

Infants' Learning of Novel Words in a Stochastic Environment

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In everyday word learning words are only sometimes heard in the presence of their referent, making the acquisition of novel words a particularly challenging task. The current study investigated whether children (18-month-olds who are novice word learners) can track the statistics of co-occurrence between words and objects to learn novel mappings in a stochastic environment. Infants were briefly trained on novel word–novel object pairs with variable degrees of co-occurrence: Words were either paired reliably with 1 referent or stochastically paired with 2 different referents with varying probabilities. Infants were sensitive to the co-occurrence statistics between words and referents, tracking not just the strongest available contingency but also low-frequency information. The statistical strength of the word–referent mapping may also modulate real-time online lexical processing in infants. Infants are thus able to track stochastic relationships between words and referents in the process of learning novel words.

Keywords: language acquisition, statistical learning, word learning, stochastic environment, online processing

As Lila Gleitman (1990) famously noted, when a parent coming home from work opens the door, she is more likely to say “What did you do today?” than “I’m opening the door.” If the words and the world do not always match, how do young children learn the meanings of new words? Although multiple factors—syntactic (Booth & Waxman, 2003; Gleitman, 1990; Hall & Graham, 1999), sociopragmatic (Baldwin, 1993; Clark & Grossman, 1998; Tomasello, Strosberg, & Akhtar, 1996), conceptual (Booth, Waxman, & Huang, 2005; Dewar & Xu, 2007), and constraint based (Markman, 1994; Markman, Wasow, & Hansen, 2003)—help delimit possible referents in early word learning, the inconsistency of word-to-world mappings in the learning environment makes the acquisition problem complex. For example, 6–10-month-olds in middle-class Western cultures hear labels in the presence of their referent approximately 70% of the time (Harris, Jones, & Grant, 1983). Thus, about 70% of the time that a child hears a word like *dog*, a dog might be present, but for the remaining 30% of the time, there is no dog visible. Instead, the infant might be presented with

another plausible referent such as a leash or an empty food bowl that may also covary with the word *dog*. In infants' early word-learning environments, observable mappings between objects and words are stochastic, statistically related but not perfectly predictable. Moreover, more than one word may be directed at any particular object. A dog might not simply be a *dog*; it might also be *golden*, *wet*, and *Ari*. To the extent that a learner can track multiple potential labels that occur with low probabilities across different contexts, learners might be able to detect cross-situational mappings between words and referents (e.g., Siskind, 1996). Labeling statistics could therefore be a potential source of information for infants learning novel words.

Infants, as well as adults, are sensitive to naturally occurring statistical information in the environment. Adults possess implicit, though not infallible, knowledge of word, segment, and letter frequencies of their native language (reviewed in Kelly & Martin, 1994). Infants have been shown to be sensitive to probabilistic information that might be useful in learning a language. For example, distributional (frequency-based) information could help learners to create phonetic (Maye, Weiss, & Aslin, 2008; Maye, Werker, & Gerken, 2002) and syntactic (Cartwright & Brent, 1997; Gervain, Nespor, Mazuka, Horie, & Mehler, 2008; Mintz, 2002) categories, and to parse the nouns from determiners in noun phrases (Shi, Cutler, Werker, & Cruickshank, 2006). Tracking of transitional probabilities (sequential co-occurrences) between adjacent syllables could aid in segmentation of the speech stream into its component words (Saffran, Aslin, & Newport, 1996), while a sensitivity to nonadjacent speech elements might contribute to learning grammatical dependencies (Gómez, 2002; Newport & Aslin, 2004).

Recent experimental work suggests that aspects of word learning may also benefit from sensitivity to statistical information (Smith & Yu, 2008; Xu & Tenenbaum, 2007a, 2007b; Yu & Smith, 2007). In recent research, Smith and Yu (2008) presented infants with scenes of two words and two potential referents without any information about which word went with which ref-

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erent. Within a scene, word–referent pairings were ambiguous, but across scenes word–referent pairings were perfectly consistent, and infants successfully used this perfectly predictable information across scenes to learn novel word–referent mappings. While Smith and Yu’s study provides evidence of cross-situational mapping in infants, the infants’ word learning environment actually contains words and referents that are imperfectly correlated. No study has yet examined whether infants are able to learn novel word–referent pairings in a stochastic environment.

