Filling in the Mechanisms: How do LMs Learn Filler-Gap Dependencies under Developmental Constraints?

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Abstract

For humans, filler-gap dependencies require a shared representation across different syntactic constructions. Although causal analyses suggest this may also be true for LLMs (Baguraev et al., 2025), it is still unclear if such a representation also exists for language models trained on developmentally feasible quantities of data. We applied Distributed Alignment Search (DAS, Geiger et al. (2024)) to LMs trained on varying amounts of data from the BabyLM challenge (Warstadt et al., 2023), to evaluate whether representations of filler-gap dependencies transfer between wh-questions and topicalization, which greatly vary in terms of their input frequency. Our results suggest shared, yet item-sensitive mechanisms may develop with limited training data. More importantly, LMs still require far more data than humans to learn comparable generalizations, highlighting the need for language-specific biases in models of language acquisition.[1]

1 Introduction

A major question in language acquisition asks how learners can make generalizations about infinite utterances on the basis of finite input. Many cognitive models have proposed and revised many claims about the linguistic representations humans could use to solve this learning problem, which often apply abstract, language-specific rules to learn from specific pieces of data (Yang, 2004; Perkins et al., 2022; Pearl, 2023). Language models (LMs), on the other hand, lack these biases, yet still posit some important syntactic generalizations (Futrell et al., 2019; Warstadt et al., 2020; Linzen and Baroni, 2021; Wilcox et al., 2024). These successes have led some researchers to question the need for language-specific representations altogether (Piantadosi, 2023; Futrell and Mahowald, 2025).

One particular case that evaluates this debate involves *filler-gap dependencies*. Filler-gap dependencies are a type of syntactic relation formed when a constituent (or the filler) is displaced from its canonical position (the gap) and interpreted in another position. These gaps can exist across various constructions including, but not limited to, wh-questions (*"What did the student make _?"*), relative clauses (*"the robot that the student made _"*), and topicalization (*"This robot, the student made _"*).

Filler-gap dependencies are a useful test case for evaluating the representations necessary for language acquisition, as they not only require learners to recognize hierarchical structure across items in a sentence, but also notice an empty syntactic position that is not overtly realized. Many linguistic theories claim that despite superficial differences, these constructions may share an abstract underlying mechanism (Chomsky, 1977; Culicover et al., 1977; Gazdar, 1982; Kaplan and Bresnan, 1982; Postal, 1999). Evidence from real-time processing supports these claims; adults exhibit similar behavioral patterns across multiple filler-gap constructions (Crain and Fodor, 1985; Traxler and Pickering, 1996; Sprouse et al., 2016; Kush and Dillon, 2021, among others). Determining how a generalized representation can be learned from linguistic data is thus a major area of investigation.

LMs are relevant to addressing this question since they are examples of a "domain-general, weakly biased" learner (Wilcox et al., 2024). Their successes with some constraints on filler-gap dependencies have led to claims that the dependency *is* learnable without language-specific knowledge (Wilcox et al., 2018, 2024). These results have since been challenged, highlighting that LMs may not represent filler-gap dependencies in a human-like manner (Bhattacharya and van Schijndel, 2020; Lan et al., 2024; Howitt et al., 2024; Chang et al., 2025). Although analyses of LM probabilities show

[1] Our code and data are available at: https://github.com/atreydesai/developmental-filler-gap

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mixed results, causal interventions on LMs' internal states could tell a more definitive story as to whether a shared representation of filler-gap dependencies persists across constructions. Boguraev et al. (2025) do apply causal interpretability methods (Geiger et al., 2024; Mueller et al., 2025) in service of this question. Through causal analyses of LMs' latent spaces, they identify representations of a filler-gap dependency using examples of one construction, manipulate the representation for a different filler-gap construction to see how knowledge of filler-gap dependencies in one construction *transfers* to others, and identify shared underlying structure across various types of filler-gap dependencies. However, even if Boguraev et al. (2025) show a shared representation of filler-gap dependencies may be learnable in principle, their results do not address whether inductive biases are needed for humans, as they evaluated LMs trained on data that matches neither the content nor the quality of data available to human learners (Wilcox et al., 2025). Chang et al. (2025) do investigate LMs trained on human-scale data, but rely on probability measures for one type of filler-gap dependency.

In our study, we run causal interventions on LMs (Boguraev et al., 2025) trained on data from the BabyLM challenge (Warstadt et al., 2023), which reflects material that English-speaking children could be exposed to, up to 12 years of age. Our experiments show that LMs may posit a shared representation of filler-gap dependencies across high and low frequency constructions, but rely on far more input than human learners (Perkins and Lidz, 2021). This representation is also far less general than the fully shared mechanisms proposed by linguists. Even if a filler-gap dependency is learned for one construction, it can be generalized to other items with that construction, but not to other constructions with the filler-gap dependency.

Overall, our results show that domain-general learning mechanisms like prediction may be sufficient to learn some shared filler-gap structure in principle, but this is not possible with human-like input, pointing to the need for language-specific inductive biases to (Yang, 2004; Portelance and Jasbi, 2024) to learn relevant linguistic generalizations. Developmentally aware evaluation should also include timing of human acquisition alongside the amount and type of training data. Children demonstrate sensitivity to core syntactic structure quite early, such as filler-gap representations by 18 months (Perkins and Lidz, 2021). A model is only developmentally plausible if comparable generalizations emerge on a similarly early developmental timescale.

2 Background

Filler-gap dependencies are shared across syntactic constructions that show different surface forms, even if they may serve different semantic and discourse functions (Schütze et al., 2015). Looking at the following sentences, (1) is a *wh-question*, while (3) is an example of *topicalization*.

(1) *Who* did the teacher like _ ?

(2) Did the teacher like?*

(3) *The author*, the teacher liked _ .

(4) The teacher liked.*

In (1) *who* is the object of *like*, and in (3), *The author* is the object of *liked*. These constituents, which are **fillers**, are fronted to form a dependency with the **gaps**, which are unpronounced but marked with _ for readability. Learning the generalization also involves recognizing where the dependency may *not* be valid, such as (2) and (4), which show that (1) and (3) are respectively ungrammatical without the fillers. Syntactic configurations called *islands* make extracting a filler ungrammatical (Chomsky, 1977). This has made recognizing filler-gap licensing a particularly relevant test case when evaluating syntactic structure in language models.[2]

2.1 LM Surprisal and Filler-Gap Dependencies

Many studies use LMs to compute the *surprisal*, or negative log probability, of a word conditioned on its context. The surprisal of a word (or any linguistic unit) quantifies its expected processing difficulty given preceding context (Levy, 2008), and evaluating LMs' surprisals at particular points in a sentence effectively identifies which parts are expected to be more difficult to process (Futrell et al., 2019).[3] Work evaluating LMs on syntactic structure has often relied on comparing two minimal pairs of sentences, such as (1) vs. (2) and (3) vs. (4), where the ungrammatical version should

[2]Refer to Wilcox et al. (2024), Howitt et al. (2024), and Chang et al. (2025) for further discussion relating to language models and island constraints.

