior in the wild against those of animals housed in zoos, farms, and kennels (Bereton & Fernandez, 2022). For example, just as enriched ecological communities are composed of a greater number of species than impoverished communities, enriched animal habitats (e.g., those with adequate enclosure size, appropriate social grouping, and/or sufficient variety of food sources) induce a greater variety of behavior than impoverished habitats (e.g., those with inadequate enclosure size, inappropriate social grouping, and/or insufficient variety of food sources).

Bereton and Fernandez (2022) conducted a literature review to determine the most frequently used diversity indices in the field of behavioral diversity. They found that two measures accounted for 98.2% of the analyses used to calculate behavioral diversity: Shannon entropy (H; 70.5%) and richness (S; 27.7%).

Richness refers to a simple count of unique species (ecology) or behavior (zoology)[1] within a given area. For example, a forest consisting of

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[1]Notably, zoologists typically rely on ethograms which range from highly detailed to vague topographical descriptions in lieu of operant classification.

both oak and pine trees would have a richness of two. Richness is considered an important parameter of biodiversity for both theoretical and pragmatic purposes (e.g., prioritizing areas for conservation). However, Jost (2019) noted that, "An oak forest with a few pine trees is very different from a pine forest with a few oak trees" (p. 56). Similarly, an individual with a robust mand repertoire who otherwise emits very few tacts is different than an individual with a robust tact repertoire and an omnibus mand, even though both of these individuals would have a richness count of two. That is, richness fails to capture the relative abundance of species or behavior, which can lead to misleading conclusions if this measure is used alone.

Shannon entropy (*H*) is the most commonly used statistical formula to calculate behavioral diversity, appearing in 70% of the literature because it mitigates the limitations of richness (Bereton & Fernandez, 2022). Entropy is defined as a lack of order or predictability and was first introduced in the mid-1800s by Clausius to help describe the disorder found in thermodynamics (Shannon & Weaver, 1949).

Shannon describes entropy as "a measure of the degree of randomness, or of 'shuffledness'" (Shannon & Weaver, 1949, p. 12). Shannon entropy has been used beyond the study of thermodynamics, and has now been utilized across analytic levels, whether examining genes, species, or entire ecosystems and across a number of fields including physics, chemistry, information theory, sociology, and ecology, among others (Gaggiotti et al., 2018; Konopiński, 2020; Sherwin, 2018). High entropy values indicate randomness, while low entropy values indicate orderliness. For example, in the context of behavioral diversity, Shannon entropy has been used to quantify the freedom of choice within the English alphabetical system, which turns out to be approximately 50% to human freedom and 50% to statistical prediction (Shannon & Weaver, 1949).

Similarly, linguists have employed other diversity indices to measure the range of languages spoken across a geographic region and the variety of words written across texts. For example, Greenberg (1956) applied eight diversity indices to calculate the probability that two randomly selected people from a region would speak different dialects. For Greenberg's analysis, the spoken languages served as different "species," while relative abundance was measured by counting the number of speakers (Patil & Taillie, 1982). Diversity measures have also been applied to studies of word frequency as an index of literary style (Herdan, 1966; Yule, 1944). For these analyses, an author's words served as different "species," while relative abundance was measured by counting the frequency of their occurrence (Patil & Taillie, 1982). While useful for monitoring change over time, the practicality of these indices has been plagued by poor operational definitions (cf. Skutnabb-Kangas & Harmon, 2018).

Skinner (1957) addressed the challenges related to the codification of taxonomic units for language analysis by classifying and operationally defining different verbal operants based on their function. For example, Skinner's description of echoic control, "In the simplest case in which verbal behavior is under the control of the verbal stimuli, the response generates a sound pattern similar to that of the stimulus" (1957, p. 63), is remarkably similar to Shannon's mathematical theory of communication, "The fundamental problem of communication is that of reproducing at one point either exactly or approximately a message selected at another point" (1948, p. 379).

Diversity indices have been used to quantify the fitness of different ecosystems, ranging from those that support many species to those with species at risk of becoming endangered or extinct. The same measures can be applied to verbal behavior, when the verbal repertoire is viewed as an ecosystem. We propose that higher diversity values are indicative of speakers whose verbal behavior is multiply controlled, and therefore more sustainable. In contrast, lower diversity values may represent limited language skills restricted to specific controlling relations, and, therefore, at risk of extinction.

