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Experience-Driven Semantic Differentiation: Effects of a Naturalistic Experience on Within- and Across-Domain Differentiation in Children

Catarina Vales
Carnegie Mellon University

Sarah L. States
Phipps Conservatory and Botanical Gardens

Anna V. Fisher
Carnegie Mellon University

Organized semantic networks reflecting distinctions within and across domains of knowledge are critical for higher-level cognition. Thus, understanding how semantic structure changes with experience is a fundamental question in developmental science. This study probed changes in semantic structure in 4–6 year-old children ($N = 29$) as a result of participating in an enrichment program at a local botanical garden. This study presents the first direct evidence that (a) the accumulation of experience with items in a domain promoted increases in both within- and across-domain semantic differentiation, and that (b) this experience-driven semantic differentiation generalized to nonexperienced items. These findings have implications for understanding the role of experience in building semantic networks, and for conceptualizing the contribution of enrichment experiences to academic success.

Organized knowledge in semantic memory, encoding relevant relations about word meanings and object properties, is foundational for other cognitive abilities. A large literature has documented how structured semantic networks support memory (Bjorklund & Jacobs, 1985; Bower, Clark, Lesgold, & Winzenz, 1969), word learning (Beckage, Smith, & Hills, 2011; Colunga & Sims, 2017), language processing (Borovsky, Ellis, Evans, & Elman, 2016; Federmeier & Kutas, 1999), inferential reasoning (Coley, 2012; Gobbo & Chi, 1986; Medin, Lynch, Coley, & Atran, 1997), and knowledge acquisition (Pearson, Hansen, & Gordon, 1979; Varga, Stewart, & Bauer, 2016). Therefore, it is fundamentally important to understand how structured knowledge emerges with development and learning. Here, we directly test the hypothesis that changes in semantic structure—reflecting distinctions within and across domains of knowledge—emerge from the accumulation of experience with entities in those domains. This hypothesis is derived from a number of computational modeling studies, which we briefly review below along with limited empirical evidence supporting this hypothesis.

Computational modeling studies suggest that structured semantic representations can emerge from experience. For example, exposing a neural network to patterns of consistent co-variation among features of items in a training set (e.g., "has skin," "can fly," . . .), resulted in gradual differentiation of the network's internal representations of those items—first distinguishing across domains of "animals" and "plants," and later learning within-domain distinctions such as "flowers" and "trees" (McClelland & Rogers, 2003). In addition to this increase in differentiation for the items experienced in the training set, the model also differentiated *new items* from the experienced domains along the learned relevant features (Rogers & McClelland, 2004)—suggesting that experience with items of a

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Correspondence concerning this article should be addressed to Catarina Vales, Department of Psychology, Carnegie Mellon University, 5000 Forbes Av., Pittsburgh, PA 15213. Electronic mail may be sent to cvales@andrew.cmu.edu.

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domain promotes generalization to nonexperienced items in that domain.

This key role of experience with items of a domain in building structured semantic networks finds support within other computational approaches, including a graph-theoretic approach (Hills, Maouene, Maouene, Sheya, & Smith, 2009; Peters & Borovsky, 2019) and a hierarchical Bayesian approach (Kemp & Tenenbaum, 2008). Importantly, changes in semantic structure emerged even though these models were never trained on domain membership; instead, these computational modeling studies suggest that semantic structure emerges from learning shared item features, presumably through gradual accumulation of experiences with items in a domain.

Despite providing a mechanistic framework for understanding how changes in semantic structure emerge from experience, the predictions from these computational modeling studies remain sparsely examined in children. Existing supporting evidence includes work showing that individual differences in children's early experiences (e.g., having a special interest in a domain such as dinosaurs, spending time in nature, or owning a pet) are related to performance in tasks thought to rely on semantic structure (Coley, 2012; Gobbo & Chi, 1986; Inagaki, 1990). Numerous cross-sectional studies also documented age-related increases in semantic differentiation that are broadly consistent with the patterns of gradual differentiation suggested by the computational models discussed above (e.g., Carey, 1985; Keil, 1979; Mandler & McDonough, 1993; Pauen, 2002; Unger, Fisher, Nugent, Ventura, & MacLellan, 2016). Additionally, a recent longitudinal study showed increased semantic differentiation in preschool age children over a period of 5 months (Fisher, Godwin, & Matlen, 2015). Together, these studies provide *indirect evidence* that the accumulation of experience over relatively long periods of time leads to increased semantic differentiation.

