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Two- and three-year-olds track a single meaning during word learning: Evidence for Propose-but-verify

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Abstract

A child word-learning experiment is reported that examines 2- and 3-year-olds' ability to learn the meanings of novel words across multiple, referentially ambiguous, word occurrences. Children were told they were going on an animal safari in which they would learn the names of unfamiliar animals. Critical trial sequences began with hearing a novel word (e.g., "I see a dax! Point to the dax!") while seeing photos of two unfamiliar animals. After responding and performing on two filler trials with known animals, participants encountered the novel word again ("I see another dax! Point to the dax!") in one of two experimental conditions. In the Same condition, participants saw the animal they pointed to previously when hearing "dax" alongside another unfamiliar animal that had been seen before but not paired with "dax". In the Switch condition, participants saw the animal they had not pointed to previously alongside the unfamiliar animal. Children were well above chance on Same trials, but at chance on Switch trials. Thus, although children could remember a previously selected referent and use it to inform later referent selection (Same condition), a potential referent that was not previously selected and merely co-occurred with the target word (Switch condition) was either not remembered, or simply deemed irrelevant to word meaning. This finding suggests young children do not store multiple possible meanings from a single word occurrence, but rather restrict learning to what they deemed to be the unique referent of the novel word in the moment, testing that word-meaning hypothesis on the next occurrence.

Keywords

cross-situational word learning; fast mapping; statistical learning; propose-but-verify

When it comes to interpreting incoming speech, everyone seems to have a one-track mind. Listeners aim for a single intended meaning of each utterance even in the face of ambiguity. When we hear a word with more than one meaning, we only briefly consider the alternatives, driving our mind toward a single contextually appropriate meaning as quickly as possible, usually within a quarter second of the word's encounter (e.g., Tanenhaus, Leiman & Seidenberg, 1979; Swinney, 1979). The same is true for resolving temporarily ambiguous phrases, and reference resolution; listeners prefer to identify the communicative intentions of the speaker as quickly as possible, never holding open alternatives for any

substantial period of time (see, e.g. Henderson & Ferreira, 2004; Tanenhaus & Trueswell, 2006; and references therein). Although this single mindedness occasionally gets us into trouble, as seen in temporary misunderstandings and garden-paths, more often than not we efficiently make use of multiple sources of information to converge rapidly on a single “correct” meaning. Early commitment does not appear to be because our massively parallel brain could not simultaneously keep a handful of choices in play at once. Rather, it seems likely that early commitment better serves the needs of communication to be rapid even with some sacrifice of accuracy.

There are striking parallels between the single-minded aspect of language comprehension as just discussed, and properties of novice word learning. These latter are the focus of the present paper. Again, much of the modern literature documents an early commitment procedure, this time toward the inference to a plausible referent (hence, ultimately, meaning) for a newly heard word. In a visuo-social world that is actually replete with things, properties, relations, and actions, young learners seize on a single interpretation using an assortment of social and semantic plausibility heuristics (e.g., Baldwin, 1993; Markman, 1990; Medina, Snedeker, Trueswell & Gleitman, 2011). This determinative selection procedure in the face of input indeterminacy is sometimes referred to as fast-mapping (e.g., Carey & Bartlett, 1978; Spiegel & Halberda, 2011); the potential cue structure of the world is evidently rich and restrictive enough so that error is rare enough to be tolerable. To this extent, early commitment can enter into the explanation of the rapidity of vocabulary learning: For over a lengthy period during the life span (cf. Bloom, 2000) novices are acquiring a half-dozen or more words in the span of each day, while Willard Quine’s anthropologist visiting a new tribe delays his choices just about forever, contemplating the infinitely many warranted possibilities for “Gavagai!” as a rabbit wanders by (Quine, 1960).