The primary objective of this research was to employ diversity measures to quantify the elementary verbal repertoire in terms of ecological fitness. Given the ubiquity of Shannon entropy throughout the behavioral diversity literature, along with its historical foundation in communication theory, this paper endeavors to explore the potential utility of diversity measures in evaluating the language of an individual diagnosed with autism spectrum disorder (ASD). In doing so, we aim to contribute to the understanding and quantification of the elementary verbal repertoire and broaden the methodological approaches utilized in language development research.

METHOD

Verbal Operant Experimental Analysis

A verbal operant experimental (VOX; Mason et al., 2024) analysis offers a methodologically straightforward, yet rigorous means of testing specific verbal responses (a topography-based dependent variable) across distinct sources of stimulus control (tact, echoic, mand, and intraverbal conditions) using a multi-element experimental design. The outcomes of the VOX analysis allow for the quantification of the existing elementary verbal repertoire by comparing its outcomes to a hypothetical norm - a speaker whose language is balanced across the elementary verbal operants. It is also useful for measuring change over time and comparing treatment effects within individuals and across groups.

For our purposes, the VOX analysis was administered following the procedures outlined by Mason and colleagues (2024), to help determine stimulus conditions that maintain similar response topographies. Following these procedures, mand, tact, echoic and intraverbal control were tested in a pseudo-randomized manner. Throughout all conditions, topography-based responses, referred to as referents, were tested in sets of three and alternated until a sufficient sample size was collected.

The first condition tested in this analysis is responses under tact control. In this condition, the child has unrestricted access to preferred items. When the child picks up an item, the tester asks, "What's this?" and then provides praise if the child names the item within 5 seconds. The label the child uses for the item serves as the referent in the remaining conditions. This process is repeated until the child engages with three items, regardless of whether or not the child labels the items.

The mand condition starts with a preference assessment (multiple stimulus without replacement) utilizing the three items identified in the tact condition. After a selection, the child plays with the item for 30 seconds. Next, the experimenter removes the item, ensuring it is out of sight, and asks, "What do you want?" If the child asks for the item by utilizing the referent within 5 seconds, they then get it back for another 30 seconds. This procedure is repeated until all items selected in the tact condition are tested.

In the echoic condition, all items labeled in the tact condition are removed. At 30-second intervals, the experimenter provides an echoic discriminative stimulus, like, "Say ball", for each item tested in the tact condition. Praise is given for correct responses within 5 seconds.

Similarly, in the intraverbal condition, all items from the tact condition are removed. At 30-second intervals, the experimenter provides a fill-in-the-blank frame or a wh- question based on play in the tact and mand conditions, for example, "You roll the ___" or "What do you roll?" Praise is given for correct responses within 5 seconds.

Upon completion, the outcomes of this analysis enable us to assess the prevalence of a verbal operant class relative to other operant classes and compare the entire verbal repertoire over time or across participants. This precision is crucial for accurately evaluating the strengths and weaknesses in an individual's verbal repertoire, affording new ways to quantify the verbal repertoire.

Beta Diversity Measures: Visualizing Gamma, Alpha, Beta

Archival VOX data were analyzed using diversity measures to compare topographically related responses across different verbal operants. Applied to the analysis of verbal behavior, diversity metrics quantify responses (i.e., species) across operants (i.e., sites) in terms of both richness and abundance. In its strictest sense, beta diversity is the ratio between gamma (regional) and alpha (local) diversities (Jost, 2007; Whittaker, 1960). This yields information about the relationship and degree of difference between local and regional communities.

Table 1 illustrates this and delineates the presence or absence of a verbal response across each condition. The column titled "Tact" indicates that the presence of the item[2] acted as a discriminative stimulus for the response "Ball." However, the child did not respond with "ball" under mand (i.e., "What do you want?"), echoic (i.e., "Say ball") and intraverbal (i.e., "What do

[2] In conjunction with the vocal S^D, "What is it?", if needed.