[3]However, see Huang et al. (2024) for evidence that LM surprisal cannot reflect the quantitative effects of processing difficulty for particular types of syntactically complex sentences.

typically have a higher surprisal than the grammatical version (Marvin and Linzen, 2018; Warstadt et al., 2020; Gauthier et al., 2020).

Surprisal from LSTM language models shows positive results, reflecting the presence and absence of fillers and gaps in English sentences with embedded wh-questions (Wilcox et al., 2018). These results have been extended to Transformer models and many other island constraints on wh-questions(Wilcox et al., 2024).[4] Ozaki et al. (2022) evaluated LSTM surprisal across a range of other filler-gap constructions, including topicalization, and found that model performance for each construction is highly correlated with its frequency, suggesting that LMs are more frequency-sensitive than human judgments across filler-gap constructions. They do not present evidence whether this generalization is shared *across* constructions.

Since surprisal cannot directly test for a shared representation across constructions, several other studies have examined the effects of enriching models' training data with more examples of filler-gap constructions. Simulated priming studies on wh-movement (Bhattacharya and van Schijndel, 2020; Prasad et al., 2019) have shown some evidence for a shared representation of filler-gap dependency, but not constraints on the dependency. More recent studies have retrained LMs by augmenting their training data with positive examples of a dependency. Lan et al. (2024) show that augmentation improves LMs' performance on complicated filler-gap constructions (parasitic gaps and across-the-board movement). Extending this approach across constructions, Howitt et al. (2024) adopted their methodology and found that augmenting LSTMs' training data with instances of one construction (clefting and topicalization) failed to improve performance on detecting filler-gap licensing and islands for other constructions (wh-movement, clefting, topicalization, and tough-movement).

Although surprisal can effectively show whether LMs are able to assign probabilities appropriately for cases of filler-gap licensing, it may not necessarily directly reflect LMs' internal representations. Retraining LMs can help address whether they posit a shared representation for filler-gap dependencies, but results have been mixed.

[4]Results are more mixed in Norwegian (Kobzeva et al., 2023) and Dutch (Suijkerbuijk et al., 2023), which have different filler-gap structures from English.

2.2 Causal Interventions

In order to evaluate whether LM representations can indeed encode linguistic features of interest, several studies have adopted *causal intervention* methods from mechanistic interpretability. Broadly speaking, these approaches manipulate an LM's internal representations of individual items to find aspects of its representational space that are causally responsible for a desired feature (Wang et al., 2021; Lasri et al., 2022; Hao and Linzen, 2023; Kryvosheieva et al., 2025, among others, see Mueller et al. (2025) for a review). Arora et al. (2024) evaluated causal intervention methods on models from the Pythia series (Biderman et al., 2023), run on a large-scale suite of syntactic constructions (Gauthier et al., 2020), including wh-movement. Arora et al. (2024)'s best-performing method, Distributed Alignment Search (DAS) (Geiger et al., 2024), learns a rotation of the representation space to identify a direction; when intervened upon, this vector maximizes the probability of a counterfactual output label. We provide further description of this method in 4.3. Boguraev et al. (2025) applied DAS to Pythia-6.9B, finding evidence for a shared representation across seven types of filler-gap constructions. In their analysis, they identify an underlying "transfer network" that evaluates whether the representation from one filler-gap construction can successfully be implanted in another, injecting the learned source direction into a matched base sentence from a different construction, shifting the model toward the filler-gap-consistent prediction for said target construction. More frequent constructions, such as wh-questions, act as "source" nodes in the network towards infrequent "sink" nodes such as topicalization. Despite unequal contributions to the shared representation, evidence for such a representation did exist. They also identify a "lexical boost"[5] effect based on whether the examples involved in the intervention share the same level of animacy, that is, stronger causal effects when both sentences in the intervention describe animate or inanimate subjects.

2.3 Developmentally Plausible Data

Although Boguraev et al. (2025) shows evidence for an LM positing a shared mechanism for filler-gap dependencies, they relied on a Transformer

[5]This term is borrowed from psycholinguistic studies using syntactic priming, where human processing gets facilitated by similar sentence structures (Traxler et al., 2014).

model with billions of parameters, trained on a Web-scale corpus (Gao et al., 2020). These results make the case that filler-gap dependencies are learnable with a domain-general mechanism in principle, but have less to say about questions of *human* language acquisition (Wilcox et al., 2025). Children are able to understand constraints on filler-gap dependencies around ages 3-5 (De Villiers and Roeper, 1995; Friedmann et al., 2009, among others), while more recent evidence suggests they begin to demonstrate this sensitivity as early as 18 months (Gagliardi et al., 2016; Atkinson et al., 2018; Perkins and Lidz, 2021).[6]

The BabyLM Challenge (Warstadt et al., 2023) trains models on approximately 100 million tokens, the estimated linguistic input of a child around 12 years of age (Gilkerson et al., 2017). The data and models from BabyLM allow researchers to answer questions about human language acquisition that would be difficult to test experimentally, while providing learners with training data mimicking children's input. A prior evaluation of BabyLM models' performance on filler-gap licensing and island constraint violations found partial but incomplete acquisition, with performance varying substantially across island types (Chang et al., 2025). However, their findings are limited to wh-movement, which frequently occurs in children's input (Furrow et al., 1979), but models should also be evaluated across other constructions that appear less frequently to see if they posit a shared representation.

3 Research Questions and Hypotheses

Our study seeks to evaluate whether a causal cross-construction representation for filler-gap dependencies is learnable under a domain-general mechanism, provided that a learner has access to child-like amounts of input data. If LMs *were* learning a shared representation across construction types, then the spatial relationships between grammatical and ungrammatical examples in the latent space would be aligned across constructions. To this end, we aim to replicate findings from Boguraev et al. (2025) on a model trained on the corpus used in the BabyLM challenge, in service of extending results from linguistically informed mechanistic interpretability studies to questions about language development. We evaluate the model on both a high-frequency construction: wh-questions, compared to a low-frequency construction, topicalization. We propose the following three research questions:

- **RQ1:** Can a language model with relatively few parameters and human-like training data still posit a causal representation of filler-gap dependencies? If so, when does this effect emerge?
- **RQ2:** Are representations construction-specific, such that within-construction interventions yield stronger causal effects than cross-construction transfer?
- **RQ3:** Is the causal intervention more effective when representations are transferred from high-frequency to low-frequency constructions?

