Applying Diversity Measures to the Analysis of Verbal Behavior

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Abstract

This study explores 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 Shannon entropy and beta 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 entropy 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

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Diversity indices have been used by various fields (e.g., ecology, biology, zoology, environmental sciences, urban planning, agriculture, 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 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 both oak and pine trees would have a richness of two. While richness is considered an important parameter of biodiversity for both theoretical and pragmatic purposes (e.g., prioritizing areas for conservation), 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). That is, richness fails to capture the relative abundance of species or behaviors, which can lead to misleading conclusions if this measure is used alone.

The concept of richness can be contextualized and further understood by factoring in abundance. Using abundance measures, the maximum diversity value occurs when all “species” are equally common, while the

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

minimum diversity value occurs when a single “species” dominates (Jost, 2019).[2] Shannon entropy - also referred to as the Shannon diversity index and the Shannon-Wiener index - is widely used to calculate ecological diversity and is the predominant strategy for quantifying behavioral diversity (Bereton & Fernandez, 2022). Shannon entropy (a Hill number of order $q = 1$) has been proposed as a unifying measure of diversity across multiple levels, whether analyzing genes, behavior, species, or entire ecosystems (Gaggiotti et al., 2018; Konopiński, 2020; Sherwin, 2018). Entropy can be transformed into true diversity (${}^{1}D$) by taking its exponential function, which Jost (2006, 2007) regards as the *effective number of species.* Higher values indicate greater richness with more even distribution.

Originally, Shannon entropy (Shannon, 1948) was developed to quantify the uncertainty of the occurrence of a given verbal response in a region. Specifically, as described by Shannon, “The fundamental problem of communication is that of reproducing at one point either exactly or approximately a message selected at another point” (p. 379). Skinner (1957) would later define this phenomenon as echoic control.

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

[2] Hereforeward, the term “species” is used as the taxonomic unit for both interbreeding organisms and operant behavior.

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 have been plagued by poor operational definitions (cf. Skutnabb-Kangaas & 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. After first describing the functional independence of the elementary verbal operants, Skinner elaborated on their multiple causation, noting that the strength or selection of any given verbal response is a function of many variables operating concurrently, including the speakers conditioning history and the current context. Given the history of using diversity measures to demonstrate variation in biological communities, behavioral variation across animal habitats, and the study linguistics, it's reasonable to consider that diversity measures can play a role in our understanding of the interaction of verbal operants.

The use of diversity indices in the analysis of verbal behavior has been notably absent in the existing literature. The primary objective of this research is to bridge this gap by employing diversity measures (richness and abundance) to examine the elementary verbal repertoire. Given the ubiquity of Shannon entropy in quantifying biodiversity, 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 & Andrews, 2019) 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 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 was administered following the procedures outlined by Mason and colleagues (2024), to help determine stimulus conditions that maintain similar response topographies.

Beta Diversity Measures: Visualizing Gamma, Alpha, Beta

The archival VOX data were analyzed using diversity measures, as they afforded us with a unique way to compare topographically related responses across different verbal operants. Applied to the analysis of verbal behavior, diversity metrics quantify response (i.e., species) diversity across operants (i.e., sites) in terms of both richness and abundance. In its strictest sense, beta diversity was the ratio between gamma (regional) and alpha (local) diversities (Whittaker, 1960; Jost, 2007). This gives us information about the relationship and degree of difference between local and regional communities.

To analyze VOX data in relation to beta diversity, we classified “sites” based on the elementary verbal operants (mand, echoic, tact, intraverbal), and “species” as the different responses emitted by the child. Table 1 illustrates this and delineates the presence or absence of a verbal response across each condition. For example, the table indicates that the presence of the item served as a discriminative stimulus for the response, "Ball," (i.e., Tact), but not for mand, echoic, or intraverbal sources of control. This suggests that the child's verbal response was truly functionally independent, as it was not observed across multiple verbal relations. Similar results were found for each response assessed within the VOX analysis.