Despite the explanatory potential of the single-referent hypothesis we have just introduced, there are other reasonable approaches to how words are learned so fast and so accurately in early life. In contrast to single-hypothesis theories, these explanations make use of the massively parallel architecture of the brain to resolve ambiguity in the referent world of words across multiple encounters rather than individually in the moment of each encounter. Under this view, learners hold their referential decision in abeyance, extracting and storing the multiple alternatives from each contextual occurrence, while looking for a statistical winner gradually across multiple word encounters (e.g., Siskind, 1996; Smith & Yu, 2008; Yu & Smith, 2007). Experimental evidence that seemingly offers strong support for what we will call “global-intersective”, “cross-situational” word learning comes from laboratory demonstrations that adults (Yu & Smith, 2007) and even young children (Smith & Yu, 2008), when exposed to a series of referentially ambiguous word learning trials, show evidence of extracting the word-referent statistical winner at test. In the words of the researchers, learners “can resolve the uncertainty problem in another way, not by unambiguously deciding the referent in a single word-scene pairing, but by rapidly evaluating the statistical evidence across many individually ambiguous words and scenes” (p. 1558, Smith & Yu, 2008).

As we have suggested elsewhere though (Medina et al., 2011; Trueswell, Medina, Hafri, & Gleitman, 2013), two learning procedures (one for fast-mapping and one for cross-

situational learning) may not be necessary to explain existing findings and to account for early vocabulary acquisition generally. A single-hypothesis procedure that tests across learning instances could in principle accomplish the kind of learning observed by Yu and Smith (2007) and Smith and Yu (2008). In particular, learners, perhaps driven by the need to establish a single intended meaning for any given speech act (Waxman & Gelman, 2009), store just one plausible meaning for the word from its occurrence, testing that meaning upon the next lexical encounter (*propose-but-verify*, Medina et al., 2011; Trueswell et al., 2013). When a meaning is confirmed, it is reinforced; when it is not confirmed, a new meaning is identified with the previous meaning either being discarded (Trueswell et al., 2013) or downgraded in its likelihood (Koehne, Gleitman & Trueswell, 2013; under revision). Across multiple, referentially ambiguous occurrences of a word, learners converge on the statistically likely candidate by the nature of the regularities in the input rather than by tracking all the regularities simultaneously – a correct guess once made, will get reinforced by the context of the next occurrence of the word.¹

Trueswell et al. (2013) offered what might be considered strong experimental evidence supporting a single-hypothesis word-learning procedure like *propose-but-verify*. In the study, adult subjects heard an utterance containing a novel word (“I see a dax! Click on the dax.”) in the presence of several referent images (e.g., a bear, a door, a hand, a ball and a dog). Subjects would select a referent by clicking on an image. Then, after several intervening trials, subjects encountered “dax” again in a new context that contained a referent image that was common to both learning instances amongst several distractors (e.g., a bear, a shoe, a car, an eye and a cat). Subjects who had selected the bear on the first occurrence of the word were well above chance at selecting the bear again on the second occurrence. But, those who selected a different referent on the first occurrence were at chance selecting the bear on the second occurrence, even though the bear was common among both occurrences. This pattern was found even when the first occurrence had just two referents (e.g., a bear and a shoe): subjects who chose the shoe went on to be at chance when selecting the bear among five alternatives on the word’s next occurrence. These responses are expected by *propose-but-verify*: the only thing learned about the word “dax” from its first occurrence (or, the only thing considered relevant) was the selected meaning, and not the surrounding context or alternative referents. A global-intersective account incorrectly predicts above-chance sensitivity to these alternatives.