A smaller body of research has also shown effects of brief learning experiences on children's semantic networks. For example, participating in enrichment learning activities at a zoo—whether a week-long program (Unger & Fisher, 2019) or a single session (Badger & Shapiro, 2019)—lead to pre- to posttest changes in children's grouping of animals in biologically meaningful ways. Although broadly consistent with the predictions from computational modeling studies, by only examining changes in a single domain, the existing studies have not examined *across-domain differentiation* as a direct result of experience. Furthermore, prior studies have not assessed whether experience-driven changes in children's semantic structure *generalize to nonexperienced items* from the experienced domain—a key prediction of some computational models (Rogers & McClelland, 2004). The current study was designed to address these limitations and provide the first direct test of the hypothesis that the accumulation of experiences with items in a domain leads to increases in *within-* and *across-domain differentiation* in children's semantic structure that *generalize* to nonexperienced items.

The Present Study

To test the hypothesis above, we examined changes in semantic structure in preschool- and kindergarten-aged children enrolled in summer camps at a botanical garden; these young children are unlikely to have highly differentiated representations of biological categories targeted by the camps (Hatano et al., 1993; Unger et al., 2016). Unlike prior studies that recruited *separate* training and control groups (Badger & Shapiro, 2019; Unger & Fisher, 2019)—leaving open the possibility that differences between groups were driven by factors other than the learning experience—all participants were children whose parents enrolled them in a program at the same botanical garden. Also unlike prior studies which examined changes in a single domain, we measured changes in *within-* and *across-domain* differentiation of two biological domains in children who completed one of two summer camps. The programs had equivalent structures, activities, and duration but targeted two distinct biological domains—"bugs" and "plants." As typical of enrichment experiences (Callanan, Cervantes, & Loomis, 2011; Rogoff, Callanan, Gutierrez, & Erickson, 2016), both camps included hands-on activities and interaction with social partners. Example activities for the "bugs" program include creating a t-shirt displaying an insect's body parts, hunting for insects, and enacting the lifecycle of a butterfly; example activities for the "plants" program include decorating a t-shirt with plant stamps, hunting for pumpkin seeds, and enacting the lifecycle of a seed (see Table S1 for more details). Crucially, these activities exposed children to multiple items of the target domain, presumably increasing exposure to the features that differentiate biological categories within and across domains.

Before starting the first day's activities and after finishing the last day of the program, children completed a spatial arrangement task which has been used to measure semantic structure in adults and children (Goldstone, 1994; Unger et al., 2016), and allows for efficient collection of pairwise similarity judgments. Each child individually arranged cards depicting simple outlines of bugs and plants on a board by placing close together items that were of the same kind. The physical distance between pairs of items was used as an index of representational similarity: items placed at shorter distances were judged as more similar. Past work suggests that performance on this task is not driven solely by perceptually available features of the stimuli but reflects children's semantic structure. For example, similar age-related changes emerged whether semantic differentiation was assessed with simple line drawings or colorless wooden blocks (Fisher, Godwin, Matlen, & Unger, 2015; Unger et al., 2016), children produced comparable arrangements when they were asked to sort the same cards more than once in the same testing session (Unger et al., 2016), and children's performance in this task has been shown to be related to other cognitive processes thought to rely on semantic structure (Fisher, Godwin, & Matlen, 2015; Fisher, Godwin, Matlen, & Unger, 2015).

To examine changes in semantic differentiation, we compared the relative distances at which different pairs of items were placed on the board at pre and posttest. If experiencing multiple items of a domain increased *within-domain* differentiation for that domain, then children's arrangements of within-domain items should reflect increased differentiation. For example, a child who participated in the "bugs" program should place *insects* farther apart from *noninsect* "bugs" at posttest compared to pretest. Similarly, if experiencing items of a domain changes that domain's representation relative to other domains, then all children should increasingly differentiate *across-domains* by placing items from the domains of "bugs" and "plants" farther apart at posttest compared to pretest.