Table 1

Raw Data from a VOX Analysis

		Operants			
		Mand	Echo	Tact	Intraverbal
Responses	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
	Swings	0	1	0	0

Defining responses and operants as species and sites, respectively, allowed us to calculate alpha, gamma, and beta diversity for the speaker’s verbal repertoire. Alpha (i.e., *local* diversity) is the diversity value for an individual sample, such as a single forest stand, an individual tributary, or an 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., *regional* diversity) is the total diversity measured throughout a community, such as an entire forest, watershed, or verbal repertoire. Here, gamma diversity represents the number of unique responses observed across all operants.

Table 2

Calculation of Alpha, Beta, and Gamma Diversity

		Operants (Sites)				Regional Richness	
		Mand	Echo	Tact	Intraverbal		
Responses (Species)	Ball	0	0	1	0	1	
	Legos	0	1	0	0	1	
	Dolls	0	1	0	0	1	
	Cookies	0	1	0	0	1	= 6
	Magnets	0	0	1	0	1	
	Swings	0	1	0	0	1	
Local Diversity		0	4	2	0	➡ = 3;	β = 2

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):

(1)

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 extreme 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.

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

Table 3

A Verbal Repertoire with Minimum Diversity

		Operants				Regional Diversity	
		Mand	Echo	Tact	Intraverbal		
	Car	1	1	1	1	1	
	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	=3
Responses	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	=3; β=1	

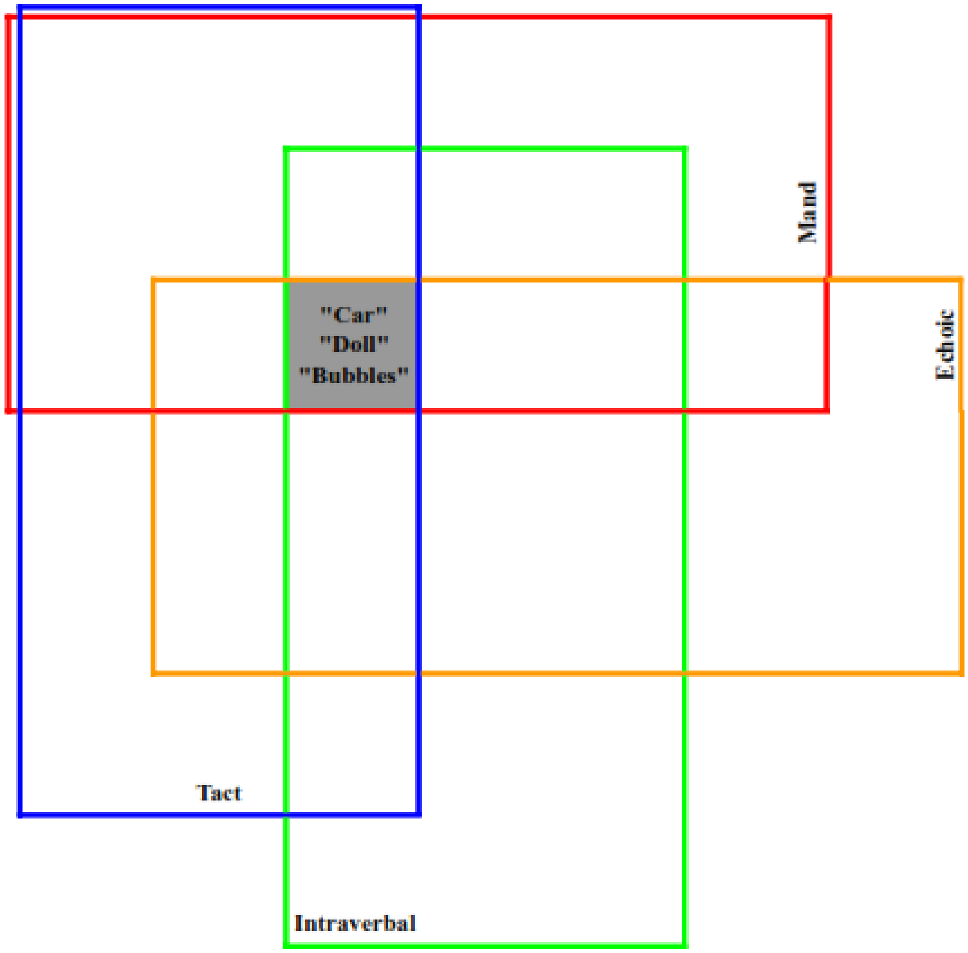


Table 4 displays hypothetical VOX data for a speaker whose verbal repertoire was assessed across 12 referents, for a total of 48 possible responses. In this example, the speaker responded to three different referents across each condition, for a total of 12 responses. As in Table 3, alpha is three. However, here, gamma is 12, which yields a beta of four and represents maximal diversity.