The Trueswell et al. (2013) findings do however come from adults, not children. Although there is some reason to believe that observational word learning is similar in adults and children (e.g., Gillette, Gleitman, Gleitman & Lederer, 1999; Medina et al., 2011; Piccin & Waxman, 2007; Smith & Yu, 2008; Snedeker, Geren & Shafto, 2007), there are also key differences between adults and children that might lead to the prediction that children approach observational word learning using a global-intersective method rather than a

¹Although Smith and Yu (2008) acknowledged this as a possible explanation of their findings, they advocated for a purely associative, global-intersective account, which was further detailed in Yu (2008). And indeed, a modelling effort by Yu and Smith (2012) revealed that both a single-hypothesis testing procedure and a global-intersective procedure can account for the findings of Yu and Smith (2008). Stevens, Gleitman, Trueswell and Yang (submitted) find the same thing and further show that a single hypothesis-testing model may offer the best fit of the Yu and Smith findings. It is for these reasons that further experimental procedures and tests – like those reported here – are important for clarifying the theoretical picture that is forming about cross-situational word learning.

single-hypothesis testing procedure like propose-but-verify. Most notably, young children learning their early vocabulary (e.g., age 1;6 to 3;0) likely have only a partial understanding of how reference works (e.g., Karmiloff-Smith, 1979; Maratsos, 1976), and, for example, may not fully appreciate that a definite expression like “the dax” should have a unique referent. In addition, children in this age range tend to have less focused attention (e.g. Ruff & Lawson, 1990) and poorer selective attention abilities (e.g., Huang-Pollock, Carr, & Nigg, 2002) than older children and adults. Any of these differences could result in younger children connecting multiple possible referents to the same linguistic act, resulting in a learning process that more resembles global-intersective accounts.

Moreover, recent work from Dautriche and Chemla (2014) and Yurovsky and Frank (2015) suggest that adults who are engaged in observational word learning may maintain at least partial knowledge of the referential alternatives afforded by a single word-learning instance. And indeed, our own work suggests that this can be the case with adults under very simplified contextual settings, such as when only two referential alternatives appear on every word occurrence (Experiment 3, Trueswell et al., 2013). It is possible then that the more diffuse attention of children could enhance consideration of alternatives even further than adults, leading to a pattern in younger populations that is even more consistent with a global-intersective learning procedure. On the other hand, young children may seize on a single alternative, even in the simplest of ambiguous settings containing only two alternatives, allowing just one meaning to enter into learning from each word occurrence, as suggested by propose-but-verify.

The present experiment sought to test these two possibilities – namely, whether young children will engage in a global-intersective or propose-but-verify procedure during observational word learning. We tested thirty-two 2-year-old and 3-year-old children (ages 2;1 – 3;5, mean age 2;9) in a child-friendly version of the observational word learning task of Trueswell et al. (2013), using a design that controlled for prior referent selection and referent familiarity. Children in this age range were selected because they are known to still be engaged in rapid vocabulary growth, including the learning of novel object and animal labels (e.g., Goldin-Meadow, Seligman & Gelman, 1976). Children in the study were told they were “going on an animal safari” in which they would learn the names of animals. The critical trial structure was like that shown in Figure 1. Children first (Trial 1, Familiarization) heard someone refer to a known animal in the presence of that animal and a novel animal (“I see a cow! Point to the cow!” while seeing a cow and a novel animal) thereby exposing the child to a novel animal without it being labeled. The very next trial (Trial 2, Learning) involved hearing a novel word (“I see a dax! Point to the dax!”) while seeing two other novel animals, either of which could be the dax. After responding and encountering two filler trials involving the labeling of known animals, the child then encountered “dax” again (Trial 5, Test) hearing “I see another dax! Point to the dax!”. What the child saw at Test depended on how they had responded during Learning, by using a Same/Switch procedure (Bower & Trabasso, 1963; Yurovsky & Frank, 2015). In the Same condition, the child was presented with the *same* animal she had pointed to previously on Trial 2 alongside the unlabeled novel animal from the Familiarization trial. Thus in the Same condition, the child was asked to pick between two equally familiar animals, only one of which co-occurred with “dax” previously. In the Switch condition, the child was instead presented with the animal she had

not pointed to previously, alongside the same unlabeled animal from the Familiarization trial. Here too the child is selecting between two equally familiar animals only one of which co-occurred with the word “dax”. However, here the animal was not the animal the child had previously selected to be the referent of dax. A global-intersective account predicts above chance performance in both the Same and Switch conditions, whereas propose-but-verify predicts performance will only be above chance for the Same trials; for Switch trials, neither animal was ever selected as the referent of “dax”, and hence no preference should be observed between the two animals.

