Computational Number Encoding in Infants

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Abstract

Gennari et al's 2023 computational model of developmental cognitive neuroscience demonstrates approximate number sense in infants. EEG data from 12-week-old infants exposed to auditory and visual stimuli showed higher responses to larger numerical stimuli. Computational decoders used EEG responses as training data for three testing decoders: Number, Duration, and Rate. The tests compared the Number decoder, as the variable of interest, with the duration and rate decoders and identified a primary number sense in infants. The computational model ran each decoder through three primary training-testing schemata, with two testing sets in each. Number identification in infant training data support the core knowledge hypothesis. Additionally, testing sets' primary number sense is predictable between auditory and visual stimulus decoders, providing one of the first empirical bases for the multimodality of numbers in the developing cognitive system. Finally, each decoder for both modal stimuli showed representational similarity to the cognitive system, supporting the study's overall experimental validity.

Introduction

Gennari et al. adopted a Cognitive Neuroscience design to assess approximate numerosity in infants within the primary senses of vision and audition. Approximate number sense (ANS) is the relative understanding of quantitative magnitude. For example, exact number sense identifies the precise number of rings a bell makes, and approximate number sense determines whether the second time a bell sounds is greater or less than the first. ANS is the ability to discriminate between quantities. Infants are typically unable to distinguish between exact numbers in any primary sensory modality (e.g. sight, sound). Therefore, to assess the youngest, most innate numerical abilities, infants' approximate numerosity is measured within sensory modalities. Gennari et al. prioritised auditory and visual stimuli as the two primary sensory modalities targeted in their 2023 study. The primary design was effective in supporting the Core Knowledge Hypothesis of innate primary sensory modes, a neurological basis, as evidenced by EEG training data, and a computational model of cognition, as tested by trained decoders on ANS testing sets.

The Core Knowledge Hypothesis posits that the innate core systems provide a basis for adult cognitive capacities. Innate systems underlying cognitive capacities are displayed in shared cortical lobe organisation between infant and adult brains (Spelke & Carey, 1996). For example, the Occipital lobe processes vision in the dorsal cerebral cortex in both young children and mature adults, with a more consistent definition in mature adults. The development of a primary sensory modality grows through social learning iterations across developmental phases (Spelke et al, 2013). To further demonstrate the existence of core systems, particularly the innateness of numerosity, training data are drawn from the least neurologically developed participants possible: 3-month-old infants (12 weeks old).

Measuring the number of sensory modalities poses challenges, particularly for 12-week-old infants. Gathering accurate training data is essential for the validity of any subsequent computational decoding. A resting baseline was established across all participants (n = 26) by measuring electroencephalography (EEG) activity at rest. Sleeping infants accounted for all auditory stimulus responses, and recently awakened infants accounted for all visual stimulus responses. Unconscious and resting neural activations were recorded across all 256 EEG nodes. Faster activations indicate greater surprisal in infants and have faster stimulus identification. So, a faster activation to the larger stimulus indicates a number response. Therefore, ANS responses emerged among all stimulus pairs.

Gennari's decoder model is a novel design because its computational modelling of number cognition covers several training and testing schemata. First, the computational tests require accurate training data, and using high-resolution EEG activations while infants are at rest addresses measurement validity issues in previous studies. Next, measurement validity is ensured by consistently identifying ANS activation as a *primary sensory quantity*, as supported by patterns of positive responses during sleep. Reliable measurements also overcome magnitude confounding, such as a longer stimulus being mistaken for a larger number of stimuli, and are instead cross-referenced within the design to confirm representational similarity. Therefore, regular responses to larger numbers while unconscious primarily provide credible training data to test whether number sense can be decoded from infant brain data. Finally, decoded numerosity as a primary sensory quantity is cross-examined for its modal complexity. Whereas vision is a monomodal example of core systems, numerosity is tested for its decoded predictability across both auditory and visual modalities. Overall, this Computational Model of number in infants aims to address the validity and magnitude of neurological training data, the decoded predictability across testing sets, and the multimodality of numerical cognition.

Modelling Approach and Details

The decoder is trained on two primary channels: a Multivariate Pattern Analysis (MVPA) and a Representational Similarity Analysis (RSA) channel. The MVPA channel encompasses the training-testing schemata across all decoders, and the RSA channel reassesses the validity of the computational measure of magnitude. The decoders are divided into three subsets:

1. Number Decoder - ANS, Independent Variable of interest
2. Duration Decoder - Each Tone's duration/Visual onset
3. Rate Decoder - Frequency of Tones/Visual offset.

The number decoder tests the variable of interest by separately cross-examining it with the duration and rate decoders. The interest of cross-examination is to determine the degree of variance in primary senses attributable to numerosity alone.