Table 1. Archival VOX Analysis Data Collected from a Three-Year-Old African American Boy with Autism

Responses	Operants			
	Mand	Echo	Tact	Intraverbal
Ball	0	0	1	0
Legos	0	1	0	0
Dolls	0	1	0	0
Cookies	0	1	0	0
Magnets	0	0	1	0
Swing	0	1	0	0

you roll?") sources of control. In this example, we can see that "magnets" also occurred exclusively under tact sources of control and that "Legos," "Dolls," "Cookies," and "Swing" occurred exclusively under echoic control.

Defining topographically distinct verbal responses as "species" and functionally distinct verbal operants as "sites" allowed us to calculate alpha, gamma, and beta diversity for the speaker's verbal repertoire. Alpha (i.e., α; *local* diversity) is the diversity value for an individual sample, such as a single forest stand, an individual tributary, or a verbal operant class. For the present analysis, alpha diversity is calculated by averaging the number of responses recorded for each operant (see Table 2). Gamma (i.e., γ; *regional* diversity) is the total diversity measured throughout a community, such as an entire forest, watershed, or entire verbal repertoire. Here, gamma diversity represents the number of topographically unique responses observed across all operant.

Unlike alpha and gamma diversity, which are measured directly, beta diversity is a derived quantity representing the degree of change in response distribution across different operants. A high beta-diversity value indicates a greater difference in the number of responses across operants. A low beta-diversity value depicts greater similarity in the number of responses across operants. While the calculation of beta diversity has been the topic of much debate among ecologists (Ellison, 2010), Whittaker (1960) suggested the following formula as "the simplest measure of beta diversity" (p. 321):

$$\beta = \gamma \,/\, \alpha$$

For the analysis of verbal behavior, beta ranges from one, identical findings across all operants, to the number of operants sampled; in this case, four. A high beta-diversity value indicates disproportionate responding across verbal operants. A low beta-diversity value represents a balanced verbal repertoire but says nothing about the abundance of responses therein.

To illustrate the calculation of beta diversity, we present two hypothetical examples that highlight both the cost and benefit of a one-number summary. Table 3 displays hypothetical VOX data for a speaker whose verbal repertoire was assessed across 12 referents, for a total of 48 possible responses. In this example, the speaker responded to the same three referents across all conditions, for a total of 12 responses. Alpha and gamma both equal three, which yields a beta of one and represents minimal diversity.

The bottom of Table 3 shows a Venn diagram with precise overlap between the three responses, "Car," "Doll," and "Bubbles." The middle box of the diagram is shaded to indicate the union of these three responses occurring under mand, tact, echoic, and intraverbal sources of control. No other responses occurred outside of this field, indicating minimum diversity within the verbal repertoire.

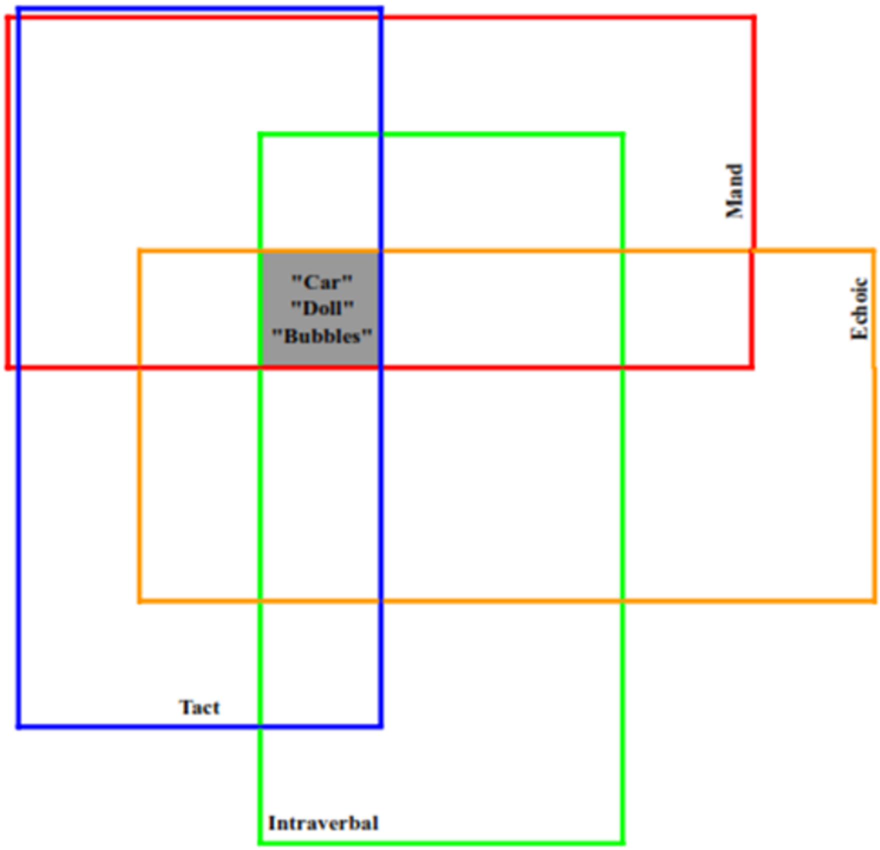
Table 4 also displays hypothetical VOX data for a speaker whose verbal repertoire was assessed across 12 referents, for a total of 48