Method

Participants

Thirty-two monolingual (17 female), typically developing children (ages of 2;1 to 3;5, mean 2;9) were recruited from preschools in the greater Philadelphia area. Six additional children were tested but not included because of equipment error ($n = 1$), failure to reach an established threshold for accuracy on filler trials ($n = 3$, accuracy $< 80\%$ on fillers), and because of age² ($n = 2$). Children’s parents were given informed consent in accordance with the IRB protocol of the University of Pennsylvania and were compensated with a small toy.

Procedure and Materials

Each child was tested individually in a quiet room and seated in front of a table with a monitor and with an experimenter on their left and right sides. The child was then instructed that they were going on a “safari” and to point at the animals that the computer asked about. Each trial presented two animals, while the child heard a carrier phrase (i.e., “Oh look!”) followed by “I see a __ . Point to the __ .” Images were photos of known (e.g., cow) and unknown (e.g., axolotl) animals. Critical trial sequences consisted of five trials containing a Familiarization trial, a Learning trial, two Filler trials, and a Test trial (see Figure 1), using the procedure described above. In between each trial was a 1000ms fixation involving a cartoon image of a safari jeep while a jingle was played. This fixation was chosen to give children neutral feedback after each trial so that they were not told whether or not they selected the “correct” animal.

Children completed 36 trials (six critical trial sequences, in addition to two practice trials and four additional filler trials at the start of the experiment to familiarize children with the task). Thus children were tested on six novel words in total. Experimenters manually entered children’s pointing responses by pressing one of two keys on the computer that controlled the stimulus display. All sessions were video and audio recorded in order to ensure that no errors were made during this input, and to allow for the offline scoring of responses.

Children were run in a between subject design on either a “Same” or “Switch” list. Within each condition, a second additional list was created that reversed the left and right position of the animals that appeared during the learning trial, so as to control for position. Two additional lists were then created that were identical to these two lists except that new animal

²Both children were age 3;10. They were excluded because we wanted a smaller age range and a younger sample. Including these children does not change any of the effects seen in the results section.

pairs were randomly reassigned to each novel word, to increase variability of word-animal and novel animal pairings across subjects. Position of the carry-forward image at test was also counter-balanced, such that it matched the left-right position from learning on only half of all test trials in any list. Four additional lists were then created in which trial order was reversed, for a total of 16 lists (eight “Same” and eight “Switch” lists). Across the Same and Switch lists, children were balanced for age and gender. Stimuli were presented using E-Prime 2.0.

Coding of Responses

Children’s pointing responses to the six test trials were coded for accuracy. A trial was coded as “correct” if the child pointed to the animal that had appeared during the previous trial involving that same word. It was coded as “incorrect” if the child selected the animal that had appeared previously during the Familiarization trial (and hence had not occurred with the word).³

Results and Discussion

Children’s accuracy patterns (Figure 2) were consistent with a propose-but-verify learning procedure and not a global-intersective one. In particular, while children in the Same condition were well above chance (mean = .83, SD = .22, $t(15)=6.00$, $p<.001$), children in the Switch condition were no different from chance (mean = .45, SD = .19, $t(15)=1.00$, $p=.33$). This resulted in a main effect of condition in a multi-level logit model with condition (Same versus Switch) as a fixed effect with by-subject and by-item random intercepts and by-subject random slopes for the effect of condition⁴ (est. = 1.11; $z = 4.03$, $p<.001$).