We create three hypotheses based on these questions. First, the version of the model trained on all 100 million tokens in the BabyLM training corpus *should* learn an abstract filler-gap mechanism that is detectable and transferable by DAS from one construction to another, based on some of the positive results from Chang et al. (2025). However, due to the lack of language-specific inductive biases, we do not predict a strong causal effect before 10 million tokens. This is because the BabyLM checkpoint for 10 million tokens mimics the linguistic input of children from ages 2-5 years (Warstadt et al., 2023), while English-speaking children are able to recognize filler-gap dependencies around 18 months (Perkins and Lidz, 2021) (**H1: Misaligned Emergence Hypothesis**). Second, since LMs likely learn the filler-gap dependency in a piecemeal fashion (Ozaki et al., 2022; Howitt et al., 2024), we expect stronger causal effects for within-construction interventions compared to cross-construction interventions. We also hypothesize that transfer improves when both constructions share the same level of animacy, to replicate Boguraev et al. (2025)'s findings for lexical boost effects. (**H2: Construction-Specificity Hypothesis**). Third, given the greater prevalence of wh-questions in language corpora, as opposed to topicalization, and existing work showing learning correlates with input frequency (Ozaki et al., 2022; Boguraev et al., 2025), we expect an asymmetrical, one-way transfer from wh-questions (more

[6]Most of this work relies on wh-questions and relative clauses to argue that children rely on a shared representation of filler-gap constructions. However, a recent cross-linguistic corpus study finds evidence for topicalization in children's utterances around the age of 2 (Bosch and Biberauer, 2025).

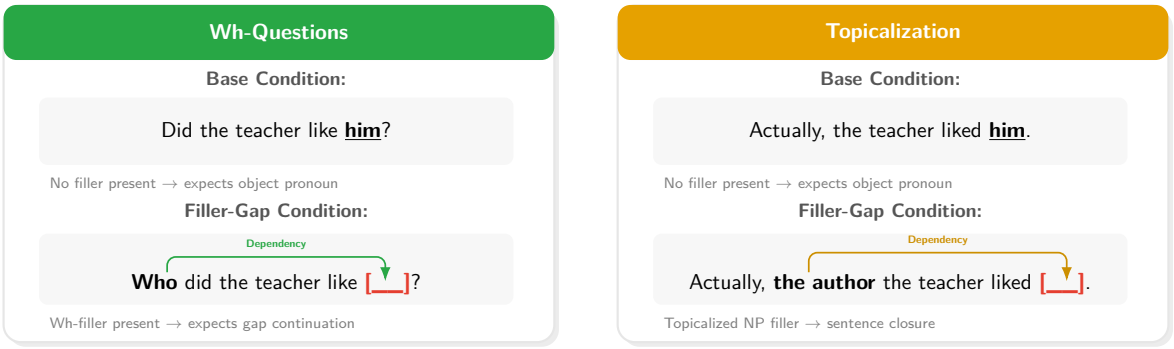

Figure 1: The diagram contrasts Wh-Questions (left, green) and Topicalization structures (right, orange).

frequent) to topicalization (less frequent) (**H3: Frequency Modulation Hypothesis**).

4 Methods

4.1 Model

We use the BabyLM-100M model (Warstadt et al., 2023). This model uses the GPT-2-small architecture (Radford et al., 2019) trained on the BabyLM Strict-100M corpus, consisting of a set of approximately 100 million words as training data designed to mimic the total linguistic input received by an English-speaking child until early adolescence (around 12 years of age) (Gilkerson et al., 2017; Warstadt et al., 2023).

The corpus consists of relevant data from the British National Corpus, the CHILDES language acquisition database, the Switchboard Dialog Act Corpus, subtitles from children's TV shows, and simplified Wikipedia articles (Charpentier et al., 2025).

Multiple checkpoints for the model across the training process were also released. We evaluate several checkpoints where the model received increasing amounts of input (1M–100M tokens): 10 checkpoints from 0–10M tokens and 9 checkpoints between 10M–100M tokens. Additionally, nine additional checkpoints (100M–1000M) are used in extended analysis in the appendix.

4.1.1 Constructions

We use two filler-gap constructions that have different levels of frequency: matrix wh-questions (high frequency) and topicalization (low frequency), based on Ozaki et al. (2022). This combination allows us to systematically evaluate whether knowledge of high-frequency constructions can be transferred to less frequent ones that may barely be present in children's input.

Wh-Questions (High Frequency). We use single-clause matrix wh-questions, such as *"What did the doctor do ___?"* and *"What did the student read ___?"* Wh-questions are very common in natural language and exist in child-directed speech (Furrow et al., 1979). Prior work demonstrates that neural LMs readily acquire sensitivity to wh-dependencies in English (Wilcox et al., 2024). This makes Wh-questions a plausible construction for a high-frequency "source" in transfer experiments.

Topicalization (Low Frequency). We employ fronted object topicalization with an optional discourse marker, such as *"The student, the teacher liked ___."* or *"Actually, the book the author read ___."* Topicalization is extremely uncommon in natural language and almost absent from child-directed speech (Roland et al., 2007). Related work finds that LMs fail to display the correct behavior for topicalization (Ozaki et al., 2022), even when augmented with examples in the training data (Howitt et al., 2024).[7] In addition, when analyzing transfer of the filler-gap mechanism across constructions, Boguraev et al. (2025) found topicalization had a low "out-degree" in their transfer network: despite receiving other constructions, topicalization rarely transfers to them. This makes topicalization a strong candidate for a low-frequency "sink" construction for our experiments.

We created minimal pairs following the original template and methodology of Boguraev et al. (2025). Each pair compares a base sentence with no filler-gap dependency with a filler-gap sentence containing a matrix wh-question or a topicalization setup. The model's expected next-token prediction

[7] Howitt et al. (2024) show that including a discourse marker leads to slight qualitative improvements, but the generalization is only learned in one direction, when the filler is present.

differs based on the two predicted gaps (marked with _).

4.2 Materials

Replicating the experimental structure of Boguraev et al. (2025), we test sentences with both animate and inanimate fillers. Animate fillers use *who* (wh-questions) or NPs with perceived life or agency, such as *the author* (topicalization). In contrast, inanimate fillers use *what* (wh-questions) or nonliving and nonsentient NPs such as *the book*. This creates four dataset template variants: *wh_animate*, *wh_inanimate*, *topic_animate*, and *topic_inanimate*.