Table 2. Calculation of Alpha, Beta, and Gamma Diversity using Archival Data

		Operants (Sites)				Regional Richness	
		Mand	Echo	Tact	Intraverbal		
Responses (Species)	Ball	0	0	1	0	1	$\gamma = 6$
	Legos	0	1	0	0	1	
	Dolls	0	1	0	0	1	
	Cookies	0	1	0	0	1	
	Magnets	0	0	1	0	1	
	Swing	0	1	0	0	1	
Local Diversity		0	4	2	0 ➡	$\alpha = 1.5$;	$\beta = 4$

Table 3. A Verbal Repertoire with Minimum Diversity with Hypothetical Data

		Operants				Regional Diversity	
		Mand	Echo	Tact	Intraverbal		
Responses	Car	1	1	1	1	1	γ = 3
	iPad	0	0	0	0	0	
	Cookies	0	0	0	0	0	
	Doll	1	1	1	1	1	
	Juice	0	0	0	0	0	
	Legos	0	0	0	0	0	
	Magnets	0	0	0	0	0	
	Playdoh	0	0	0	0	0	
	Markers	0	0	0	0	0	
	Bubbles	1	1	1	1	1	
	Chips	0	0	0	0	0	
	Puppy	0	0	0	0	0	
Local Diversity		3	3	3	3	α=3; β=1	



possible responses. In this example, the speaker responded to three different referents across each condition, for a total of 12 responses. As in Table 3, α = 3. However, here, γ = 12, which yields β-diversity = 4 and represents maximal diversity.

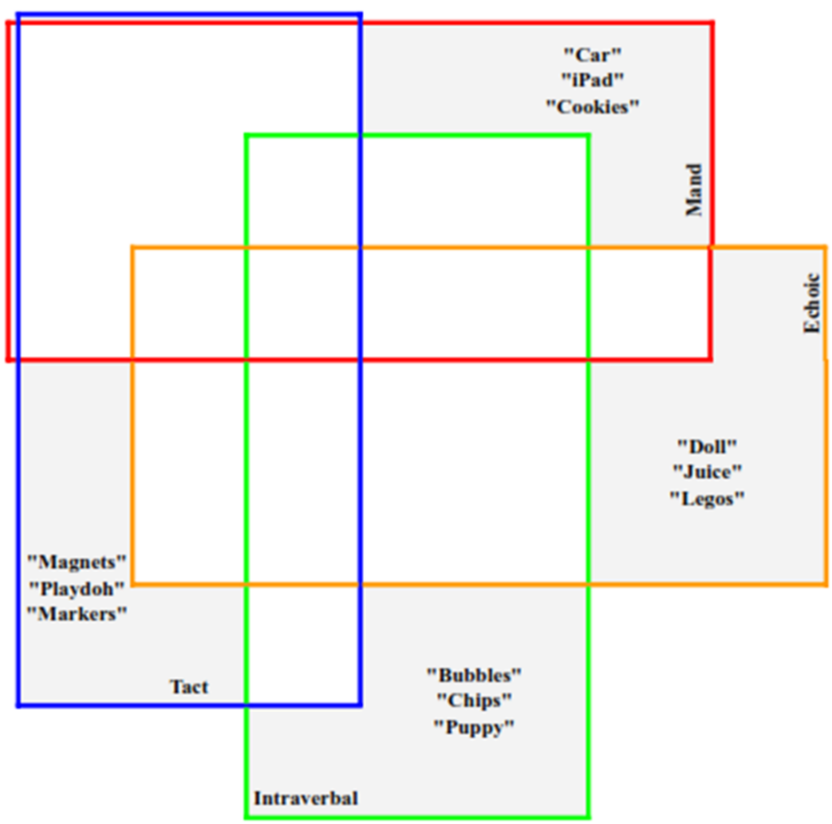
The bottom of Table 4 shows a Venn diagram with no overlap between the 12 responses recorded in the VOX analysis. The outer fields of each set are shaded to indicate that each of the three responses occurred exclusively under mand, tact, echoic, or intraverbal sources of control, which is a stark contrast from Table 3. No other responses occurred outside of this field, indicating maximum diversity within the verbal repertoire.

