Mutual Exclusivity as a Special Case of Cross-Situational Statistical Learning: Non-Selectivity of Word-Object Associations

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Children learn words in ambiguous situations, where multiple objects can potentially be referents for a new word. Yet, researchers debate whether children form and maintain a single word-object hypothesis – and revise it if falsified by later information – or whether children establish a network of word-object associations whose relative strengths are modulated with experience. To address this issue, we presented 4- to 12-year-old children with sets of mutual exclusivity trials, thereby offering them with obvious initial hypotheses – that the novel object is the referent for the novel word. Despite their initial preference for the novel object, children maintained an association between the novel word and the name-known object, thus suggesting that early word-object associations are non-selective, in a manner not dissimilar to cross-situational statistical learning.

Keywords: Early word learning; Associative process; Language acquisition; Cross-situational statistical learning; Non-selectivity

Over their first few years of life, children acquire a large vocabulary. While word learning situations can take many forms, researchers have invested considerable effort uncovering learning mechanisms that children, and adults, employ in ambiguous situations. Such situations, for example, arise when multiple objects act as potential referents for a novel word, a situation described as possessing referential ambiguity, or offering a mapping problem (Quine, 1960). Researchers have described how children and adults can integrate multiple ambiguous situations to establish stable word-object mappings; a situation described as cross-situational learning. Yet, the mechanisms underlying cross-situational learning are the focus of an intense debate; do children, and adults, keep track of multiple potential word-object associations, as described in *cross-situational statistical learning* accounts (CSL; Dautriche & Chemla, 2014; Smith & Yu, 2008; Yu & Smith, 2007; Suanda, Mugwanya, & Namy, 2014; Vlach & Johnson, 2013), do they keep track of only one single candidate referent at any time, following *single-hypothesis* accounts (e.g., Berens, Horst, & Bird, 2018; Medina, Snedeker, Trueswell, & Gleitman, 2011; Markman, 1990; Trueswell, Medina, Hafri, & Gleitman, 2013), or do they use elements of both, depending on memory and attention resources (Yurovsky & Frank, 2015)?

Under the single-hypothesis perspective, word learners establish a single initial mapping between a word and an object. This initial mapping is maintained (or confirmed) unless it is falsified by subsequent evidence – a *propose-but-verify* account (Medina et al., 2011; Trueswell et al., 2013), recently supported with neuroimaging evidence (Berens et al., 2018). This account has been extended to two- and three-year-olds (Woodward, Gleitman, & Trueswell, 2016) and suggests that children, like adults, store just one hypothesised referent for each word. This approach also echoes early views on Mutual Exclusivity (ME; Markman, 1990; Markman & Wachtel, 1988), that young children initially reject additional associations to a name-known

word, and that “mutual exclusivity would result from a more general principle, either a one-to-one mapping principle (Slobin, 1978; Slobin & Ferguson, 1973) or the uniqueness principle (Pinker, 1984; Wexler & Culicover, 1980) applied to word learning.” (Markman & Wachtel, 1988, p.149).

This strict interpretation of ME has since been nuanced, as evidence suggests that ME should rather be seen as a tendency, modulated by communicative context or language exposure (e.g., Byers-Heinlein, Werker, 2009; Houston-Price, Caloghiris, & Raviglione, 2010; Kalashnikova, Escudero, & Kidd, 2018; Kalashnikova, Mattock & Monaghan, 2015; Malone, Kalashnikova & Davis, 2016), rather than a rule or a hard constraint. Similarly, single-hypothesis perspectives suggest that, while young children may form a single initial mapping between a word and a referent, this initial mapping should be rejected if new evidence indicates it should be falsified. These perspectives converge insofar as, in absence of counter-evidence, a *single* mapping between a word and a reference is expected.

In contrast, CSL accounts suggest that children (Smith & Yu, 2008; Suanda et al., 2014; Vlach & Johnson, 2013) and adults (Dautriche & Chemla, 2014; Yu & Smith, 2007) form and maintain multiple associations between words and referents. The strengths and relative importance of these associations evolve across trials and are updated as additional evidence (e.g., co-occurrence between words and objects) is being accumulated. From this perspective, word learners maintain a *network* of word-object associations, rather than single mappings between words and objects, as posited by single-hypothesis accounts.

The primary aim of the present contribution is to test whether children establish and maintain multiple associations between words and objects – in line with CSL accounts – or whether they only maintain a single association between words and objects – congruent with

single-hypothesis accounts. To this end, we presented children with two sets of “classical” ME trials; in each set, two images were presented to the child – illustrating one novel object and the other a name-known object – while a novel label is heard. Then, during test trials, both name-known “distractors” are presented side-by-side while novel labels used during ME trials are being uttered.