Different combinations of the following lexical items are used in respective templates: **Subject NPs** (50 animate nouns: *teacher, doctor, manager*, etc.), **Verbs** (30 transitive verbs: *like, admire, follow*, etc.), **Auxiliaries** for wh-questions (7 verbs: *did, will, could*, etc.), and **Licensing adverbs** for topicalization (25 adverbs: *Actually, Frankly, Surprisingly*, etc.). We verified all materials consist of one token for the model and occur within the BabyLM corpus.[8]

This yielded approximately 21,000 unique sentence pairs for wh-questions and 1,875,000 for topicalization per animacy condition. Topicalization randomly selects both the sentence-initial adverb and the topicalized filler phrase, increasing the amount of unique sentences. However, both pools remain substantially larger than 2000 pairs sampled for DAS training, maintaining sentence diversity for generalization.

4.3 Distributed Alignment Search (DAS)

Distributed Alignment Search (DAS) is a causal intervention method to test if a high-level concept aligns with the internal weights of a language model (Geiger et al., 2024). We can define a minimum causal model for a filler-gap dependency using a binary variable: FILLER_PRESENT $\in \{0, 1\}$. This variable causally influences gap expectations and the model's next-token predictions.

Given a *source* sentence with a filler (Figure 1) and a *base* sentence without a filler (Figure 2), we can intervene based on the internal representations of the base sentence by implanting the learned filler-gap DAS feature from the source, as seen in figure 2. A successful implementation should shift the prediction of the model from the base label (*him*) toward the source label (*?*). This would suggest that the filler-gap dependency is encoded at the intervention site (Wu et al., 2024).

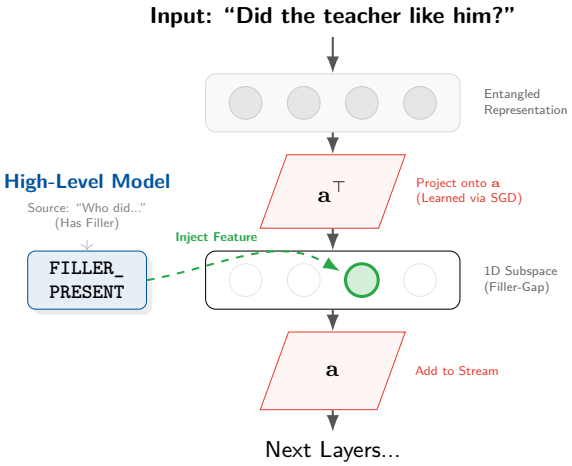

Figure 2: To create a DAS vector, we learn a direction $\mathbf{a}$ to align neural representations with the binary variable FILLER_PRESENT. We intervene by projecting the difference between the source and base representations onto $\mathbf{a}$ and injecting it into the base sentence.

4.3.1 Training

Following prior work, we use a 1-dimensional variant of DAS (Geiger et al., 2024; Arora et al., 2024; Boguraev et al., 2025). Given an embedding space with dimensionality d, for each layer ℓ and token position p, we learn a *direction vector* $\mathbf{a}_{\ell,p} \in \mathbb{R}^d$ that defines a one-dimensional subspace in which the filler-gap feature is encoded, between the model's representations of the base construction at ℓ and p ($\mathbf{h}_{\text{base},\ell,\mathbf{p}} \in \mathbb{R}^d$) and the source construction ($\mathbf{h}_{\text{source},\ell,\mathbf{p}} \in \mathbb{R}^d$). Once the vector $\mathbf{a}$ is learned, the intervention projects the difference between the source and base representations onto $\mathbf{a}$ and adds it to the base representation:

$$\tilde{\mathbf{h}} = \mathbf{h}_{\text{base}} + \mathbf{a}\mathbf{a}^\top(\mathbf{h}_{\text{source}} - \mathbf{h}_{\text{base}}) \quad (1)$$

This intervention preserves the orthogonal dimensions of the base representation and only modifies the value along the learned feature direction $\mathbf{a}$. The direction is optimized to minimize cross-entropy loss between the counterfactual predictions of the model after intervention and the source sentence labels.

We use a batch size of 25, 80 training steps per layer-position combination, and a learning rate of 5×10^{-3} to train each DAS vector. We provide further information on hyperparameter selection in

[8] See Nair and Resnik (2023), Giulianelli et al. (2024), and Oh and Schuler (2025) for discussion of tokenization and psycholinguistic applications.

Appendix A. Due to the comparatively low number of layers in BabyLM's architecture, we test all 12 layers across 6 token positions aligned to template slots: prefix (position 0), filler (position 1), auxiliary/complementizer (position 2), article (position 3), subject NP (position 4), and verb (position 5).

4.3.2 Evaluation Metrics

We primarily use the **ODDS** metric to quantify the magnitude of the causal effect through measuring how much the intervention shifts log-probabilities toward the counterfactual outcome. This is given by the formula:

$$\begin{aligned}\textbf{ODDS} &= \log \frac{P(\text{base} \mid \text{clean})}{P(\text{source} \mid \text{clean})} \\ &+ \log \frac{P(\text{source} \mid \text{int})}{P(\text{base} \mid \text{int})}\end{aligned} \tag{2}$$

In Equation (2), 'clean' refers to a standard forward pass without an intervention, while 'int' refers to a forward pass where the DAS intervention is applied.

A positive **ODDS** value suggests the intervention successfully shifts predictions toward the source; in addition, the higher the **ODDS** values, the stronger the causal effects.

We establish the following qualitative thresholds following Arora et al. (2024): values near 0 show little to no causal effect (comparable to random baselines), values in the 3–6 range demonstrate emerging to moderate causal structure (as seen in smaller models such as Pythia-14M), and values greater than 8 indicate strong causal mechanisms (as seen in larger models such as Pythia-6.9B).

We primarily report **MAX ODDS** , or the maximum **ODDS** value across all layers at a given position. The goal of DAS is to localize the feature to specific layers, so the maximum represents the layer-position combination with the most effective causal effect.

4.3.3 Experiments

We run two types of experiments: *localization* and *transfer*, to evaluate generalizations within and across construction types.