Thus, although children could remember a previously selected referent and use it to inform later referent selection (Same trials), a potential referent that was not previously selected and thus merely co-occurred with the target word (Switch trials) was either not remembered, or simply deemed irrelevant to word meaning. One might be concerned that the between subjects design led children in the “Switch” condition to lose interest and begin selecting randomly once they realized that their initial choice never occurred as an option on a word’s second occurrence. This would predict that children would start out above chance on Switch trials and as the experiment progressed drop to chance or even below-chance levels. However this was not the case: Proportion correct on the first trial of the experiment (Switch: 0.53; Same: 0.94) was similar to the final trial of the experiment (Switch: 0.47; Same: 0.81), and a multilevel logit model that included condition, order (1 - 6) and their interaction as fixed effects with by-subject and by-item random intercepts and by-subject random slopes for the effect of condition⁵ yielded no effect of Order (est. = $-.17$; $z = -1.46$, $p=.14$) and no interaction between order and condition (est. = $-.16$; $z = -1.41$, $p=.16$) – only the effect of condition (Switch vs. Same) was significant (est. = 1.17; $z = 3.99$, $p<.001$).⁶ Finally, we note that the age of the child showed no reliable effect on accuracy in either the

³We excluded from analysis test trials in which the child selected the wrong animal during the Familiarization trial (i.e., the child selected an axolotl when they were told to point at a cow; $n = 1$) and in which the child pointed to both animals simultaneously ($n=2$).

⁴By-item random slopes for the effect of condition were dropped due to convergence issues.

⁵By-item random slopes for the effect of condition were dropped due to convergence issues.

Switch ($r = -.15$, $p = .16$) or the Same ($r = .05$, $p = .61$) condition, suggesting that children of all ages employed a similar learning procedure.

As a cautionary note, while our observed difference between performance in the Same and Switch conditions is robust, a post-hoc power analysis with the program *G*Power* (Erdfelder, Faul, & Buchner, 1996) found our reported difference between Switch performance and chance has only 80% power to detect large effect sizes ($d > .75$). Indeed, it is possible that with many more subjects, we could detect a small effect of 2-year-olds tracking multiple alternatives, i.e., reliably above chance performance in the Switch condition. An above-chance effect would likely be very small indeed, since average proportion correct from our “first” sixteen subjects is 0.45, which is below rather than above chance (contra the global-intersective theory). Below chance performance would suggest an inhibitory effect on competitors during referent identification, which would be evidence for an even stronger variant of the present account of the data. One could also argue that our experiment is quite “demanding” for an associative learning mechanism (although note that adults perform well-above chance on a similar 2-referent condition with only one learning trial, see Yurovsky & Frank, 2015). But, if such simple conditions (2 referents, with an interval of 2 trials between learning instances) flummox the associative mechanism that underlies learning generally, we must wonder about its explanatory power.

Conclusions, Implications, and further Predictions

Our findings suggest that young children are, if anything, *more* likely than adults to employ a single-hypothesis testing procedure like propose-but-verify when engaged in an observational word-learning task. These findings were obtained despite the expectation that children’s more diffuse attention and possibly weaker knowledge of reference might push them toward a learning procedure that considers more alternatives, like that proposed in a global-intersective procedure. The findings are even more striking when one considers that memory demands were so minimal as to render a global-intersective procedure close to trivial: Just two referent images appeared on each learning instance, and the instances were separated by just two trials involving known words. Despite these limited memory demands, children still showed no sensitivity to referents that had not been chosen along the path of learning. Adults under these same conditions (two referents per word occurrence) show memory for the unselected alternative (Experiment 3, Trueswell et al., 2013; Yurovsky & Frank, 2015) but behave more and more like the children in the present study as the referential set size and the distance between word occurrences increase to levels that are arguably more representative of the natural word-learning environment (Medina et al., 2011; Smith, Smith & Blythe, 2011; Trueswell et al., 2013; Yurovsky & Frank, 2015).