Strict ME accounts would suggest that children should not display a preference for either image, as they should have rejected a second association to the name-known images during ME trials. Other single-hypothesis accounts would suggest that test trials falsify children’s hypotheses that the novel image is the referent for the novel label (provided that this was their initial hypothesis) and would predict that children should randomly pick a new referent, as suggested by the propose-but-verify account (Medina et al., 2011; Trueswell et al., 2013; Woodward et al., 2016). In contrast, preference for the matching name-known image would indicate the children have *not* inhibited the formation of an additional association between the name-known image and the novel label, and that, instead, they have established multiple associations between words and objects, a view congruent with CSL accounts (e.g., Smith & Yu, 2008; Suanda et al., 2014; Vlach & Johnson, 2013).

The secondary aim of the present contribution is to evaluate whether children do, indeed, establish an association between the novel image and the novel label during ME trials, beyond “merely” displaying novelty preference for the novel image when hearing a novel label. Studies that investigated whether infants retain novel word associations following ME responses obtained varied results. Although Mervis and Bertrand (1994) found that 16- to 20-month-old infants displayed ME during ME trials and showed evidence of word learning during test trials, Horst and Samuelson (2008) found that 24-month-old infants were only able to display ME

during the ME trials, but failed to retain the novel label to novel object mappings. Mather and Plunkett (2011) and Bion, Borovsky and Fernald (2013) conducted similar studies using eye-tracking paradigms. Mather and Plunkett's 16-month-old infants did not show an ME effect during ME trials, yet they learned novel word-object associations for one of the novel labels, while Bion et al.'s 24-month-olds displayed evidence of ME but failed to display evidence of retention. Together, this suggests that while ME may lead to the formation of novel word-object associations, it is a fragile process that may be modulated by task difficulty and the age of participants.

In sum, the current study aims at evaluating whether children retain word-object associations formed during ME trials, as well as testing whether such word-object associations are unique – as suggested by single-hypothesis accounts – or non-selective (additional associations are formed between novel words and name-known objects) – in line with CSL accounts. The study was carried out as an object-selection task on an iPad with 4- to 12-year-old children, an age range covering reported qualitative changes in word learning behaviour in CSL paradigms (Fitneva & Christiansen, 2017).

Method

Participants. One hundred and seventy-four children who participated in the Summer Scientist Week programme in The University of Nottingham were recruited in this study. Twenty-six participants who spoke more than one language at home were excluded from the analysis to ensure that the results of the experiment would not be impacted by the number of languages spoken at home (e.g., Houston-Price et al., 2010). Of the remaining 148 English monolingual children, 65 were boys and 83 were girls. The children's age ranged from 4 years

to 12 years ($M = 7.36$ years, $SD = 2.06$). Ethics approval was granted by X (BLINDED FOR REVIEW).

Stimuli. The visual stimuli were images obtained from Frank, Sugarman, Horowitz, Lewis, & Yurovsky (2016). Each image had a resolution of 640 x 480 pixels and depicted an object on a grey background. Following Frank et al. (2016), the size of the images was set to fit comfortably on an iPad screen, with the width of the image set to 400 pixels and the height set to maintain the ratio of the image. Two novel labels, *dax* and *modi*, were used. Each novel label was associated with a novel image and a familiar image (see first two rows of Fig. 1). The instruction to search for an image was “find the ___!”, which was recorded by a female native English-speaker in an infant-directed manner.

--- Insert Figure 1 around here ---

Procedure. The experiment was carried out using an iPad. Before the start of the experiment, a warm-up task prompted children to tap on dots and smiley faces presented on the screen of the iPad. This task allowed children to familiarise themselves with the iPad. After the warm-up task, children were given instructions about the experiment; that they would be presented with two images, would be asked to find an object, and would have to respond by tapping one of the displayed images. Once the children had indicated that they had understood the procedure, the experiment began.

The experiment itself consisted of three blocks; ME training, a word learning test and a selectivity test (see Fig. 1). In each trial, a pair of images was displayed on the screen while the instruction (the carrier sentence “find the ___!”) was played. The pair of images remained on

screen until the child made a response by tapping on one of the images. During ME training, the pair of images presented were a name-known and a novel image, while a novel label was uttered, in line with classical ME designs. Two image pairs, *modi*-cat and *dax*-carrot, allowed every child to learn, via ME, two novel labels for two novel images (see first two rows of Fig. 1). Each pair was presented four times, such that each target appeared on each side of the screen twice.

In the word learning test, children were tested on whether they had formed an association between a novel label and the corresponding novel image; an attempt to replicate Mather and Plunkett's (2011) findings that ME can lead to the formation of word-object associations. Thus, the image pairs were made up of the two novel images shown during ME training (see third row of Fig. 1), whereas the auditory stimuli were the novel labels *modi* and *dax*. Each image pair was repeated once, with the target appearing on each side of the screen once.