1. **Wh → Wh (within-construction localization)**: Train DAS on wh-questions, test on held-out wh-questions
2. **Topic → Topic (within-construction localization)**: Train DAS on topicalization, test on held-out topicalization
3. **Wh → Topic (forward transfer)**: Train DAS on wh-questions, test on topicalization
4. **Topic → Wh (backward transfer)**: Train DAS on topicalization, test on wh-questions

The localization experiments (Wh→Wh, Topic→Topic) quantify the extent to which the DAS can identify filler-gap representations within each construction type. Likewise, cross-construction transfers (Wh→Topic, Topic→Wh) test if representations of a given construction are generalizable across the filler-gap constructions. If the transfer is symmetric, **ODDS** retention should be similar in both directions. If frequency modulates transfer, we predict asymmetrical transfer towards the high-frequency (Wh → Topic) direction.

4.4 Statistical Analysis

We fit a linear model predicting **MAX ODDS** from number of training tokens, transfer direction, and animacy:

$$y = \beta_0 + \beta_t \mathbf{x}_{\text{tokens}} + \beta_d \mathbf{x}_{\text{dir}} + \beta_a \mathbf{x}_{\text{anim}} + \epsilon \tag{3}$$

Where y is **MAX ODDS** , and $\mathbf{x}$ represents the fixed effects for token count, transfer direction, and animacy. Post-hoc contrasts used estimated marginal means with Holm-Bonferroni correction for 171 pairwise comparisons (Lenth and Piaskowski, 2017). Cohen's d is used to measure effect sizes using the residual standard deviation.

5 Results

We present the results from 19 BabyLM checkpoints in the developmentally plausible range (1M–100M tokens) across multiple constructions (wh-questions, topicalization) and animacy conditions (animate, inanimate). All experiments were repeated on a minimum of 6 seeds to establish tighter bounds of confidence. The linear model achieved $R^2 = 0.53$, $F(22, 4537) = 235$, $p < .001$.

5.1 Developmental Trajectory

Figure 3 shows **MAX ODDS** across training on all four transfer directions. Filler-gap localization significantly increased with training duration ($F(18, 4537) = 264.3$, $p < .001$), from near zero at 1M tokens (**MAX ODDS** ≈ 0.8) to a robust effect by 100M (**MAX ODDS** ≈ 10.6 for Wh→Wh). Qualitatively, relatively stronger causal effects (**MAX**

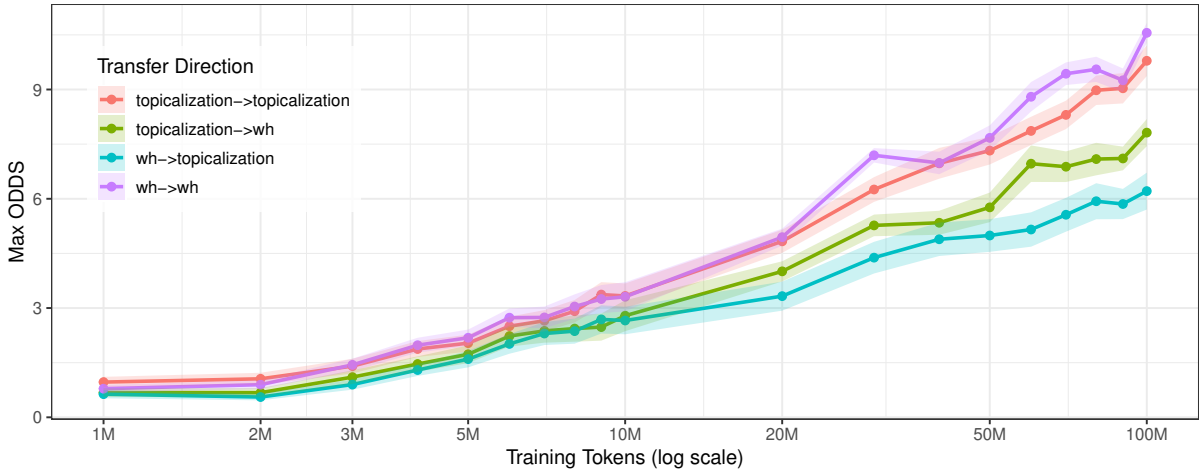

Figure 3: Developmental trajectory of all filler-gap mechanisms across training. Error bands show ±1 SE across a minimum of 6 seeds. All four conditions show a monotonic increase with training tokens.

ODDS > 8) began emerging after around 50M tokens, while the effects are weaker (**MAX ODDS** ≈ 3) around 10M tokens.

5.2 Within-Construction Localization

Both constructions displayed successful within-construction localization, increasing with training tokens. At 100M tokens, Wh→Wh achieved **MAX ODDS** = 10.56 (SD = 2.11) and Topic→Topic achieved **MAX ODDS** = 9.79 (SD = 3.24). Compared to the results of the transfer experiments, within-construction localization effects consistently exceeded cross-construction transfer effects (mean difference = 1.33 **MAX ODDS** , t = 17.4, $p < .001$, d = 0.52), showing that high performance on one dependency type does not completely generalize to others.

5.3 Cross-Construction Transfer

Unlike the frequency-based prediction in Hypothesis 3, Topic→Wh transfer *exceeded* Wh→Topic transfer throughout training (difference = 0.57 **MAX ODDS** , t = -5.29, $p < .001$, d = -0.22). At the 100M checkpoint, Topic→Wh achieved **MAX ODDS** = 7.82 versus Wh→Topic's **MAX ODDS** = 6.21.

This transfer asymmetry could be due to wh-questions developing a more construction-specific representation that transfers less effectively across other types of filler-gap constructions. Conversely, a more general mechanism may be reflected in topicalization when it is learned, due to little to no presence in the input. In an exploratory analysis, we also evaluate later checkpoints for the model as it was trained on more data, and find that the trend does not persist. Instead, both types of cross-construction transfer have similar causal effects on models with more input (Appendix A.3).

Contrast	**Est.**	**SE**	t	p	d
Within–Across	1.33	0.08	17.4	<.001	0.52
Wh→Topic–Topic→Wh	-0.57	0.11	-5.3	<.001	-0.22
Animate–Inanimate	0.68	0.08	8.6	<.001	0.26

Table 1: Post-hoc comparisons from linear model. Negative asymmetry results suggest Topic→Wh outperformed Wh→Topic.

5.4 Animacy Effects

We find further evidence of a "lexical boost" effect predicted by Boguraev et al. (2025). DAS transfer was significantly stronger when animacy of training and evaluation matched relative to animacy-mismatched conditions (difference = 0.67 **MAX ODDS** , t = 4.86, $p < .001$, d = 0.28).