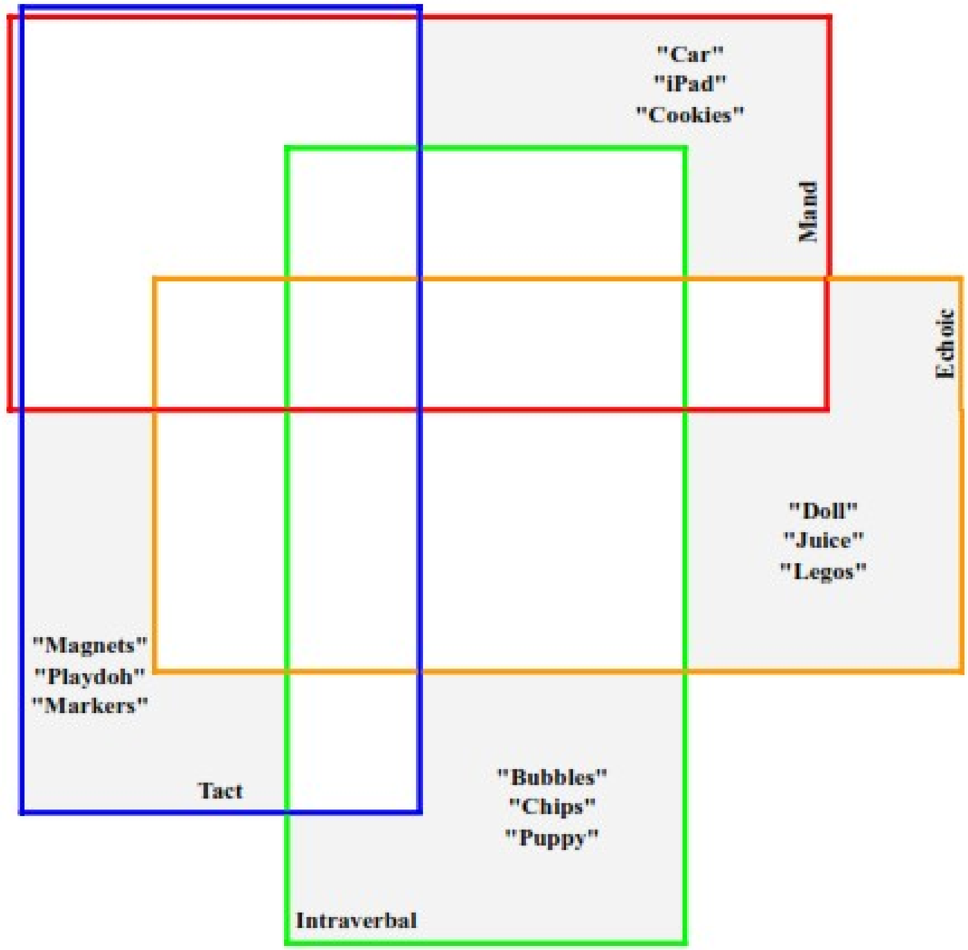
The bottom of Table 4 shows a Venn diagram with no overlap between the 12 responses recorded in the VOX analysis. The outer fields of each set is shaded to indicate that each of the three responses occurred exclusively under mand, tact, echoic, or intraverbal sources of control. No other responses occurred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

Note that the maximum beta value is equal to the number of operants sampled and will vary accordingly. For example, if intraverbal control is omitted from the assessment, the maximum value for beta would be three. Similarly, were a fifth variable (e.g., manded stimulus selection) 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. Consequently, we recommend converting beta to an index.

Table 4

A Verbal Repertoire with Maximum Diversity

		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	=12
	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	
Local Diversity		3	3	3	3	=3; β=4	



Shannon Diversity

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). The above-noted limitations of such a simple formula, however, have led researchers to develop more comprehensive 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 orrelative abundance of each species.