In the selectivity test, the two *name-known* images used during ME training (typically referred to as distractors in ME experiments) were displayed while in each trial, one of the novel labels used during ME training was uttered. Target selection (that is, tapping on the name-known image from the same training pair) was taken as evidence that an association between the name-known image and a second label was *not* inhibited during ME. This test block also consisted of two counterbalanced trials for each image pair. The order of presentation of the word learning test block and the selectivity test block was randomised across participants.

Filler trials, consisting of two familiar images, one of them being named, were presented every four trials, so as not to discourage the children by presenting only trials with unknown labels. Attention getters were introduced between each block so as to capture the

attention of the participants.

Analysis. Accuracy results were analysed via hierarchical mixed-effect logistic regressions using the lme4 package in R (Version 3.3.1; Bates, Mächler, Bolker & Walker, 2014), where selecting target images was coded as 1 and distractor images as 0. As the data was of binary outcome with multiple fixed effects, mixed-effects logistic regression was used to estimate effects of different variables on response accuracy. We started our analysis with a full model M0 that included participants and items as random effects, block type (ME training, word learning test, selectivity test), age and interaction between age and block type as fixed effects. We compared the full model with the following restricted models; M1 in which the interaction term was dropped from the full model, M2 in which age and interaction were omitted, and M3 – the null model – which only included participants and items as random factors. Model fit was assessed using chi-square tests on the log-likelihood values to compare different models.

Results

Removing the interaction between age and block type did not significantly reduce the goodness of fit, as indicated by the likelihood ratio test ($\chi^2(2) = 2.16, p = .339$). Age and block type were, however, significant. Removing age significantly decreased the goodness of fit ($\chi^2(1) = 4.05, p = .044$) and so did block type ($\chi^2(2) = 375.59, p < .001$). Children performed significantly better in ME training than word learning test ($\chi^2(2) = 11.32, p = .003$) and selectivity test ($\chi^2(2) = 150.28, p < .001$). Children also performed significantly better in the word learning test than in the selectivity test ($\chi^2(2) = 245.61, p < .001$). Age correlated significantly with performance in the word learning test ($r_s(146) = .174, p = .035, 95\% \text{ CI}$

[.005, .319]) but not with ME training ($r_s(146) = -.022, p = .788, 95\% \text{ CI } [-.130, .192]$), nor with selectivity test ($r_s(146) = .113, p = .171, 95\% \text{ CI } [-.083, .238]$).

Chi-square analyses, conducted by comparing the distribution of target successes to a baseline distribution in which the target/distractor responses are random (unbiased), showed that for each age group (with the exception of 4–5 years of age), children were biased towards one image (in our case, without exception towards the target, see Table 1 for proportion of accurate responses); children performed above chance in all block types.

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Discussion

Children, and adults, frequently encounter new words when multiple potential referents are present in their visual scene. The nature of learning mechanisms in such ambiguous naming situation has been under scrutiny over decades and theories fall essentially into two groups. The first group argues that learners establish and maintain a *single hypothesis* that is either confirmed or falsified with additional information (in which case a new, single, hypothesis is established). Single-hypothesis accounts can be considered to include early descriptions of learning mechanisms; the one-to-one mapping principle (Slobin, 1978; Slobin & Ferguson, 1973), the uniqueness principle (Pinker, 1984; Wexler & Culicover, 1980), as well as early accounts of ME (Markman & Wachtel, 1988). These views have gained recent traction and are supported by additional evidence (Medina et al., 2011; Trueswell et al., 2013; Woodward et al., 2016; Berens et al., 2018). In contrast, CSL accounts suggest that children (Smith & Yu, 2008; Suanda et al., 2014), and adults (Dautriche & Chemla, 2014; Yu & Smith, 2007), create and maintain a rich network of multiple associations between words and objects. The strength and

relative importance of these associations are modulated when additional evidence is gained.

Yet, CSL accounts typically present participants with sets of novel objects, thus making initial hypotheses, or associations, equiprobable. What if children are presented with an initial situation that favours one hypothesis? Would they still entertain the possibility that other hypotheses can hold, and create additional associations? To find out, we presented 4- to 12-year-old children with two sets of ME “training” trials, thus offering them the possibility of establishing two novel word-object associations. Subsequent test trials investigated whether children displayed evidence that they had also retained associations between the novel labels and the name-known distractors – a view congruent with CSL accounts – or not – thus suggesting that they only tracked a single hypothesis.