In the current study, we examined whether 18-month-old infants could learn relationships between stochastically presented words and referents, more closely capturing infants’ natural word-learning environments (Gleitman, 1990; Harris et al., 1983). Infants were presented with novel objects and novel words an equal number of times, but the probability of association between particular words and particular objects was manipulated: Some words always occurred in the presence of their referent (10 times); other words were stochastically linked, associated most frequently with one object (8 times) and less frequently with another (2 times; see Table 1). Using this manipulation, we examined whether 18-month-old infants were able to compute co-occurrence statistics to learn stochastic word–referent mappings. Specifically, we asked two questions: (a) Could infants learn word–referent mappings in a stochastic environment, and if they could, (b) which of the multiple available statistics did they encode? Specifically, did they learn only the most predictive of available statistics, or, alternatively, did they learn multiple mappings? Finally, we explored the effect of mapping statistics on infants’ online processing by analyzing infants’ looking behavior in real time.

Method

Participants

Twenty 18-month-old infants (10 girls, 10 boys; $M_{\text{age}} = 18$ months 13 days, range: 17 months 19 days–19 months 29 days) completed the experiment. An additional 30 infants were excluded due to technical errors (5), having a sibling with severe developmental delays (1), parental interference (2), eyes difficult to code (1), becoming inattentive or fussing (12), or not finishing the experiment (9). We recruited infants from the hospital at the time of birth and subsequently contacted their parents by phone to invite their participation in the study. All infants resided in the Pacific Northwest of North America and were from English-speaking homes. Although we did not collect demographic information, congruent with other studies, the sample was likely to be predominantly middle class and of European American descent.

Materials

Auditory stimuli consisted of three monosyllabic nonwords following a consonant–vowel–consonant (C_1VC_2) construction

Table 1
Labeling Frequencies Between Objects and Words

Object	Word 1	Word 2	Word 3
Object 1	10		
Object 2		8	2
Object 3		2	8

(/lam/, /pin/, /sæb/). They were recorded using a flat intonation contour (average pitch: 262 Hz, 277 Hz, and 256 Hz, respectively) by a voice-trained female native English speaker and were presented at 67 +/- 3dB. Words were balanced for the phonotactic probability of positional segment frequency—the probability of a particular consonant in word-initial position—and biphone frequency—the probability of a particular C_1V or VC_2 combination within words (frequency counts provided by M. Vitevitch, personal communication, February 8, 2001; see also Vitevitch & Luce, 2004).

Visual stimuli were three novel objects, which we designed and animated using Strata 3D to provide three-dimensional visual cues and then converted into QuickTime movies. We designed the objects to encourage word learning by making them perceptually dissimilar from each other, both in color and shape (Diesendruck & Shatz, 1997; Smith, Jones, & Landau, 1992) and by moving them across the frame as a cohesive bounded unit either horizontally or vertically, beginning and ending in the center of the screen (Spelke, 1990; Werker, Cohen, Lloyd, Casasola, & Stager, 1998).

Procedure

Infants sat on their parents’ lap in a dimly lit room facing a projection screen. Visual stimuli were projected onto the screen, and sounds were played from two speakers placed behind the screen. An attention-getting squishy ball was shown between trials in order to regain infants’ attention. Sound presentation was controlled from a separate room using Habit 2000 software (Cohen, Atkinson, & Chaput, 2000) on a Macintosh G4 processor. Parents wore headphones playing music to mask the sounds that were played.

Training. During training, infants were presented with 30 labeling events between words and objects. Each word and each object were presented 10 times. One object was always presented with the same word (10 out of 10 labeling events), while the other two objects were given two labels, one label occurring with a high frequency (8/10) and the other with a low frequency (2/10) (see Table 1). Training trials were 3 s long, with the label spoken once during each trial, 500 ms after trial onset. Trial onset was contingent on infants’ looking at the screen. Training trials were presented in one of two semirandom orders constrained such that objects and words were never repeated in consecutive trials.

Test. Immediately after training, infants’ learning of the word–object associations was assessed in 12 test trials with a looking-while-listening variant of the intermodal looking paradigm in which two training objects were shown side by side presented with one training word (Fernald, Pinto, Swingley, Weinberg, & McRoberts, 1998; Golinkoff, Hirsh-Pasek, Cauley, & Gordon, 1987). In this type of test situation, infants who have learned a word–object link look longer at the object that matches the word being played. Each 6-s test trial began with a 3-s silent period in which both objects moved simultaneously on the screen. After 3 s, the test period commenced: One word was presented, and infant looking time was monitored for the remaining 3 s of the trial. Infants were required to look at both objects during the silent period in order for that trial to count. Test trials were presented in one of two semirandom orders such that a given word and a given pair of objects never repeated in consecutive trials. Across the 12 test trials, every object was used both as a target and as a distractor. Because it was not possible, given infants’ limited attention span,