Note that the same value for beta in Table 3 would have been achieved if the speaker had responded to all 48 trials. However, the difference between α = 3, γ = 3 and α = 12, γ = 12 is substantial, and represents two distinct repertoires. Consequently, we recommend reporting beta only within the context of both alpha and gamma to ensure accurate interpretation.

When calculating beta, the maximum value is equal to the number of operants sampled and will vary accordingly. For example, if intraverbal control were omitted from the assessment, the maximum value for beta would be three. Similarly, were a fifth variable (e.g., auditory-visual conditional discriminations) added to the assessment of mand, tact, echoic, and intraverbal control, the maximum value for beta would be five. The lack of standardization may preclude direct comparisons of the verbal repertoire. For this reason, we recommend converting beta to the Shannon diversity index, as described in the next section.

Table 4. A Verbal Repertoire with Maximum Diversity with Hypothetical Data

		Operants				Regional Diversity
		Mand	Echo	Tact	Intraverbal	
Responses	Car	1	0	0	0	1
	iPad	1	0	0	0	1
	Cookies	1	0	0	0	1
	Doll	0	1	0	0	1
	Juice	0	1	0	0	1
	Legos	0	1	0	0	1
	Magnets	0	0	1	0	1
	Playdoh	0	0	1	0	1
	Markers	0	0	1	0	1
	Bubbles	0	0	0	1	1
	Chips	0	0	0	1	1
	Puppy	0	0	0	1	1
						$\gamma = 12$
Local Diversity		3	3	3	3	α=3; β=4



Shannon Diversity Index

As noted by Whittaker (1972), beta diversity was intended as a simple method of quantifying "the extent of differentiation of communities along habitat gradients" (p. 214). In terms of verbal behavior, this could be described as the differentiation of responses across verbal operant classes. The above-noted limitations of such a simple formula have led researchers to develop more comprehensive and standardized indices of diversity. Shannon entropy (H) is one of the most well-known diversity indices, and the most commonly used metric for calculating behavioral diversity (Cronin & Ross, 2019). In addition to richness, Shannon entropy captures evenness, which is the correlative abundance of each species.

Calculating Shannon entropy (see Appendix 1) requires a change in scale; the speaker now serves as the site, the verbal operants as different species, and the specific verbal responses are counted as members of those species. Applied to the analysis of verbal behavior, this index is calculated by identifying and counting the number of unique responses found in each operant class. Next, the proportion of each operant is found by dividing the number of responses in a given operant by the total number of responses across all operants. This provides a proportion (pi) for each operant (i).

$$p_i = \frac{Number\ of\ responses\ per\ operant\ (i)}{Total\ number\ of\ responses}$$

The proportion of each operant is then multiplied by the natural logarithm of that proportion. These values are then summed and multiplied by -1.

$$H = -\sum(p_i \cdot \ln(p_i))$$

As applied here, H can range from 0 (nonverbal) to 1.39 (fluent). This arbitrary index can be relatively difficult to interpret. Following the recommendation of Jost (2006, 2007), we then take the exponential of H to convert Shannon entropy into the *effective number of operants*, a metric that calculates the range of multiple control[3]:

$$^1D = exp\ (H)$$

Shannon diversity index (^1D) can then be interpreted as the effective number of operants within the speaker's verbal repertoire, ranging from 1, functionally independent, to 4, multiply controlled[4]. Higher values indicate greater diversity, with many evenly distributed operants. Conversely, lower values suggest lower diversity, with either fewer operants represented or multiple operants with a highly skewed distribution.