6 Discussion and Conclusions

This study applies causal interventions to determine how a language model learns filler-gap dependencies when provided with developmentally realistic amounts of training data from the BabyLM corpus, determining if findings from larger LMs (Boguraev et al., 2025) apply in this setting. Using DAS, we evaluated BabyLM-100M's generalizations in four experimental conditions: localization within constructions and transfer across constructions, for two types of filler-gap dependencies, wh-questions and topicalization. Our results show that the model

learns a shared representation for filler-gap dependencies, but still requires far more data than children would, and is still highly sensitive to variation across constructions.

Regarding **RQ1**, which asks both whether and when LMs learn a causal representation, we find evidence in favor of our misaligned emergence hypothesis. Although the BabyLM-100M model showed strong causal effects when trained on the full corpus, they failed to emerge when the model received human-like quantities of training data. The full corpus was comparable to the input available to English-speaking adolescents (up to around 12 years) (Warstadt et al., 2023), while children's sensitivity to filler-gap dependencies emerges prior to two years of age, and robust knowledge develops between the ages of 3 and 5. In their description of the BabyLM corpus, Warstadt et al. (2023) report that the 10M checkpoint corresponds to children's linguistic knowledge between the ages of 2 and 5. If the model *were* learning with a human-like mechanism, we would expect moderate causal effects prior to this checkpoint, and strong causal effects at 10 million tokens, yet we only identify weak effects, if any.

RQ2 asks whether the learned representations are specific to particular constructions. We found evidence for this construction-specificity hypothesis because the localization experiments consistently performed better than the transfer experiments. That is, generalization within examples of the same construction was far more effective than transferring representations across constructions. We also replicated the lexical boost effects when animacy gets matched during the intervention, suggesting this feature may transfer across items. Regarding the direction of transfer, as discussed in **RQ3**, we found improved performance generalizing from topicalization to wh-questions, which was the opposite of our predictions in the frequency modulation hypothesis. Future work can determine if this happens because LMs may learn more item-sensitive representations of filler-gap constructions early during training, only generalizing these representations after receiving far more input than humans.

Overall, instead of positing a single, general representation of filler-gap constructions, LMs learn item and construction-specific representations. Future work should extend DAS to evaluate learning the filler-gap dependency in both directions and sensitivity to island constraints, across more diverse construction types.

When modeling human language acquisition, however, our results show LMs trained solely on next-word prediction are not sufficient to learn appropriate syntactic generalizations with human-like input. Instead, we emphasize the need to model learning with explicit inductive biases over structured hypothesis spaces, in the spirit of Perkins et al. (2025); Portelance et al. (2025). LMs can still play a role in this enterprise, through reflecting inductive biases architecturally (Murty et al., 2023) or specifying possible hypothesis spaces (Misra and Kim, 2024; Portelance and Jasbi, 2024). Our work joins a conversation (Yang et al., 2026; Zhou et al., 2026) about the need to further constrain models of language acquisition to better match human behavior by emphasizing how even developmentally constrained LMs require superhuman amounts of input to make correct linguistic generalizations.

Limitations

This study only focused on English, limiting the generalizability of these results to other languages where filler-gap dependencies behave differently under LMs (Kobzeva et al., 2023; Suijkerbuijk et al., 2023). Additionally, the training corpus is based on text input alone, while children learn from spoken data, multimodal environments, and social interaction (Meylan et al., 2023; Vong et al., 2024). Since this study focused on extending Boguraev et al. (2025)'s results to a BabyLM-scale model, we did not evaluate whether it could recognize the absence of filler-gap dependencies, and for island constraints, which have been used in surprisal-based studies (Ozaki et al., 2022; Wilcox et al., 2024; Howitt et al., 2024; Chang et al., 2025). More complex materials would also be useful to ensure results are not associated with confounding factors like punctuation, since we extract representations from periods and question marks. Lastly, although DAS was the best-performing method from Arora et al. (2024), measures like Boundless DAS operate over subspaces instead of single dimensions (Wu et al., 2023; Geiger et al., 2024), and could have yielded stronger causal effects.

Ethical Considerations

This work used publicly available data and models, which are described further in the original publications. We do not foresee any risks associated with this work, as we used the data for their intended

purpose to study human language acquisition. Generative AI (GenAI) was used in this project. We used Antigravity[9] to design plots and refactor code, and Claude Opus 4.5 to refine paper writing for brevity. We never use GenAI for writing text from scratch in this paper. We take complete responsibility for any GenAI errors. By discussing GenAI usage here, we aim to encourage other researchers to do the same.

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A Appendix

A.1 Hyperparameter Selection

Early experiments found that the default hyperparameters reported in the Boguraev et al. (2025) codebase (batch size 25 $\times$ 16 steps) resulted in undertrained DAS vectors. This is possible because the Pythia 1.4B model has far more parameters and was trained on far more data compared to BabyLM-100M.

We conducted a hyperparameter sweep to determine optimal DAS training parameters. Figures 4 and 5 show **MAX ODDS** across different batch sizes (8, 16, 25, 32) and training steps (40, 60, 80, 100, 120) for the Wh→Wh within-construction condition at the 100M checkpoint. Based on these results, we selected a batch size of 25 with 80 training steps (2000 total samples) for all experiments.

The learning rate was fixed at the default value of 5×10^{-3} used in Arora et al. (2024).

A.2 Animacy Figures

Supplementing the statistical tests for animacy effects in 5.4, we plot the increase in **MAX ODDS** across training split by lexical matching conditions. Figure 6 compares the causal performance when the intervention source and target base sentences share the same animacy status (Animate → Animate) versus differing animacy status (Animate → Inanimate). Results show a consistent gap between the two conditions, suggesting the learned representation may retain sensitivity to lexical features, such as animacy, through the pretraining process.

To separate animacy effects from construction-specific variance, the reported metrics for both Figure 6 and statistical testing are averaged across wh-question and topicalization constructions.

A.3 Beyond Developmental Constraints

We also present our results for the full 1 billion token training trajectory (100M–1000M tokens)[10] based on additional checkpoints released for the BabyLM model to better understand how filler-gap mechanisms continue to develop beyond developmentally plausible input levels. We see cross-construction generalizations plateau after 100M tokens, and performance begins to overlap for both sets of results. LMs could require more input to learn a representation specific to topicalization, since it rarely shows up in children's input. These results confirm our overall claims that localization within examples of one construction is stronger than transfer across constructions, while showing inconclusive evidence for our third hypothesis regarding interactions between construction frequency and transfer.

[10]The model received 1000M tokens because it was trained on the 100M token dataset for 10 epochs.