for us to fully counterbalance the presentation of individual objects as targets and distractors across trials, we verified that there was no intrinsic preference for particular objects by analyzing infants' looking time during the silent portion of the test trials (before the word onset). This analysis indicated no effect of specific items on infants' looking time, $F(2, 38) < 1$, $p = ns$. Infants' looking behavior was coded off-line frame by frame (30 frames per s) by a highly trained observer blind to the probability condition being tested and the label being presented on any given trial. Each trial was coded by a second blind observer, and interrater reliability was high (Pearson's $r = .984$, $p < .01$).

The effect of labeling frequency on infants' word-object mappings was examined in three unambiguous test conditions in which the test word had occurred with one test object either 10, 8, or 2 times and had never occurred with the other test object (10:0, 8:0, and 2:0 test trials, respectively). The distractor object in unambiguous test trials was Object 1 in the 8:0 and 2:0 test trials, and Object 2 or Object 3 in the 10:0 test trials (see Table 1). We tested the effect of conflicting low-frequency labeling events on infants' word-object mappings in a more sensitive ambiguous test condition in which we used a test word that had occurred with both test objects during training: 8 times with one object, and twice with the other (8:2 test trials). We thus were able to examine whether infants encoded low-frequency information in two ways: first, by testing for successful performance in the 2:0 test trials and second, by comparing performance on 8:0 trials with performance on 8:2 test trials in which conflicting low-frequency information, if tracked, might worsen performance. Infants' sensitivity to the probability of co-occurrence between words and objects was examined by analyzing both overall looking time and the time course of infant eye movements (Fernald et al., 1998; Golinkoff et al., 1987).

Results

Overall Looking Time Analyses

The observation window began at 300 ms after word onset to account for processing delay and time to initiate an eye movement (Fernald, Perfors, & Marchman, 2006; Marchman & Fernald, 2008) and lasted 1,000 ms, until 1,300 ms after word onset. This window is somewhat shorter than that typically used in the looking-while-listening procedure (which can vary between 1,433 and 1,633 ms; Fernald et al., 2006, 1998; Marchman & Fernald, 2008). However, previous studies examined infants' recognition of known words, whereas the learning of novel words may follow a different time course during the test phase. We calculated the proportion of looking time toward the high-probability match (henceforth called hiP target) by dividing the amount of time the infant looked at the hiP target by the total amount of time the infant looked at both objects. Looks away from the screen were not included. As preliminary analyses revealed no effect of training order, test order, or sex or any interactions (all $ps = ns$), we collapsed across these factors in subsequent analyses. A repeated measures analysis of variance (ANOVA) with four probability levels (10:0, 8:0, 2:0, and 8:2) showed a significant effect of probability, $F(3, 57) = 2.87$, $p = .05$, partial eta effect size $\eta_p^2 = .13$, observed power = .63, see Figure 1. A planned contrast between the high (10:0, 8:0) and low (2:0) unambiguous trials revealed a trend toward significance, $t(19) = 1.88$, $p = .08$, $r = .23$. A planned contrast between the unambiguous and ambiguous test trials revealed a reliable difference between the 8:2 and the 8:0 test conditions, $t(19) = 2.83$, $p = .03$, $r = .32$, suggesting that