Measuring Change over Time

To demonstrate the application of diversity measures of verbal behavior, we analyzed archival VOX data for a three-year-old, Asian male child diagnosed with ASD. Both English and Vietnamese were spoken at home, and the assessment was conducted in English. VOX data were collected prior to starting early intensive behavioral intervention (EIBI), and again after six months, and then after 12 months of intervention (see Table 5).

At the time of his intake assessment, the speaker had a beta diversity score of 2.67. The corresponding Venn diagram shows that 100% of his responses were under echoic control, with 33% of those also under tact control, and another 17% mand. No responses were observed under intraverbal control. Using Shannon's ^1D, his verbal repertoire was calculated to be under the effective control of 2.33 verbal operants.

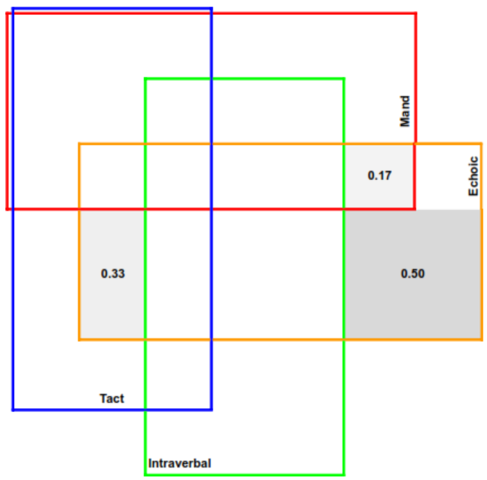
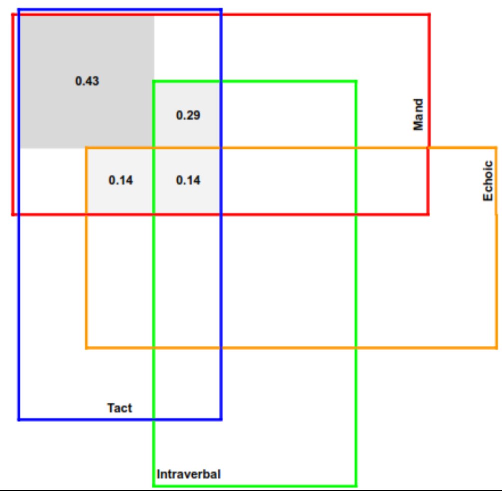
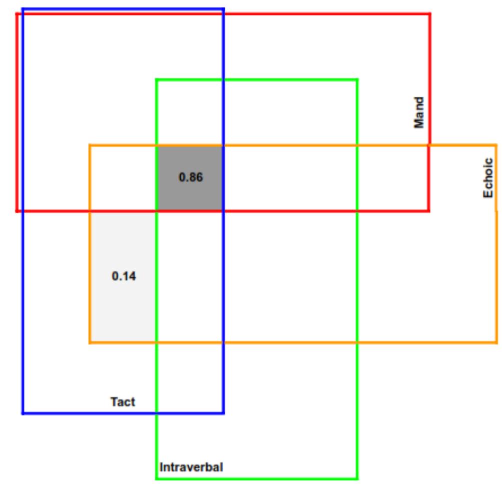
After six months of EIBI, the beta diversity score decreased to 1.47. All responding occurred at the union of tact and mand control, of which 43% were also under intraverbal control and 28% also echoic. At the six-month mark, Shannon's ^1D calculated his verbal repertoire to be under the effective control of 3.55 verbal operants.

At the end of one year, the beta diversity score decreased to 1.08. Eighty-six percent of responding occurred at the union of mand, tact, echoic, and intraverbal control, with the remaining 14% at the union of tact and echoic control. Using Shannon's ^1D, his verbal repertoire was calculated to be under the effective control of 3.98 verbal operants.