Calculating Shannon entropy 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 () for each operant .

(2)

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

(3)

Following the recommendation of Jost (2006, 2007), we then take the exponential of *H* to convert Shannon entropy into the *effective number of operants*:

(4)

Shannon diversity (^{1}D) 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.[3] 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.

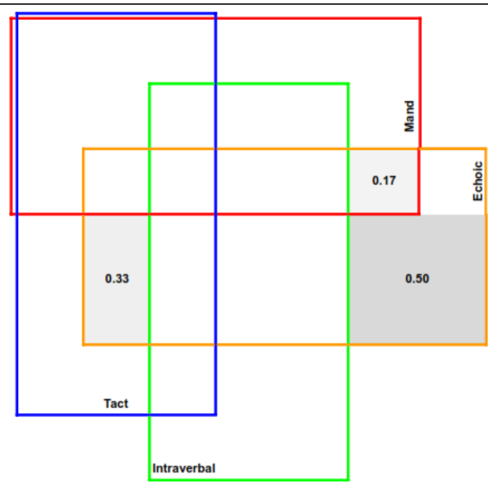
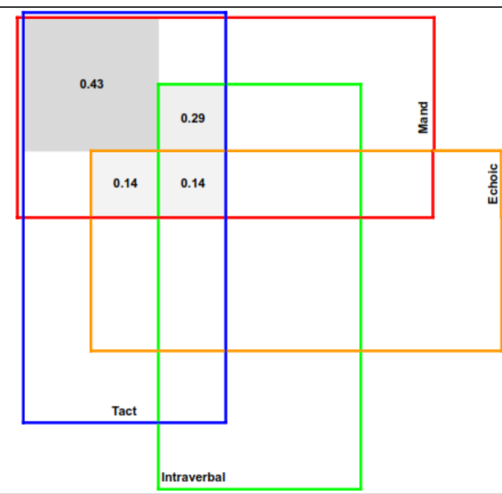
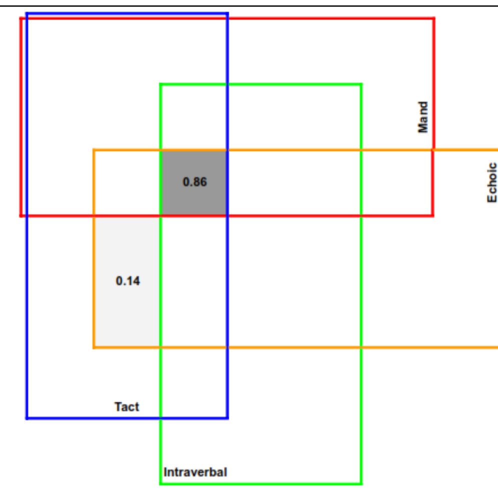
Representative Dataset

To demonstrate the application of diversity measures of verbal behavior, we analyzed 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 6 months and then 12 months of intervention (see Table 5).

[3] If no responses are found across any operants, a score of 0 would be used to indicate that the speaker is nonverbal.

Table 5

Diversity Metrics for a Child with Autism at Intake, 6 Months and 12 Months of Intervention

	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			

At the time of his intake assessment, the speaker had a beta diversity score of 2.67. The corresponding Venn diagram shows that 100% 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 ^{1}D, 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, with 43% of those also under intraverbal control, and another 29% echoic. At the six-month mark, Shannon's ^{1}D calculated his verbal repertoire to be under the effective control of 3.55 verbal operants.

At the end of a 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 ^{1}D, his verbal repertoire was calculated to be under the effective control of 3.98 verbal operants.

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. 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, ${}^{1}D$ 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 as established verbal repertoires are multiply controlled (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 ${}^{1}D$ can be used to track progress over time. However, further research is needed to fully grasp its usefulness as a variable for 1tracking typical language development, evaluating the effects of a particular intervention, or monitoring environmental changes. Additionally, future research should examine ${}^{1}D$ 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.

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., 2023; 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 does the use of diversity measures allow researchers to step beyond the level of independent responses, it also allows 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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