We probed the specificity of these hypothesized changes by (a) testing items that were experienced and *not experienced* during the program activities, and (b) examining within-domain differentiation both for the domain of the program a given child *did* and *did not* complete. If experiencing many items of a domain (e.g., many *insects* during a "bugs" camp) increases the availability of features that can be used to differentiate items within the domain (e.g., *insects* from *noninsects*), then children should be able to use the relevant features to differentiate among "bugs" that were *not experienced* during the program activities; however, any evidence of within-domain differentiation should be restricted to the domain a child experienced—and thus not occur for the nonexperienced domain.

Method

Participants

Thirty-four children of ages 4–6 were recruited from a group of children enrolled in one of two enrichment programs at a botanical garden in Pittsburgh, PA, an urban area in the northeastern of the United States. To obtain a sample size sufficiently large to assess our hypotheses, children were recruited into this study over two consecutive summers. Across the 2 years, there were 61 potential participants available for this study (on average, 15 children were enrolled in each camp). We obtained informed consent from 34 caregivers, therefore our recruitment rate was 55%. Data from five children were not included in the reported analyses due to not completing the posttest session ($N = 4$) or data loss ($N = 1$).

The final sample included data from 29 children (19 girls and 10 boys; $M = 4.5$ years, $SD = .6$). This sample size is comparable to Unger and Fisher (2019), who examined changes in semantic structure in children attending a zoo camp. Data from all children who completed both the pre- and the posttest were combined for analyses because (a) the programs' objectives and activities were identical across the 2 years, (b) the same educator lead all activities, and (c) the hypotheses were tested using a within-subjects design. Most children in the sample were Caucasian ($N = 26$); the remainder children were East Asian/Asian American ($N = 1$) or their ethnicity was not reported ($N = 2$). Children received a small gift for participating.

Stimuli and Design

The stimulus set, which included items from both programs' domains (see Figure 1), was selected based on the objectives and the items experienced in the programs. Although we consulted with the botanical garden's educators to select stimuli, they were blind to the hypotheses of this study. Within a domain, there were two kinds of items: in-category items and out-of-category items. The two categories tested were *insects* ("bugs" with three body parts and antennae) and *fruits* ("plants" that contain seeds); the out-of-category items were, respectively, "bugs" that are not insects and "plants" that are not fruits. Although in scientific classification "true bugs" are an order within the

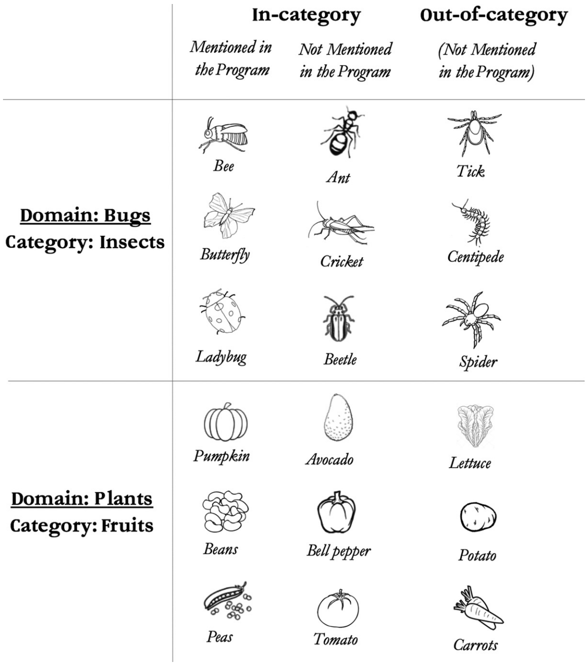

Figure 1. Spatial arrangement task stimuli (see text for details). Names are added here for clarity and were not displayed on the cards.

class of "insects"—and thus "arthropods" would be a more accurate term for the domain we tested—we use the term "bugs" as it is colloquially used to refer to insects, arachnids, and other terrestrial arthropods. Pairing these two kinds of items resulted in two types of *pairs* used for analyses, one that included two items of the same domain (in category pairs) and another that included one item of each domain (out of category pairs).

The in-category items included both items that were mentioned in the program (i.e., played a central role in at least one activity) and items that were not; all out-of-category items were not mentioned in the program. While the interactive nature of these programs makes it possible that the nonmentioned items were inadvertently briefly experienced (e.g., a child could have referenced or drawn spiders during a group activity), there would still be a considerable difference in the amount of exposure between mentioned and nonmentioned items, allowing us to probe the generalizability of the hypothesized experience-driven changes.