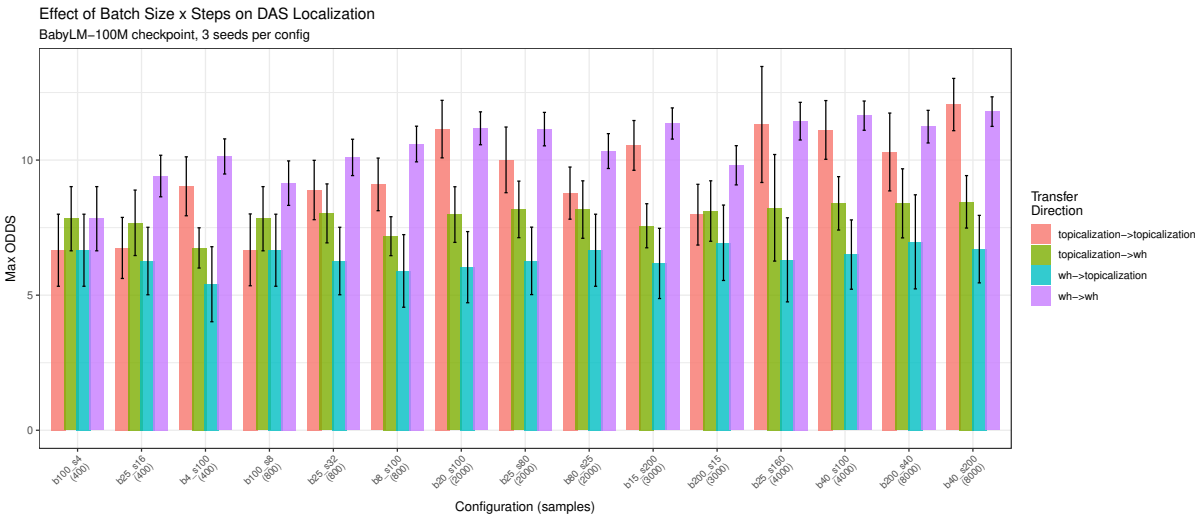

Figure 4: Hyperparameter sweep for DAS training. **MAX ODDS** increases with training samples and stabilizes around 2000 samples (batch size 25 $\times$ 80 steps).

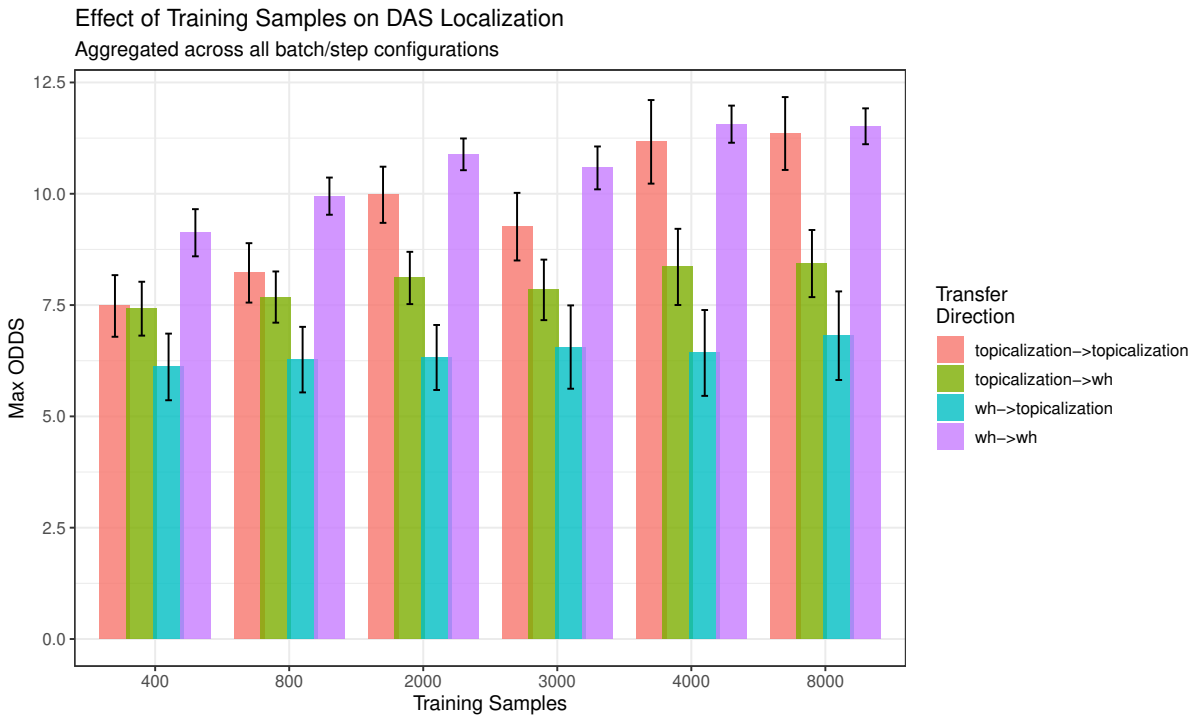

Figure 5: **MAX ODDS** as a function of total training samples, collapsed across batch sizes. Performance plateaus around 2000–2500 samples.