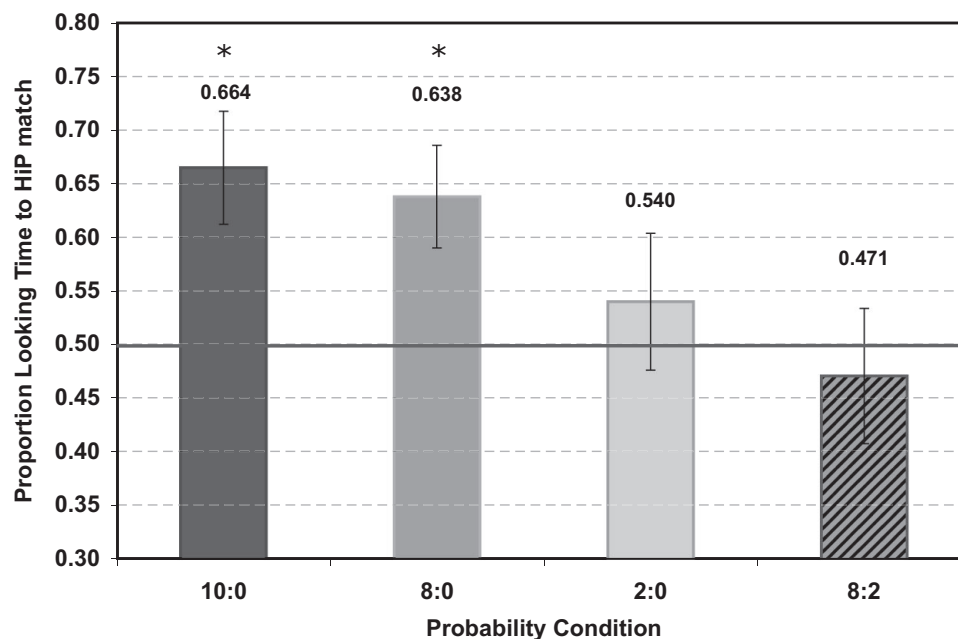


Figure 1. Proportion of infant looking time to the high-probability (HiP) match in each probability test condition in the analysis window of interest (300–1300 ms). Bars indicate the standard error of the mean. * $p > .05$.

infants kept track of the infrequent labeling events (the “2”s during training).

Finally, we compared performance in each probability condition with chance performance using two-tailed, one-sample *t* tests corrected for multiple comparisons with a Sidak-Bonferroni correction (critical alpha = .013). Of the four probability levels, infants performed better than chance on the 10:0 test condition, $t(19) = 3.12$, $p = .01$, $r = .58$, and on the 8:0 test condition, $t(19) = 2.88$, $p = .01$, $r = .55$. Neither the 2:0 test condition, $t(19) = .626$, $p = .54$, $r = .14$, nor the 8:2 test condition, $t(19) = -.467$, $p = .65$, $r = .11$, differed from chance.

Time Course Analyses

Eye-tracking behavior reflects the mental processes engaged in a particular task (Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995). Adults hearing words spontaneously fixate the matching object in the visual scene (Cooper, 1974), and adult eye movements are influenced by the degree to which competing objects match (Huettig & Altmann, 2005). To probe more fully how probabilities affect learning of novel words, we conducted an exploratory examination of infants’ real-time online processing by investigating infants’ time course in matching the hiP target (Fernald et al., 1998; Swingley & Aslin, 2000). We first calculated, for each infant, for each probability condition, the proportion of trials for which that infant fixated the hiP target at each time point in the analysis window (for example, at 300 ms, across three trials for the 10:0 condition, fixating on the hiP match twice and the low-probability match

once would earn an infant an hiP fixation proportion score of 66%). Infants’ fixation proportion scores were then averaged to derive the proportion of hiP fixations for each probability condition at each time point (see Figure 2). Infants’ fixations at word onset (0 ms) were no different from chance (all $ps = ns$), and no differences were found between the different probability conditions: one-way ANOVA, $F(3, 72) = 1.66$, $p = ns$. For 10:0 test trials, the proportion of infant fixations to the hiP target diverged from chance starting at 500 ms, $t(19) = 2.28$, $p = .04$, $r = .46$, contiguously until 800 ms, $t(18) = 2.75$, $p = .02$, $r = .53$. For 8:0 test trials, the proportion of infant fixations to the hiP target diverged from chance at 567 ms, $t(19) = 2.36$, $p = .03$, $r = .48$, lasting until 933 ms, $t(19) = 2.37$, $p = .03$, $r = .48$. There were no significant deviations from chance for either the 2:0 or the 8:2 test trials.

Discussion

Sensitivity to statistical properties of the input could contribute to aspects of human language learning from word segmentation to the acquisition of grammatical dependencies. Here we examined whether infants track statistics when learning novel words by asking two questions: (a) Can infants learn word-referent mappings when the environment is stochastic, and if they can, (b) do infants encode only the most predictive of available statistics or multiple mappings of varying statistical strengths?