Black and white line drawings representing each item were printed on 5 × 5 cm cards with a white background, for a total of 18 cards. Children were asked to arrange the cards on a board with a visible 10 × 10 grid of 6 cm squares. To examine both within- and across-domain differentiation, and examine within-domain differentiation for the domain experienced in their respective camp and the domain not experienced, children were asked to arrange all 18 cards in the same trial.

Children were tested on Monday before starting the program activities (pretest) and on Friday after completing the 5 day of the program (posttest).

Procedure

At both testing phases (i.e., pre- and posttest), each child sat with an experimenter at a table in a quiet area of the botanical garden. Children were asked to arrange cards on the board by placing close together items that are of the same kind and placing far apart items that are not of the same kind; while giving these instructions, the experimenter brought her/his hands close together and moved them apart above the board for illustration. The experimenter then laid the cards on the table, one at a time, while labeling them (e.g., "Here is a *butterfly*"); care was taken to ensure that the cards were not placed in a grid-like pattern and were previewed in a random order. Children were told that they could change the placement of the cards and could take as long as they wished to arrange all cards; children took no longer than 10 min to complete the task. After the child arranged all cards on the board, they were asked if they wanted to change the placement of any cards; the experimenter also clarified any cards that were not clearly placed (e.g., in between two grid cells). Once the child confirmed their final arrangement, the experimenter took a photo of the board for later coding.

Data Coding

The photos of all arrangements were coded by hypothesis-blind coders. Coders used the 10 × 10 grid as a coordinate plane and coded the coordinates of each card; a second coder verified the accuracy of all coordinates. From these coordinates, we calculated distance scores for pairs of items by computing the Euclidian distance between the coordinates of each card of a pair.

Results

If experience with entities of a domain increases within-domain differentiation, then children should place out-of-category items farther apart from in-category items at posttest relative to pretest, but only for the domain they experienced. Additionally, if experience with entities of a domain also increases its differentiation relative to other domains, then we would expect children to place items that belong to distinct domains farther apart from pre- to posttest. To examine these two hypotheses, we analyzed pre- to posttest changes in the mean distance between pairs of items arranged on the board. In the Supporting Information, we report analyses examining within-domain differentiation separately for each program theme.

We used a linear mixed-effects approach to test the effect of phase (pre- vs. posttest) on the non-averaged distances between pairs of items; additional fixed effects are described for each analysis. Analyses were conducted in the R environment (R Core Team, 2014) using the *lme4* package (Bates, Maechler, Bolker, & Walker, 2015). Models were fit with the maximal random effects structure (Barr, Levy, Scheepers, & Tily, 2013). The *p*-values, based on Wald tests of each model's fixed effects, were calculated using the *ANOVA* function from the *car* package (Fox & Weisberg, 2011); pairwise two-tailed contrasts were calculated using the *lsmeans* package (Lenth, 2016). Code, data, and arrangement examples are openly available: https://osf.io/g5t94/?view_only=7d930fe3de9e41a9bbbfcfbd46bc2e13.

Within-Domain Differentiation

To examine within-domain differentiation, we analyzed the distances between pairs of within-domain items belonging to the same or distinct categories before and after completing the program; Table 1 displays the results of a model testing the effects of phase (pre- vs. posttest), domain (experienced vs. not), and pair type (in- vs. out-of-category) on the distance between pairs of items. The significant three-way interaction confirms that the pre- to posttest changes were modulated by both pair type and whether the items were from the domain of the program in which the child participated.

This interaction is illustrated in Figure 2. Specifically, at pretest children placed pairs that included items of the same category (e.g., *bee-ant*) at the same average distance as pairs that included items of different categories (e.g., *bee-spider*). Pairwise contrasts confirmed that, at pretest, the mean distances between these pair types was not significantly different both for the domain experienced, $t(2,692) = 0.30$, $p = .76$, and the domain not experienced $t(2,692) = -0.37$, $p = .71$. This finding suggests that, at pretest, children did not have differentiated representations within either domain.