[3] A Hill (1973) number of order $q = 1$

[4] If no responses are found across any operants, a score of 0 would be used to indicate that no functional verbal repertoire was sampled during the VOX analysis.

Table 5. A Verbal Repertoire with Maximum Diversity with Hypothetical Dataoire with Maximum Diversity with Hypothetical Data

	Intake Assessment	6-mo Reassessment	12-mo Reassessment
Age	3 years, 3 months	3 years, 11 months	4 years, 3 months
β-Diversity	2.67	1.47	1.08
^{1}D	2.33	3.55	3.98
Venn Verbal Diagram			

DISCUSSION

The study used diversity measures, including beta diversity and the Shannon diversity index, to quantify the functional language skills of a young boy with ASD over the course of one year of EIBI. Venn diagrams were used as a means to visually analyze the data and show changes in the participant's responding over time, which could be used to make programming decisions depending on the effectiveness of treatment. At intake, the boy had a fragmented verbal repertoire, as indicated by a beta diversity of 2.67. After a year of EIBI, the boy's verbal repertoire neared unity, with a beta diversity of 1.08. However, this only showed whether the same verbal responses were represented across different operant classes. The Shannon diversity index was used to determine the relative abundance of responses within each verbal operant class. The number of effective operants increased from 2.33 to 3.98, approaching 4, which represents maximum richness and abundance.

Regarding the use of the exponential of Shannon entropy as a measure of verbal behavior, Jost (2006) argued,

> The central role this quantity plays in biology, information theory, physics, and mathematics is not a matter of definition, prejudice, or fashion (as some biologists have claimed) but rather a consequence of its unique ability to weigh elements precisely by their frequency, without disproportionately favoring either rare or common elements. Biologists would have discovered it and used it as their main diversity index even if information theory did not exist.

Applied to verbal behavior, ^1D quantifies the speaking repertoire by measuring the effective number of verbal operants. This shifts the analysis of verbal behavior from distinct categories (i.e., individual verbal operants) to a continuous scale, which is necessary for measuring the multiple controlling relations of established verbal repertoires (Michael et al., 2011). The use of diversity indices in analyzing verbal behavior broadly facilitates the measurement of the functional relationship between environmental factors and provides new research opportunities. For instance, we have shown how ^1D can be used to track progress over time. However, further research is needed to fully grasp its usefulness as a variable for tracking typical language development, evaluating the effects of a particular intervention, or monitoring environmental changes. Additionally, future research should examine ^1D as an independent variable contributing to the emergence of untrained relations, as a mediating factor for stimulus equivalence, and – more generally – as a means of describing participants in human-behavior research. As an independent variable, diversity measures may make sense of larger data sets.

When using measures from other fields, it may be necessary to reclassify the units of analysis. Functionally defined, operant classifications are flexible analytic units that can be rearranged without being redefined. This consistency sets verbal behavior research apart from previous language studies (Greenberg, 1956; Herdan, 1966) while aligning it with other natural sciences.

While we changed how we classified sites, species, and individuals, we did not change the definition of the verbal operants or a response. Here, we reconfigured our analysis in two ways. For beta diversity, we considered each elementary verbal operant as a different site and individual responses as species within that site. For the Shannon diversity, we conceptualized each verbal operant as a species and individual responses within the operant class as members of the species.

The idea of adjusting or rescaling the analytic units has been prominent in behavior analysis and science in general. For instance, some researchers have emphasized the importance of refining the scale of the response to the level of electrical activity (Armshaw et al., 2022; Armshaw et al., 2024; Vaidya & Armshaw, 2021). They used surface electromyography to facilitate shaping muscle flexions of the vastus medialis oblique. While the scale of this analysis required technology to capture a response and mathematical formulation to normalize the volume of data, it was still clearly influenced by operant conditioning.

In conclusion, not only do diversity measures allow researchers to step beyond the level of independent responses, but diversity measures also allow them to step beyond a single organism or an organism within a singular context. As Jost (2007) observed, "It is remarkable that studies of stars, electrons, and butterflies converge on these same expressions" (p. 2439), to which we now contribute the study of expressions themselves.