The answer to the first of these questions is clearly yes. Infants showed evidence of learning words in the 10:0 test

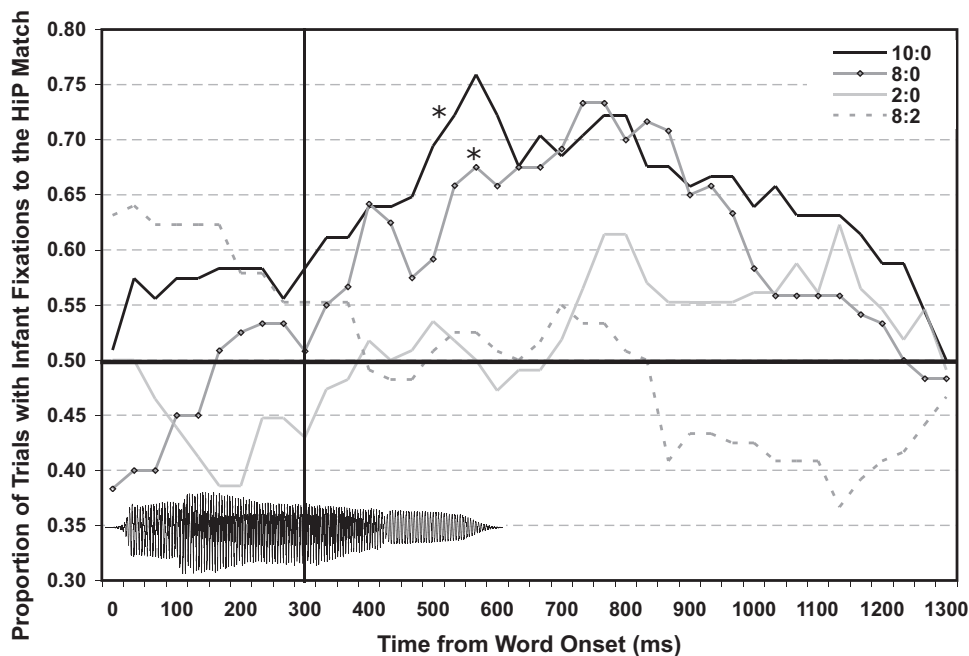


Figure 2. Proportion of trials in which infants fixated the high probability (HiP) match over time after the onset of the test word. The insert in the lower left shows the amplitude envelope of one of the test words aligned with the time course. The vertical line at 300 ms marks the beginning of the analysis window for infants’ overall looking time. Asterisks indicate the earliest time point in each series at which the proportion of infant fixations to the HiP match diverges from chance (indicated by the solid horizontal line at .50).

condition for which there were no distractors. But they also tracked stochastic co-occurrence statistics in order to learn novel word–referent mappings—they succeeded in mapping a word to its referent in the 8:0 test condition, despite the fact that both word and object were previously presented in other (less frequent) pairings. The current study leaves open the issue of how infants might internally represent these word–referent statistics, for example, in terms of probabilities or absolute frequencies (see Aslin, Saffran, & Newport, 1998 for discussion). Infants were able to use the imperfectly correlated labeling information in their natural word-learning environment to learn the meanings of novel words.

With respect to the second question of whether infants simply encoded the most predictive of available statistics or kept track of even low-frequency mappings, we found evidence that infants encoded multiple mappings. Infants' overall looking patterns suggested that they did not solely track the single most frequent label for each object but instead kept track of both high- and low-frequency word–referent co-occurrences. Although this prediction was not borne out in the 2:0 test trials, in which infants' performance was at chance, a difference was evident in the comparison between the 8:0 and 8:2 test trials. If infants were tracking only the high frequencies (8), we would have expected performance to be equivalent in the two test conditions. Instead, infants performed significantly better in the 8:0 test trials, suggesting sensitivity to the low-frequency mappings (as well as to high-frequency mappings).

Could infants have succeeded on the 8:0 test condition by simply rejecting the distractor object—the “0” object that, although familiar, had never been trained with the label currently being tested (perhaps using reasoning of disjunctive syllogisms “A or B; not A, therefore B,” e.g., Halberda, 2003)? If infants were relying solely on disconfirming information from the distractor to match the label to the other available object, they should have succeeded in both the 8:0 and the 2:0 test conditions, since both used the same distractor. But exposure to the very same “0” distractor object did not appear to be sufficient for infants to succeed in the 2:0 test condition, suggesting that infants' performance difference between 8:0 and 8:2 test trials was likely due to a sensitivity to the low-frequency mappings. At the same time, the high-frequency mapping was also fragile, as eight attested mappings were not sufficient when the infants were faced with a low-frequency competitor.

Infants' failure in the 2:0 test condition, however, also suggests that infants' learning of low-frequency mappings is fragile. While the presence of the low-frequency competitor was sufficient to compromise performance in the 8:2 relative to the 8:0 test conditions, the low-frequency pairings were not sufficient to allow mappings to be evident at test in the 2:0 test condition. It may be that the absolute number of times that the word was paired with the infrequent object in question (2) was too low for infants to make a robust mapping. Or it may be that the mere fact that the test word had been trained with another object with a relative higher frequency (8 times with a different object) weakened performance, even without a viable competitor available at test. Future studies would help select among these possibilities.