Table 1
Within-Domain Differentiation: Coefficient Estimates, Standard Errors, Wald Chi Square Tests, and Significance Level for All Predictors

Predictor	Coefficient	*SE*	χ^2	*p*-value
All pairs model				
Phase (pre- vs. posttest)	−.56	.25	11.6	**.0007**
Domain (experienced vs. not)	−.12	.22	1.32	.249
Pair type (in vs. out of category)	−.29	.17	0.07	.794
Phase × Domain	.08	.29	11.4	**.0007**
Phase × Pair Type	.35	.24	0.04	.845
Domain × Pair Type	.65	.24	2.50	.114
Phase × Domain × Pair Type	−.76	.34	5.06	**.024**
Nonmentioned pairs model				
Phase (pre- vs. posttest)	−.36	.33	6.62	**.010**
Domain (experienced vs. not)	−.09	.30	1.14	.285
Pair type (in vs. out of category)	−.26	.24	0.02	.891
Phase × Domain	.02	.41	10.1	**.001**
Phase × Pair Type	.25	.34	0.70	.404
Domain × Pair Type	.74	.34	1.56	.212
Phase × Domain × Pair Type	−.89	.47	3.55	**.059**

Note. *All pairs model* refers to the model including all pairs of items; *nonmentioned pairs model* refers to the model including only pairs of items to which children did not have considerable exposure during the program. Significant/marginal *p*-values are bolded.

At posttest, for the domain experienced, pairs that included items of different categories were placed farther apart relative to pairs that included items of the same category—but this increase in differentiation was restricted to children's experience as no such change was evident for the nonexperienced domain (e.g., "plants" for children in the "bugs" camp). Pairwise contrasts showed that, at posttest, there was a significant difference between the pair types for the domain experienced, $t(2,692) = -2.14$, $p = .032$. There was also a marginally significant difference for the domain not experienced, but in the opposite direction: pairs including items of the same category were placed *farther apart* relative to pairs including items of different categories, $t(2,692) = 1.69$, $p = .092$. This finding suggests that at posttest children's semantic structure encoded relevant within-domain distinctions—and that this change from pretest is specific to the domain experienced.

Finally, although the overall distance at which pairs of items were placed increased from pre- to posttest, this main effect of phase is difficult to interpret in the presence of the three-way

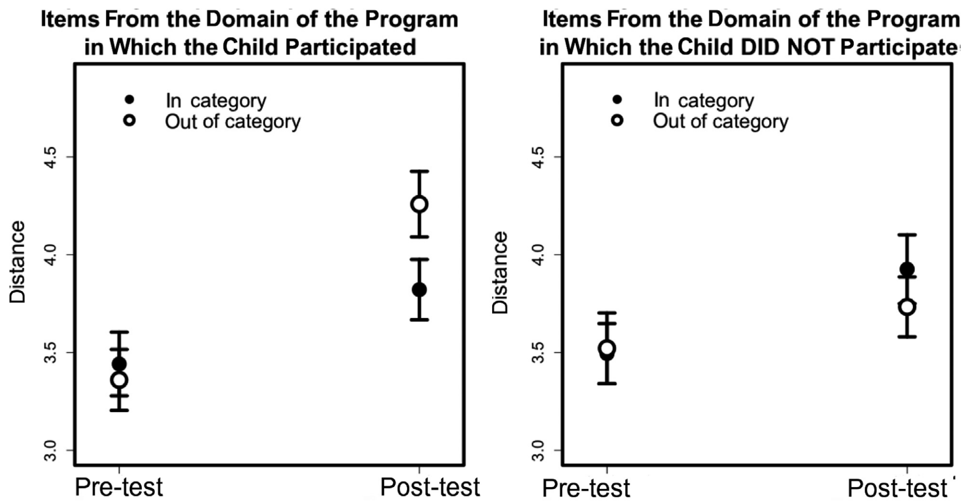

Figure 2. Within-domain differentiation: Average distance scores at pre- and posttest for within-domain pairs of items. In-category pairs include two items of the same category (e.g., two *insects*) and out-of-category pairs include two items of different categories (e.g., one *insect* and one *noninsect* "bug"). Shown above are distances from the domain of the program in which the child participated (right panel) and *did not* participate (left panel). Error bars display standard errors of the mean.

interaction. While it is possible that children were using the space on the board differently at pre- and posttest, the three-way interaction suggests that this effect of phase is modulated by pair type and domain—and thus that the increase in within-domain differentiation is experience-specific.