Children displayed a strong initial preference for the novel image in ME training trials (in line with, e.g., Golinkoff, Hirsh-Pasek, Bailey, & Wenger, 1992; Mather & Plunkett, 2011). Single-hypothesis accounts would suggest that children have established an initial hypothesis; that the novel image is the referent for the novel label. Yet, and crucially, children also displayed a preference for the matching name-known image during selectivity test trials, when hearing novel labels used during ME training trials. This situation does not sit well with single-hypothesis accounts; when the initial hypothesis is falsified by test trials (the novel label is uttered while the novel image is not present), children should *randomly* generate a new hypothesis, as suggested by the propose-but-verify account (Medina et al., 2011; Trueswell et al., 2013; Woodward et al., 2016; Berens et al., 2018), and should not display a preference for either image presented during test trials.

In contrast, children’s preference for the matching name-known image when hearing novel labels suggest that they have established multiple word-object associations during ME

training trials, despite their marked initial preference for the novel image. These non-selective associations between words and objects aligns well with CSL accounts.

In addition, children also performed well in the word learning test, thus providing evidence that they retained, at least temporarily, word-object associations formed during ME, in line with Mather and Plunkett (2011) and Mervis and Bertrand (1994). While children throughout the age range displayed evidence of retention of novel label to novel image associations, the positive age trend suggests that older children are stronger at learning novel names for novel images. While Fitneva and Christiansen (2017) reported qualitative changes between 4-year-olds and 10-year-olds, our results merely suggest a moderate age trend, suggesting older children to be more robust word learners than younger ones.

The proportion of accurate responses in the selectivity test is smaller than in the word learning test, which suggests that the association between the novel label and the novel image is stronger than the association between the novel label and the name-known image. Weaker performance in the selectivity test is also congruent with a low-level association-based account of the CSL type. The initial preference for the novel object establishes differing levels of attention towards each object. Higher attention towards an object (e.g., in our case, the novel image during ME training) would lead to a stronger association between the word and the object, and weaker associations between the same word and other objects (in our case, the name-known image). Consequently, it should be expected that the relatively weaker performance in the selectivity test reflects the initial relative preference during ME. Yet, despite the strong initial preference for the novel object, children track all possible associations between words and objects, thus suggesting that CSL also operates when *name-known* objects are being presented to the child, and not only when novel objects are being used. In other

words, our results suggest that children form a *network* of associations based on co-occurrences between words and multiple objects in their sight, as opposed to forming one-to-one associations between objects and words: word-object associations are not selective.

It is noteworthy that the observed preference for a novel object when a novel word is uttered should not be taken as evidence for the rejection of additional associations between other novel words and a name-known object. If multiple potential words can be attached to the very same object, the contribution of ME as the catalyst for *rapid* word learning should be questioned. The formation of multiple mappings from a word to multiple objects in the visual scene does not contribute to a reduction of the hypothesis space in ambiguous learning situations. Rather, it provides the child with the capacity to entertain the possibility that multiple words can be attached to an object.

The finding that children are not selective in the formation of word-object associations sits well with other recent findings that children are flexible in their interpretation of the meaning of novel words (Ramscar, Dye, & Klein, 2013) and that they engage into CSL with (multiple) objects in their visual field (Yu & Smith, 2011; Yurovsky, Smith, & Yu, 2013). Some of the early stages of word learning taking place during ambiguous naming situations, such as in ME experiments or CSL situations, do seem to be principled by low-level associationist mechanisms whereby multiple word-object pairings are being built. Strengthening of word-object associations based on co-occurrence then leads to the formation of a hierarchy of associations of different strengths, and subsequent exposure to word-object pairings results in the formation of robust word-object associations. Non-selective word learning mechanisms do not need to undergo qualitative changes during development, from early one-to-one mappings

to an age at which toddlers start learning multiple words for the same object¹, nor are they required to operate differently for monolingual and multilingual populations. Rather, non-selective word-object associations suggests a gradual development based on accrued information across varied learning situations that empowers children to entertain flexible interpretations of novel word meaning and usage.

¹ A model precisely allowing the formation of multiple associations between an object and multiple labels can show how different labels can be produced at different hierarchical levels in a context-dependent manner from low-level learning mechanisms, even in the absence of high-level strategic reasoning (Klinger & Mayor, 2011).

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Table 1

Proportion of accurate responses for each age group

Age	ME training	Word learning test	Selectivity test
4–5 ($n = 37$)	.92 (.15) ***	.78 (.26) ***	.53 (.25)
6–7 ($n = 40$)	.98 (.09) ***	.93 (.16) ***	.62 (.36) ***
8–9 ($n = 50$)	.95 (.11) ***	.89 (.21) ***	.63 (.38) ***
10–12 ($n = 21$)	.93 (.13) ***	.90 (.22) ***	.61 (.40) ***

Note. Standard deviations are given in parentheses. *** $p < .001$

Block types	Image pairs	Auditory stimuli
ME training		Find the <i>modi</i> !
ME training		Find the <i>dax</i> !
Word learning test		Find the <i>modi</i> !
Selectivity test		Find the <i>modi</i> !

Figure 1. An example of different block types.