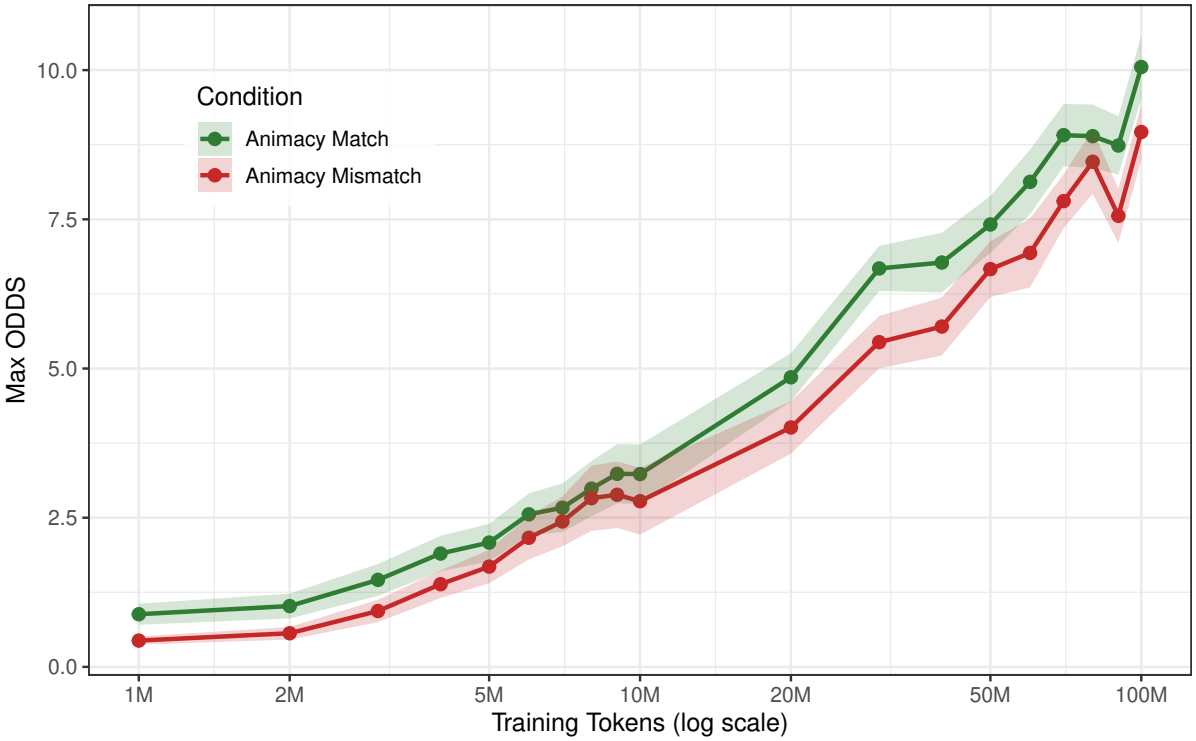

Figure 6: Developmental trajectory of lexical boost across training. Error bands show ±1 SE across a minimum of 2 seeds.

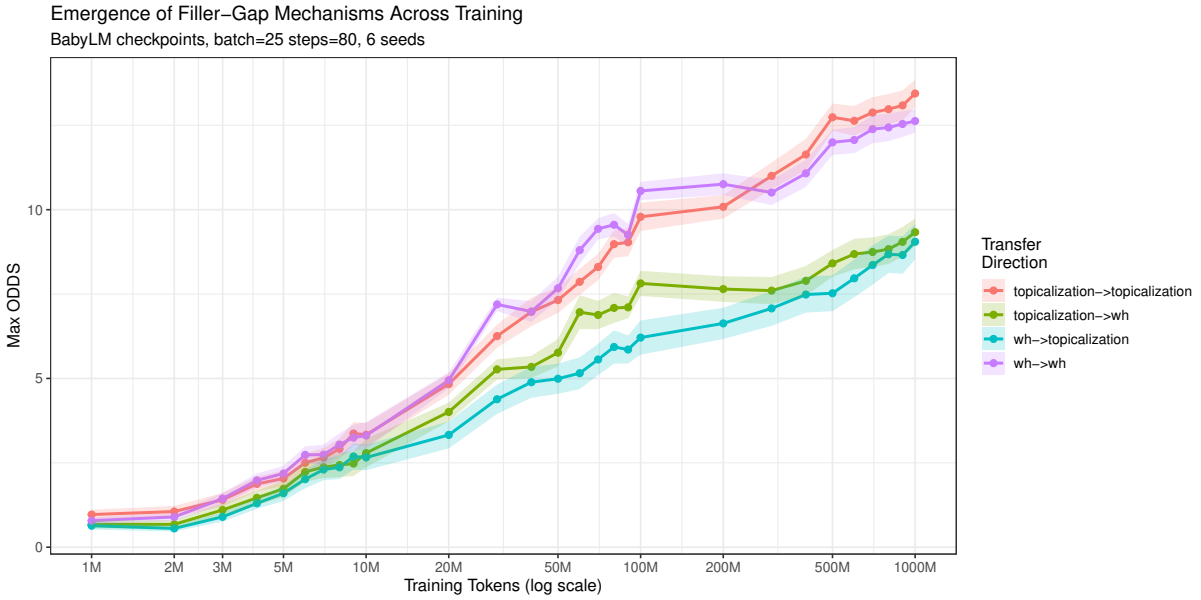

Figure 7: Full developmental trajectory from 1M to 1000M tokens. Filler-gap mechanisms continue to improve but begin to plateau around 500M–700M tokens.

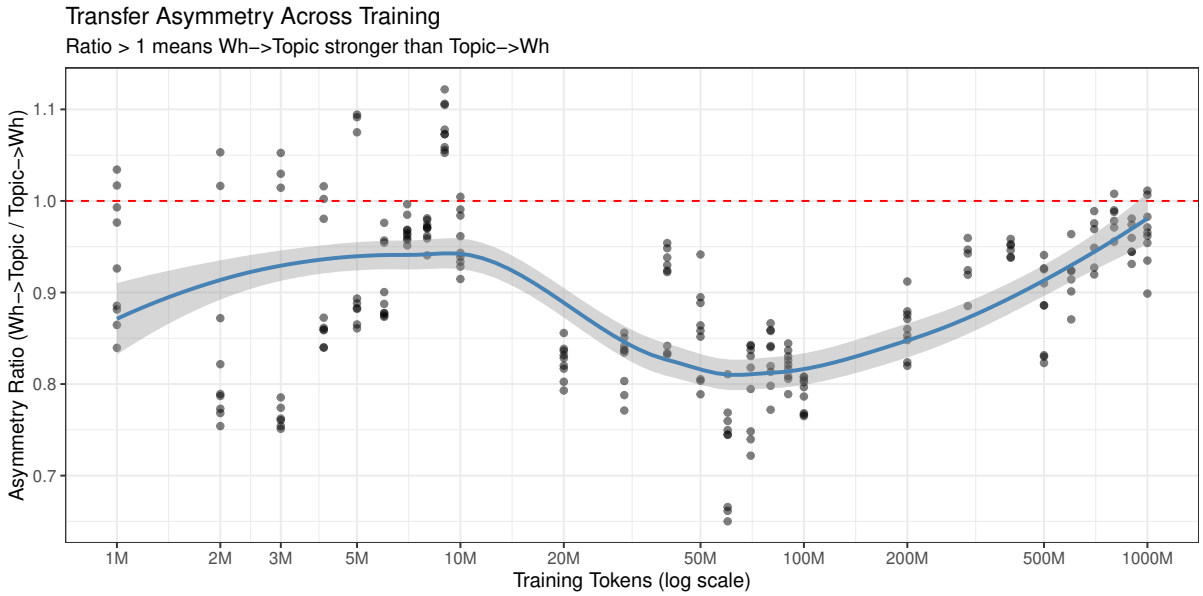

Figure 8: Transfer asymmetry across full training range. The asymmetry (Topic→Wh > Wh→Topic) persists and slightly increases at later checkpoints.