To examine if these patterns of differentiation generalize to nonexperienced items of the experienced domain, we tested the same effects as above but restricted to pairs including only items not mentioned during the program activities. Similar to the previous analysis (see Table 1), the three-way interaction was a marginally significant predictor (p = .059) of the distance scores when only nonmentioned items were included in the model. Pairwise contrasts between pair types within each phase and domain showed that the only significant difference between in- and out-of-category pairs was at posttest for pairs from the domain experienced, t (1,300) = −2.05, p = .041 (all other ts < 1.08; all other ps > .505). This suggests that the observed increase in within-domain differentiation for the domain experienced does not stem from children relying only on the items they experienced; instead, children accumulated enough experience with some items of a domain to be able to generalize this experience to items which were not part of the activities.

Across-Domain Differentiation

To examine whether children represented items of the domain they experienced as more distinct from another, nonexperienced domain, we analyzed the mean distances between pairs of items belonging to the same versus different domains before and after completing the program. As Figure 3 shows, at pretest, pairs from the same domain (two "bugs" or two "plants") were placed closer together relative to pairs from different domains (one "bug" and one "plant"),

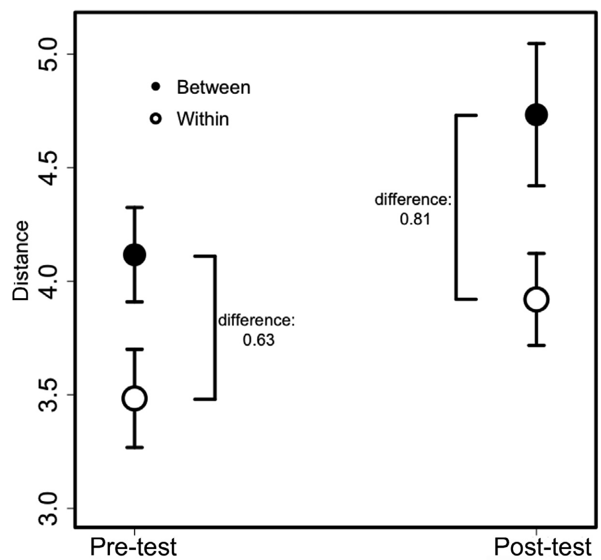

Figure 3. Across-domain differentiation: Average distance scores at pretest and posttest for pairs of items that belong to distinct domains ("between" pairs; any "bug" and "plant") or the same domain ("within" pairs; any two "bugs" or "plants"). Error bars display standard errors of the mean.

suggesting that children had somewhat differentiated representations of "bugs" and "plants" before the program. However, the magnitude of this differentiation increased at posttest; a model testing the effects of phase (pre- vs. posttest), and pair type (within vs. between domain) on the distance between pairs of items confirmed a significant interaction between these two predictors (see Table 2); pairwise contrasts confirmed that children differentiated between the two domains at both phases (pretest: $t(29.34) = 2.30$, $p = .028$; posttest: $t(29.34) = 2.96$, $p = .006$). This finding suggests that experience with entities of a domain increases its differentiation relative to other domains.

General Discussion

The present results show experience-driven changes in children's semantic structure within and across two domains. As a result of completing an enrichment program at a botanical garden, children represented items that belonged to the same category within a domain (e.g., *insects*) as more similar than items belonging to other categories (e.g., *noninsect* "bugs"), with this change being specific to the domain experienced. This result was not driven solely by increased familiarity with the items experienced, as the same pattern of results was observed both for pairs of items which were and were not part of the program activities. In other words, the effect of a brief enrichment opportunity *generalized to items that children did not experience*. The increase in within-domain differentiation was accompanied by an increase in differentiation of items from distinct domains—even though children already differentiated between the two domains at pretest. These findings both support prior findings suggesting a key role for the accumulation of experience with entities in promoting changes in semantic structure (e.g., Badger & Shapiro, 2019; Coley, 2012; Unger et al., 2016), and extend those findings by directly showing that the accumulation of experiences with items in a domain lead to increases in *within-domain differentiation* that is specific to an experienced domain (but not to specific *items* within that domain), as well as increases in *across-domain differentiation*.

Table 2
Across-Domain Differentiation: Coefficient Estimates, Standard Errors, Wald Chi Square Tests, and Significance Level for All Predictors

Predictor	Coefficient	*SE*	χ^2	*p*-value
Phase (pre- vs. posttest)	−.62	.18	8.81	**.003**
Pair type (within vs. between domain)	−.81	.27	7.09	**.008**
Phase × Pair Type	.18	.08	4.66	**.031**

Note. Significant *p*-values are bolded.