One might wonder why children (and even adults under more naturalistic conditions) tend not to use the full information available to them when converging on the desired meaning of

⁶Note also that general saliency of the animals selected during learning cannot explain our findings. For learning trials from the Switch lists, no animal was especially preferred: average selection across subjects was 8 out of 16 (50%) for any animal, ranging from 4 to 10 out of 16 (25%-62.5%). Thus it is not the case that one image was particularly “dax”-like so that every child selected it, nor is it the case that one image was so much better than one other image that the other image was never selected. Moreover, as explained in the “Procedure and Materials” section, half of the experimental lists used a different pairing of animals for each word, thereby increasing the variability of word-animal pairings across the experiment as a whole.

a word, why they discard rather than preserve unselected choices. We have suggested here that this behavior may be a product of what even the youngest language users expect about communication, that a person's utterance has just one intended meaning, and that both children and adults in their everyday acts of comprehension strive to identify that meaning as quickly as possible for the sake of rapid, efficient, real-time understanding. Notably however, we have suggested that extracting and retaining multiple alternative meanings from each word occurrence would also be quite impractical given the more specific computational demands imposed by word learning (e.g., Trueswell et al., 2013; Stevens, Gleitman, Trueswell, & Yang, submitted; see also, Newport, 1990), since a purely global-intersective learner would be faced with a staggeringly large space of meaning solutions necessarily derived from the highly ambiguous input. A similar conclusion (and computational solution) has been proposed about causal learning in children (Bonawitz, Denison, Griffiths, & Gopnik, 2014; Denison, Bonawitz, Gopnik, & Griffiths, 2013). Bonowitz et al. suggest that learners attempt to employ "fast and frugal" heuristics (e.g., Gigerenzer & Goldstein, 1996) for causal learning, which approximates optimal Bayesian inference: rather than tracking the entire space of beliefs, learners employ "a win-stay lose-sample" approach, inspired by the win-stay lose-shift principle. When immediate evidence does not support a causal belief, a new one is sampled, discarding the previous one. They find that aggregate performance across children mimics rational Bayesian inference. But this aggregate performance does not characterize individual learners, whose learning characteristics are abrupt and, roughly, single trial. Our own proposed solution for reference selection (and word-meaning belief) can be couched in similar terms, although our original motivation was entirely mechanistic: We asked, given how words are processed in context, how might the learner approach the problem of referential ambiguity? Our findings suggest sampling a single alternative and tracking this alternative is optimal in the individual.

This returns us to the problem mentioned in the introduction, that there do seem to be conditions under which adults retain more than one meaning from a single learning instance (Dautriche & Chemla, 2014; Smith, et al., 2011; Trueswell et al., 2013; Yurovsky & Frank, 2015). How can this fit with the present results? There are at least two plausible answers, which require further research. It might be that as computational demands are alleviated, e.g. by simplifying the learning conditions and/or by having greater memory capacity with age, the optimal word-learning solution begins to include partial retention of unselected referent alternatives, thereby leading to adjustments in the employed learning procedure (Smith et al., 2011). However, it is also possible that the increased use of global-intersective strategies in adults is entirely a product of the experimental setting. Adults, rather than following their natural word learning tendencies, may instead be trying to solve a puzzle set by the experimenter: Which novel words go with which pictures? This latter explanation would suggest that word learning in natural contexts is very similar in children and adults.

Further questions remain for future inquiry: For instance, what happens when children are not required to respond by pointing to a referent? Although evidence from adults suggests that this changes little about the learning procedure employed (Trueswell et al., 2013; Koehne et al., under revision), it is an empirical question whether children will continue to consider a single hypothesis per occurrence or instead adopt a more global-intersective approach. Our own expectation is that children will continue to extract just a single meaning,

or perhaps even less than a single meaning. When referential ambiguity becomes too great (consider, 10-20 alternatives), learners may decide not to retain anything from such a context. That is, when not forced to select a referent overtly (by pointing or clicking), learners may submit one or no referent to learning, depending on the degree to which context imbues confidence. Indeed, perhaps the only time a meaning hypothesis is entered into the learning machinery (for adults and children alike) is when the individual believes they have successfully understood what the speaker meant. Such feedback would come from environmental cues that precede and follow the particular communicative act, such that by possessing this hypothesized meaning, the individual can better explain and predict other aspects of the world and the communicative interchange.