The training sets contain activation responses from 256 EEG nodes across all participants and are processed using a few data-preprocessing parameters. The stimuli used are based on Weber's law, which states that the ratio of the minimum just noticeable difference between stimuli is constant. For example, research on rhesus macaques showed a considerable drop in their ability to identify a greater number of stimuli when the stimulus ratio reached about 1:3 (Jordan & Brannon, 2006). Because stimuli with greater differences yielded clear patterns of macaques' understanding of ANS, Weber's law provided a cognitive baseline for the stimulus ratios used in the current study. Infants similarly perform well with stimuli at this ratio; discerning between 4 and 12 stimuli is easier than discerning between 10 and 18 stimuli, despite the difference being 8 stimuli in both cases. The stimuli following the Weber's law ratio of 1:3 are utilised in the testing sets for this experiment, particularly 4 and 12 stimuli.

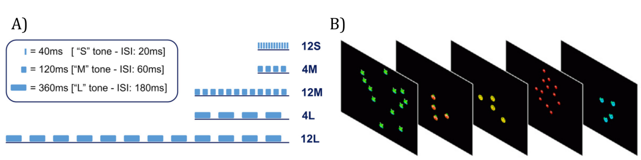

Figure 1: A) All tones were played as audio stimuli to participants. Testing pairs include 4 vs 12 tones at 720ms and 2160ms. B) Visual Stimuli of all patterns displayed to participants. Testing pairs follow the same ratio as auditory, with 4 vs 12 'dots'.

Figure 1 shows the stimuli used for training data, separated into 4:12 stimuli per sensory modality. Resting stimuli for auditory data, shown in A), use repeating patterns of the same violin tone at different rates; importantly, all testing pairs are grouped according to their shared total duration. The recently awoken stimuli for visual data, shown in B), use the same ratio as the auditory data and group pairs according to the pattern of the visual 'dots'. Then the EEG data is preprocessed with a high-pass filter of 0.5Hz to eliminate noisy data and human (infant-related) error, before being used to train the decoders.

Once training data is secured, the cognitive model must decode patterns of number, stimulus duration, and rate. All three decoders for number, stimulus duration, and rate are trained and tested using three schemata, each with two testing sets and one large training set of EEG stimulus responses, as shown in Figure 2.

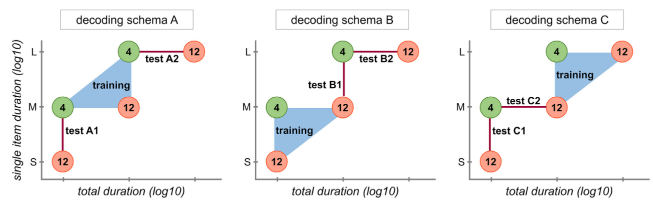

Figure 2: Schematic processing of all the testing sets A, B, and C, with two tests each. The number decoder is run through each of these schemata.

All three decoders will be run through all three schematic training and testing sets. The resulting activation variance patterns would provide evidence for ANS as a primary sensory quantity, and disprove confounding activation from both rate and duration.

Next, the auditory performance will be cross-analysed with visual performance, and any resulting overlap will provide an empirical basis for prior theories about core knowledge systems existing across sensory modalities.

Finally, the representational similarity will be assessed across all auditory ANS schemata. Additionally, RSAs will compare auditory data with visual data to assess the extent to which visual numerosity patterns align with auditory data. A significant degree of similarity between two primary sense modalities will provide a theoretical basis for abstract innate primary sensory systems, such as the ANS, to have a higher probability of multimodal cognition beyond the modalities studied here.

Experiments and Evaluation

Each of the three decoders for Number, Duration, and Rate was run through all three schemata, A, B and C. An MVPA is performed across the two testing sets within each schema. First, the Number Decoder will be cross-examined with the Duration Decoder across testing sets A1, B1, and C1 to assess how much variance in activation patterns can be attributed to stimulus length relative to ANS. Second, the Number Decoder will be cross-examined with the Rate Decoder across testing sets A2, B2, and C2 to assess the extent to which activation variance is predictably attributable to the rate of auditory stimuli relative to ANS. Finally, all tests will be reassessed using two RSAs, within-sequence and at sequence offset, to assess their magnitude validity and support any MVPA findings identifying ANS as a primary sensory quantity.