By providing direct evidence for the predictions from prior computational modeling studies (Hills et al., 2009; Kemp & Tenenbaum, 2008; McClelland, & Rogers, 2003), these results support a mechanistic framework for experience-driven changes in semantic structure—and in so doing, suggest new hypotheses for how experience changes semantic structure. For example, future work can examine how the frequency with which certain items are experienced (McClelland, & Rogers, 2003), how experiencing conceptual versus perceptual features (Hills et al., 2009), and how individual differences in linguistic input (Huebner & Willits, 2018) may drive changes in semantic structure.

Although the current results show experience-driven changes in children's semantic structure, it remains an open question what information children encoded, and the degree to which certain aspects of the enrichment programs may have contributed to these changes. The computational models discussed above suggest a key role for shared features in promoting changes in semantic structure, but they are agnostic about the mechanisms by which those features are processed and learned. Additionally, equivalent patterns of differentiation are found when using normative features of objects (Hills et al., 2009; McClelland, & Rogers, 2003) and the words that denote objects (Huebner & Willits, 2018), suggesting that there are multiple—perhaps redundant—sources of information on which children can capitalize to build structured semantic networks. It is possible that by allowing children to experience those features in multiple ways, the different activities in these programs helped children selectively attend to and encode the relevant features of the categories. This possibility is consistent with current theoretical accounts of knowledge acquisition suggesting that learning benefits from redundant, mutually constraining sets of cues (Billman & Knutson, 1996; Colunga & Smith, 2005; McRae, De Sa, & Seidenberg, 1997; Riordan & Jones, 2011; Sloutsky & Fisher, 2008; Yoshida & Smith, 2005).

The current findings are also relevant to the literature on school readiness and academic achievement. After participating in a week-long enrichment experience, children acquired more fine-grained distinctions within the biological domain they experienced, and further differentiated that domain relative to another biological domain. Because biological classification is often included in educational standards at the elementary school level, enrichment activities such as summer camps may support the acquisition of what prior research has identified as background knowledge, a key component for academic success (Morgan, Farkas, Hillemeier, & Maczuga, 2016; Pearson et al., 1979). The present results thus converge with prior work suggesting that "achievement gaps" between children from high and low socioeconomic backgrounds may be better understood as *opportunity gaps*—early differential access to opportunities to build background knowledge that slowly accumulates over time, contributing to differences in academic performance (Flores, 2007; Gorey, 2001; Kaefer, Neuman, & Pinkham, 2015; Morgan et al., 2016). Understanding the mechanisms changing children's representations of academically relevant domains can open up new avenues to develop interventions aimed at closing opportunity gaps.

Limitations

The present experiment has a few limitations that should be addressed in future work. First, although comparable to prior studies examining changes in children's semantic structure (e.g., Unger & Fisher, 2019), this study included a small sample size. Although the recruitment rate into the study was fairly high—given the many challenges of participant recruitment in ecologically valid settings (e.g., Alibali & Nathan, 2010; Bartlett et al., 2017)—and using a within-subjects design mitigated the possibility of self-selection affecting the reported findings, it would be important to verify the generalizability of these results in future work. Second, in order to maximize the allotted time to collect data from each participant at pre- and posttest, there was no independent verification of children's familiarity with the items tested. Although care was taken to select items that are likely to be familiar to children of this age (Fenson et al., 2007; Kuperman, Stadthagen-Gonzalez, & Brysbaert, 2012), and the use of a subset of these items in an enrichment program developed specifically for this age range further suggests that they were likely familiar to the participants, it would be important to verify in future work whether children's arrangements depend on the level of familiarity with the items used and the labeling of these items in the task.

Conclusions

This study presents the first direct evidence that the accumulation of experience with items in a domain promotes increases in both within- and across-domain semantic differentiation, and that this experience-driven semantic differentiation generalizes to nonexperienced items. These findings have implications for understanding the role of experience in building semantic networks, and for conceptualizing the contribution of enrichment experiences to academic success.

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Supporting Information

Additional supporting information may be found in the online version of this article at the publisher's website:

Appendix S1. Supplemental materials