It is also important to examine the learning procedure in infants younger than those we have here studied, especially given that word learning begins early in infancy (e.g., Bergelson & Swingley, 2012). For example, word learning may look different in younger children because they have a different understanding of the world and therefore may interpret implicit feedback differently. To find what is relevant in the “buzzing blooming confusion” of the referent world may pose problems of unknown complexity to very young infants.

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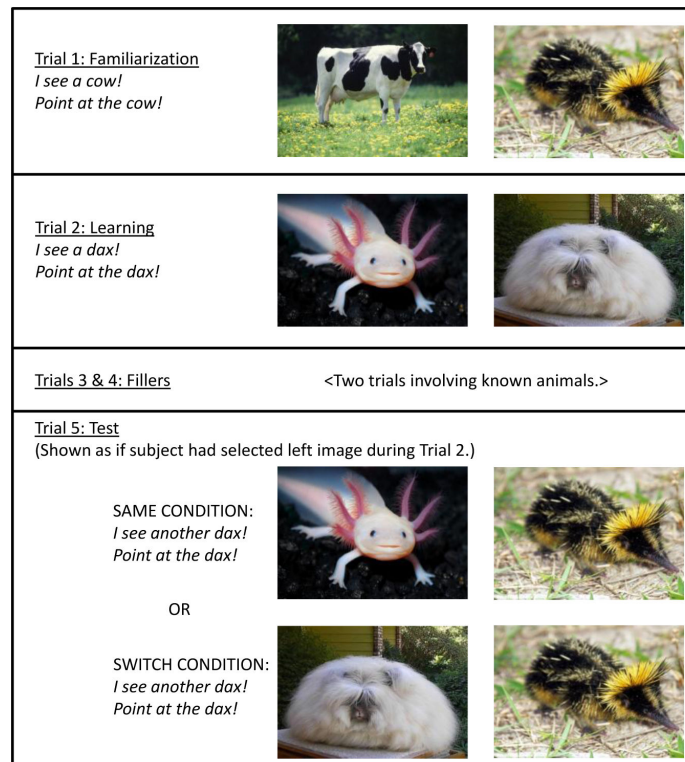


Figure 1. Example of critical trial sequence. Six critical sequences per experiment list (resulting in the testing of six novel words). Left and right positions and matching sides were counterbalanced approximately across lists.

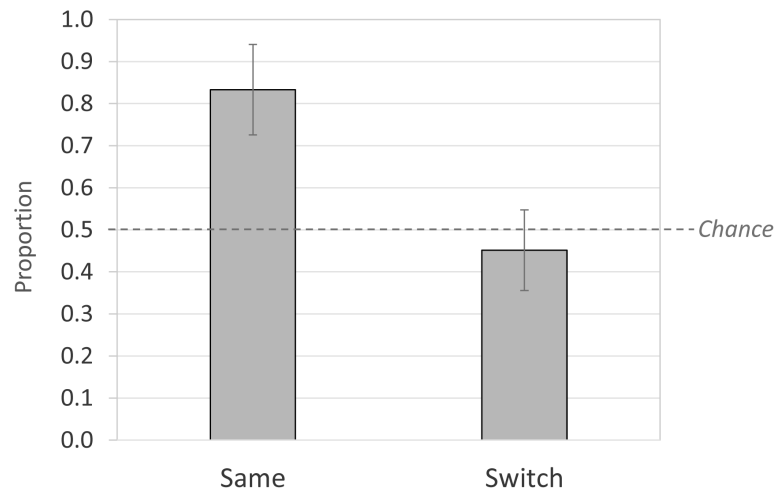


Figure 2. Proportion of correct responses for children in the Same condition and children in the Switch condition. Subject means. Error bars indicate 95% confidence intervals.