MVPA analysis tests whether infant data, when run through a series of test sets, can remember items in sequence, i.e., the first item is greater than the second. The first testing set compares the Number and Duration decoders:

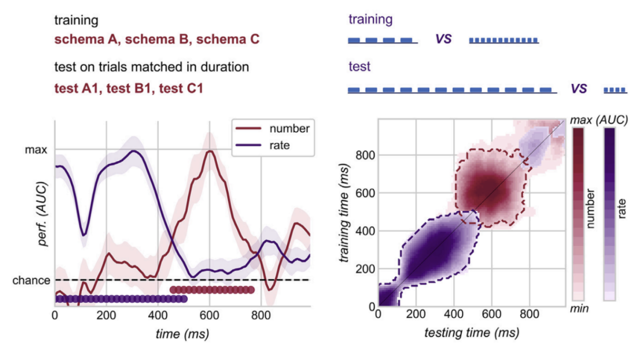

Figure 3: All decoders removed where duration-related performance was uninformative, to evaluate whether number classification could be derived from rate patterns.

In Figure 3, Number classification is tested against rate distinctions on the testing sets A1, B1, and C1 for the classes '12' vs '4'. Results demonstrate that rate-based performance (purple clusters: $p_{clust} = 0.0001$) compared to both number and rate-based performance (red filled clusters: $p_{clust} = 0.0002$) indicated no significant overlap between classifications. The lack of overlapping number classifications indicates that the number is not derived from rate-based performance on auditory trials. Alternatively, duration-based performance was also tested.

Duration-based performance was tested against Number classification on testing sets A2, B2, and C2, for class '12' vs '4' in Figure 4. An evaluation of duration-based performance (blue contours: $p_{clust} = 0.0001$, and $p_{clust} = 0.012$) compared to between-class evaluation of number and duration-based performance (red contours: $p_{clust} = 0.0123$) indicates that auditory classification for number was not contaminated by duration-related cognitive processing. Therefore, neither Rate nor Duration processing affects numerosity performance and identification, and provides auditory evidence for ANS as a primary sensory quantity.

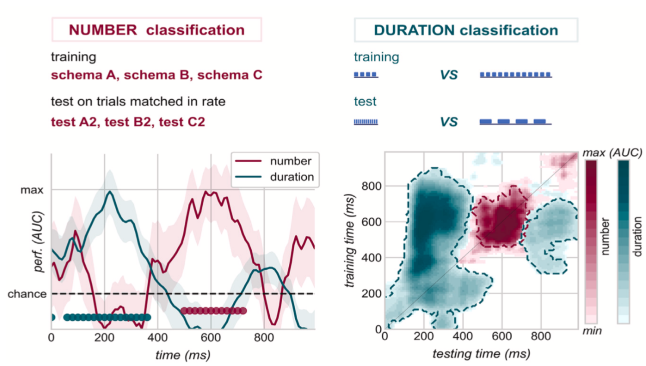

Figure 4: All decoders removed where rate-related performance was uninformative, to evaluate whether number classification could be derived from duration patterns.

Additionally, cross-examinations between auditory and visual processing of ANS assess the degree to which ANS is an auditory-only primary number sense or a multimodal cognitive system.

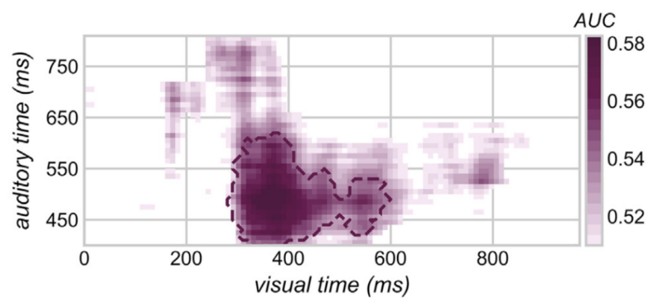

Figure 5: Generalisation across time matrix of number classifiers from auditory to visual trials. Shows performance of classifiers trained on auditory trials at times relative to sequence offset (y-axis) and tested on visual trials at times relative to visual onset (x-axis). Dashed contours indicate statistical significance (cluster permutation t test: $p_{clust} = 0.005$).

Cross-examinations in Figure 5 highlight overlap between auditory and visual time patterns in predictable EEG processing between 450 and 600ms, proving multimodality.

Finally, two RSAs were run across all three decoders and identified a defence against the magnitude argument. Recall that previous macaque studies on numerosity did not computationally test the rate or duration of stimuli as potential confounding variables from which the ANS may be derived. Yet, Gennari et al. not only ran the MVPA to ensure ANS is derived independently from both by testing one at a time, but also through representational similarity. The first RSA was run at Sequence offset, using data as soon as stimuli stopped, and found numerical similarity predict neural similarity at two time periods: an early similarity (~200ms: $p_{clust} = 0.00001$ and $p_{clust} = 0.00007$) within sequence, and a late similarity (~600ms: $p_{clust} = 0.00001$) only at sequence offset. These representational similarities in number and dissimilarities in rate and/or duration reflect total numerosity. A credible numerosity measurement counters the magnitude argument and provides clear evidence of measurement validity.