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Appendix 1: Equations and Worked Examples

Diversity Measures Applied to Archival VOX Data

		Operants				Regional Diversity (γ)	
		Mand	Echoic	Tact	Intraverbal		
Response	"Money"	0	1	1	0	1	γ = 6
	"Spinner"	0	1	0	0	1	
	"Dog"	0	1	1	0	1	
	"Chip"	1	1	0	0	1	
	"Peg"	0	1	0	0	1	
	"Bear"	0	1	0	0	1	
Local Diversity (α)		1	6	2	0	α= 2.25; β= 2.67	

Note. Calculations can be found in the referenced equations and worked example table below.

Referenced Equations and Worked Example

Equation name	**Definition**	**Equation**	**Worked out example using dataset above**
Alpha Diversity (α)	Alpha diversity, or local diversity, is the diversity within an individual sample or site. Here, alpha diversity represents the mean species richness (the average number of unique responses) per operant. It is calculated by averaging the number of responses recorded for each operant.	$\alpha = \frac{Number\ of\ unique\ responses}{Number\ of\ operants\ assessed}$	$= \frac{1+6+2+\ 0}{4}$ $= \frac{9}{4}$ $= 2.25$
Gamma Diversity (γ)	Gamma diversity, or regional diversity, is the total diversity observed across the entire community. Gamma diversity represents the total number of unique responses (species) that occur under at least one source of operant control. It reflects the overall diversity across the entire set of operants sampled.	$\gamma =$ $Responses\ that\ occur\ as\ one\ or\ more\ verbal\ operant$	**"Money":** Emitted as echoic and tact **"Spinner":** Emitted as echoic **"Dog":** Emitted as echoic and tact **"Chip":** Emitted as mand and echoic **"Peg":** Emitted as echoic **"Bear":** Emitted as echoic All 6 responses appear at least once; hence, γ = 6
Beta Diversity (β)	Beta diversity quantifies the degree of change or variation in response distributions across different operants. It is a derived value that quantifies the	$\beta = \frac{\gamma}{\alpha}$	$\beta = \frac{6}{2.5}$ $\beta \approx 2.67$

	extent of similarity across operants.		
Shannon Entropy (*H*)	A measure that captures both the richness and evenness of categories within a dataset. Shannon entropy considers each operant as a "species" and is used to calculate uncertainty when predicting the operant class of a randomly selected response. This measure incorporates both the number of operants that evoke responses (richness) and how evenly those responses are distributed (evenness). Range: 0 - 1.39	$H = -\sum(p_i \cdot ln\ (p_i))$	**Step 1. Total responses across all operants** Mand: 1 Echoic: 6 Tact: 2 Intraverbal: 0 1+6+2+0 = 9 **Step 2. Calculate the Proportion for Each Operant** $p_i = \frac{Number\ of\ responses\ in\ operant\ i}{Total\ number\ of\ responses}$ $p_{Mand} = \frac{1}{9}$ $p_{Mand} = 0.11$ $p_{Echoic} = \frac{6}{9}$ $p_{Echoic} = 0.66$ $p_{Tact} = \frac{2}{9}$ $p_{Tact} = 0.22$ $p_{Intraverbal} = \frac{0}{9}$ $p_{Intraverbal} = 0$
			Step 3. Compute Shannon Entropy (H) 3a. Calculate the contribution of each operant: **Mand** $0.11\ \times ln\ (0.11)\ \approx 0.11\ \times\ (-2.1972)\ \approx\ -0.2441$

			Echoic $0.6667 \times ln\ (0.6667) \approx 0.6667 \times (-0.4055) \approx -0.2703$ **Tact** $0.22 \times ln\ (0.22) \approx 0.22 \times (-01.5041) \approx -0.3342$ **Intraverbal** $0 \times \ln\ (0) \approx 0$ 3b. Sum these contributions: $-(0.2441) + (-0.2703) + (-0.3342) + (0) = -0.8486$ 3c. Multiply by -1-to obtain H: $H = -1(-0.8486) = 0.8486$
Shannon Diversity Index, (^1D)	Shannon diversity index (^1D) is used to convert Shannon entropy into an intuitive metric that represents the effective number of operants comprising the speaking repertoire. Range: 0, 1 - 4	$^1D = exp\ (H)$	$^1D = exp\ (0.8486) = 2.34$