The time course analysis suggests that infants' learning of statistical relationships between words and objects may have been reflected in an online measure of behavior: their eye gaze.

Although our small sample size limits statistical power, the descriptive data are suggestive: The cumulative likelihood of fixating the high-probability target peaked earliest in the 10:0 test condition, followed by the 8:0 test condition, and finally the 2:0 test condition (see Figure 2). Future work should test whether the superficial similarities between the processing curves of the three unambiguous test conditions reflect similarities in underlying processing. To the extent that processing mechanisms sensitive to probabilistically occurring information are continuous from early development to adulthood (Huettig & Altmann, 2005; McDonald & Shillcock, 2003), infants' sensitivity to stochastic word–object co-occurrences may be contiguous with adults' processing of similar stochastic relationships (Vouloumanos, 2007).

Why should learners keep track of low-probability mappings at all? One possibility is that low-probability mappings provide clues to word meanings other than the basic-level category membership of the object (e.g., adjectives, as in “the *golden* one”; Waxman & Braun, 2005; Waxman & Markow, 1995). Another possibility is that learners could consider multiple hypotheses about a word's referent and allocate different likelihoods to each possible mapping (Swingley, 2005; Vouloumanos, 2007; Xu & Tenenbaum, 2007b). In either case, tracking some information about a range of mappings could allow infants to apply traditional word-learning constraints such as mutual exclusivity (which supposes only one label per object) in a graded manner (Regier, 1996) rather than as an all-or-none constraint (Markman, 1994). It remains to be seen whether infants recruit stochastic word–object co-occurrence information in an environment with human interlocutors using more conventional naming frames.

Although a sensitivity to statistics allows infants to accumulate information about the world quickly (Kelly & Martin, 1994) word learning is likely to require a complex constellation of skills and biases (e.g., Bloom, 2000; Golinkoff, Mervis, & Hirsh-Pasek, 1994; Saylor & Sabbagh, 2004). Children's hypotheses about the possible meaning of a novel word may be constrained by default assumptions that lead them, for example, to conjecture that a novel word will label a nameless object before its parts, color, or texture (Hollich et al., 2000; Markman, 1994), while syntactic context and understanding of intentionality, as expressed through gesture, eye gaze, or pointing behavior, further constrain the possible meanings of a novel word (Akhtar & Tomasello, 2000; Baldwin, 2000; Bloom, 2000; Brown, 1957; Gleitman, 1990). But speakers can talk about dogs in the presence or absence of dogs, or in the presence of dog paraphernalia, such as leashes, biscuits, and food bowls. Thus, even equipped with these heuristics, the word learner may engage in computations that lead to correct mappings between words and objects—computations that we found infants capable of performing. Such rational statistical processes could act within a more sophisticated, Bayesian hypothesis-testing space (Xu & Tenenbaum, 2007a, 2007b) to gather information about possible word meanings quickly and proficiently during early word learning.

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Call for Nominations: *Psychology of Men and Masculinity*

The Publications and Communications (P&C) Board of the American Psychological Association has opened nominations for the editorship of *Psychology of Men and Masculinity*. The editorial search is co-chaired by Glenn Good, PhD and Lillian Comas-Diaz, PhD.

Psychology of Men and Masculinity, official journal of APA Division 51 (Society for the Psychological Study of Men and Masculinity), is devoted to the dissemination of research, theory, and clinical scholarship that advances the psychology of men and masculinity. This discipline is defined broadly as the study of how boys' and men's psychology is influenced and shaped by both sex and gender, and encompasses both the study of biological sex differences and similarities as well as of the social construction of gender.

Editorial candidates should be available to start receiving manuscripts in January 2011 to prepare for issues published in 2012. Please note that the P&C Board encourages participation by members of underrepresented groups in the publication process and would particularly welcome such nominees. Self-nominations are also encouraged.

Candidates should be nominated by accessing APA's EditorQuest site on the Web. Using your Web browser, go to <http://editorquest.apa.org>. On the Home menu on the left, find "Guests." Next, click on the link "Submit a Nomination," enter your nominee's information, and click "Submit."

Prepared statements of one page or less in support of a nominee can also be submitted by e-mail to Molly Douglas-Fujimoto, Managing Director, Education Publishing Foundation, at mdouglas-fujimoto@apa.org.

The deadline for accepting nominations is January 31, 2010, when reviews will begin.