Discussion

Overall, Gennari et al. demonstrated that approximate number sense is a primary sensory quantity, provided empirical evidence for theories of multimodal core knowledge, and defended their model against confounding variables by assessing the representational similarity of number. Within the training data, responses to number class '4' were slower on average than those to number class '12'. This data response pattern established a predictable model across three decoders, highlighting Number, Duration, and Rate performance. An MVPA was run on all three decoders with corresponding testing sets from three training-testing schemata. Analyses were conducted to determine whether the Number classification, as predicted from infant data, was derived from the Duration classification, and, in a separate analysis, whether the Number classification was derived from the Rate classification. Results identified minimal overlap in both categories and statistically significant patterns of accurate numerosity classification. Accurate number classification as a predictive variable over duration and rate indicates that ANS is a primary sensory quantity. In other words, Number cognition is a core system within the sensory brain.

Furthermore, the cross-examination of visual and auditory data reveals a bolder claim: Number cognition is a core function across sensory modalities. Numerosity within auditory performance decoders was cross-referenced with visual performance data and found significant overlap in numerical identification around the same time period of EEG activation patterns. Therefore, not only is there a numerical classification in unconscious auditory performance, but also in conscious visual performance. Numerical classification in multiple primary senses, sight and sound, serves as evidence for ANS as a core knowledge system. Such support of the core knowledge hypothesis paves the way for expansion in future research regarding the other primary senses (i.e. touch, taste, smell). For now, numerical auditory and visual overlap suggests multimodality in at least two primary senses.

Finally, statistical significance within the computational decoders would be irrelevant without measurement validity, which Gennari et al. demonstrated through representational similarity analyses. The cognitive representation of approximate number is inferred by weighing all three decoders across all three schemata for both training and testing sets. The difference in temporal overlap between Number to rate and duration highlights two cases of independent Number classification without any confounding variation. First, an early numerical activation within sequences is found to lack rate- or duration-derived confounds. And second, a later numerical activation is found only at sequence offsets without rate or durational confounds either. Such independent numerical classification, assuming no other potential unmeasured confounding variables, supports the measurement validity of Gennari et al.'s design.

Overall, the representational similarity of number classification, paired with a multimodal primary sensory quantity, supports core knowledge theories of innate Number. Despite a clear call for replication validity and unproven core knowledge hypotheses, the Numerical classification evidence favours such theories. Gennari et al.'s model is especially favoured because it is not only computational but also incorporates a Cognitive Neuroscience approach with real infant training data.

Personal Reflection

Gennari et al.'s model has many modelling and experimental strengths; however, there are multiple evaluative leaps and data limitations that were used to extrapolate bold conclusions. Positive design choices include a combined computational and cognitive neuroscience technique to base decoder patterns and predictive results on real infant data, measurement validity and defence against the magnitude argument, and novel multimodal insights. Limitations include less representative training data collected manually, 12-week-old infants making this particularly challenging, failing to account for possible prior learning (before 12 weeks), and the difficulty of interpreting correlational data.

The interdisciplinary design helped establish a model that was more cognitively representative and particularly rooted in the data of the target demographic's actual brain patterns. Many computational-only models aim to support functional numerosity at 3 months and corroborate neural findings, with similar patterns emerging automatically in untrained neural networks (Kim et al., 2021). Therefore, the model design is well thought through and theoretically sound. Furthermore, the measurement validity of Gennari et al.'s model further supports the design measures and variable choices of duration and rate to distinguish number from. Both MVPAs and RSAs that experiment on training-testing schemata provide a defence against magnitude issues when measuring approximate numbers rather than exact ones. Their experimental controls with unconscious data collection and simplified ratios of testing and training stimuli left duration and rate as among the only potential alternate sources of data variation.

There may, however, be contaminated training data variables affecting the variance in Number classification data, likely due to human error, which compromises the model's predictive validity for Number. Whilst participants were unconscious, auditory training data was collected uninterrupted; if participants woke up, visual data was recorded instead. However, the 'resting' state of the brain, once awoken, is no longer under control. The brain's resting state supports number as a primary sensory quantity, and, if awoken, age alone does not indicate a primitive cognitive function, nor does it support accurate core numerical systems. Additionally, the correlational nature of the results provides challenges for causal interpretation, despite statistical significance. Therefore, a conscious state of mind is not controlled in this study. Future research would require reassessing multimodality and reconfiguring controls during infant data acquisition to ensure accurate primary-sense recording.

In conclusion, predictive approximate number patterns support theories of a primary number sense, which is unaffected by duration and rate. And future research regarding multimodality and human data acquisition will only improve these findings.

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(Carey & Spelke, 1996) (Gennari, Dehaene, Valera, & Dehaene-Lambertz, 2023) (Jordan & Brannon, 2006) (Kim, Jang, Baek, Song, & Paik, 2021) (Spelke, Bernier, & Skerry, 2013)