Conceptual precursors to language

Susan J. Hespos[1] **& Elizabeth S. Spelke**[2]

[1]*Department of Psychology and Human Development, Vanderbilt University, Nashville, Tennessee 37203, USA*
[2]*Department of Psychology, Harvard University, Cambridge, Massachusetts 02138, USA*

Because human languages vary in sound and meaning, children must learn which distinctions their language uses. For speech perception, this learning is selective: initially infants are sensitive to most acoustic distinctions used in any language[1–3], and this sensitivity reflects basic properties of the auditory system rather than mechanisms specific to language[4–7]; however, infants' sensitivity to non-native sound distinctions declines over the course of the first year[8]. Here we ask whether a similar process governs learning of word meanings. We investigated the sensitivity of 5-month-old infants in an English-speaking environment to a conceptual distinction that is marked in Korean but not English; that is, the distinction between 'tight' and 'loose' fit of one object to another[9,10]. Like adult Korean speakers but unlike adult English speakers, these infants detected this distinction and divided a continuum of motion-into-contact actions into tight- and loose-fit categories. Infants' sensitivity to this distinction is linked to representations of object mechanics[11] that are shared by non-human animals[12–14]. Language learning therefore seems to develop by linking linguistic forms to universal, pre-existing representations of sound and meaning.

Our research focuses on the crosscutting conceptual distinctions between actions producing loose- and tight-fitting contact relationships (compare left and right columns in Fig. 1a) and actions producing containment versus support relationships (compare first and second rows in Fig. 1a). As early as Korean and English children begin to talk about such actions, they categorize them differently from one another and similarly to Korean- and English-speaking adults[9,15]. Moreover, English and Korean adults differ in their performance on non-linguistic categorization tasks involving heterogeneous examples of these actions, in accord with the differing semantics of their languages[16,17], whereas the performance of young children on such tasks has been mixed[9,10,18,19]. These findings suggest that learning the semantics of a natural language influences one's conceptualization of the world[20,21], but what is the nature of this influence? It is possible that language learning creates new conceptual categories: by hearing the expression 'put on' applied to the actions of placing a book on a table or a ring on a finger, for example, speakers of English may come to perceive similarities among these events[9,21]. Alternatively, sensitivity to conceptual distinctions that are central to the semantics of any human language may emerge before language experience and then be enhanced or diminished by subsequent experience[10]. To investigate these possibilities, we tested the sensitivity of infants living in a monolingual English environment to the conceptual distinction between actions that create tight- and loose-fitting contact relationships, both within and across the English-marked distinction between containment (in) and support (on).

The experiments used a looking time procedure, relying on infants' tendency to habituate to repeated events and look longer at novel ones[22]. Experiment 1 investigated whether infants show categorical perception of tight- and loose-fitting actions, as they do for speech sounds not present in their native language[3]. Five-month-old infants were presented with a continuum of events in which a person put a cylindrical object into a cylindrical container that held it loosely or tightly (Fig. 1a). Infants in two conditions were habituated to an event in which either a narrow cylinder (loose condition) or a wide cylinder (tight condition) was placed into a medium-width container, and then all the infants were tested with events involving the narrow cylinder and two new containers, one narrower (tight) and one wider (loose) than the container presented during habituation. Infants looked longer at the test actions that presented a change from tight- to loose-fitting containment or vice versa ($F_{1,30} = 18.59$, $P < 0.001$; Fig. 1b). As with Korean adults in past research, infants therefore divided this continuum of events into the categories of tight-fitting and loose-fitting relationships.

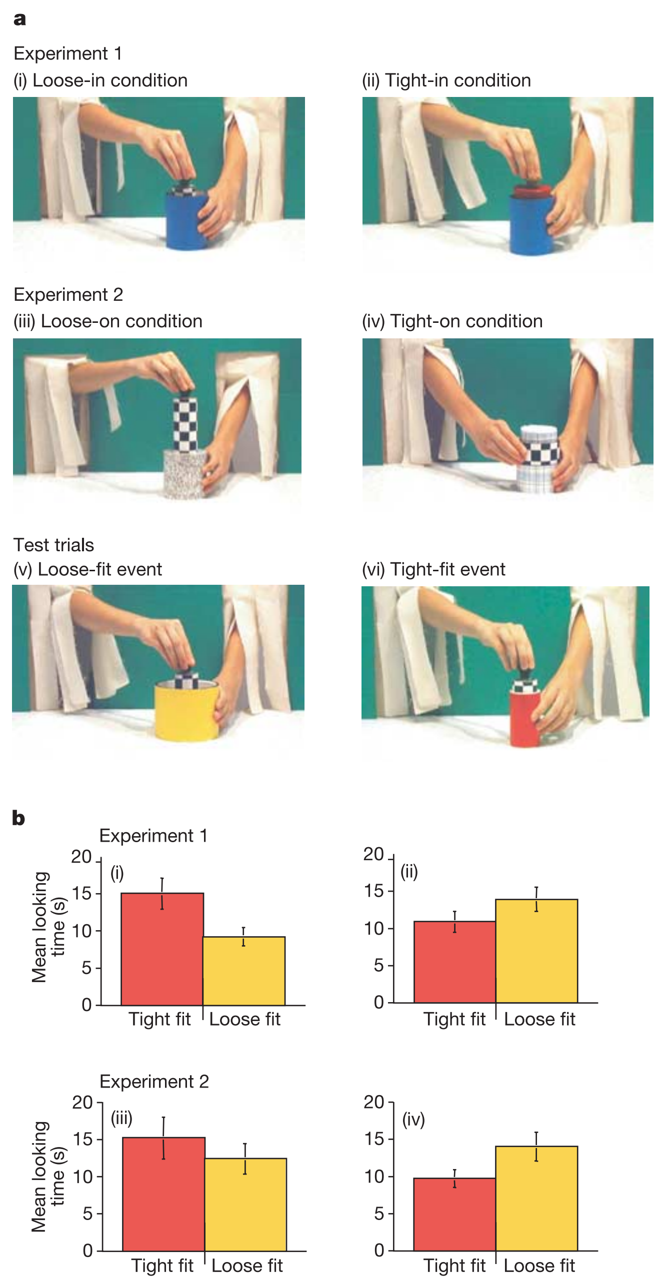

Figure 1 Infants show categorical perception of tight- and loose-fitting actions. **a**, Events for experiments 1 and 2 involving habituation to loose containment (i), tight containment (ii), loose support (iii), or tight support (iv), and testing with new loose containment (v) and tight containment (vi) events. **b**, Test trial looking times in experiments 1 (top row) and 2 (bottom row). Preference for the novel relationship was significant in each experiment. Three conditions were significant when analysed separately (condition i, $F_{1,15} = 13.21$, $P < 0.01$; condition ii, $F_{1,15} = 0.51$, $P < 0.05$; condition iv, $F_{1,15} = 6.08$, $P < 0.05$); the preference was marginal in the 'loose-on' condition (condition iii, $F_{1,15} = 1.61$, $P = 0.2$). Error bars represent standard error.

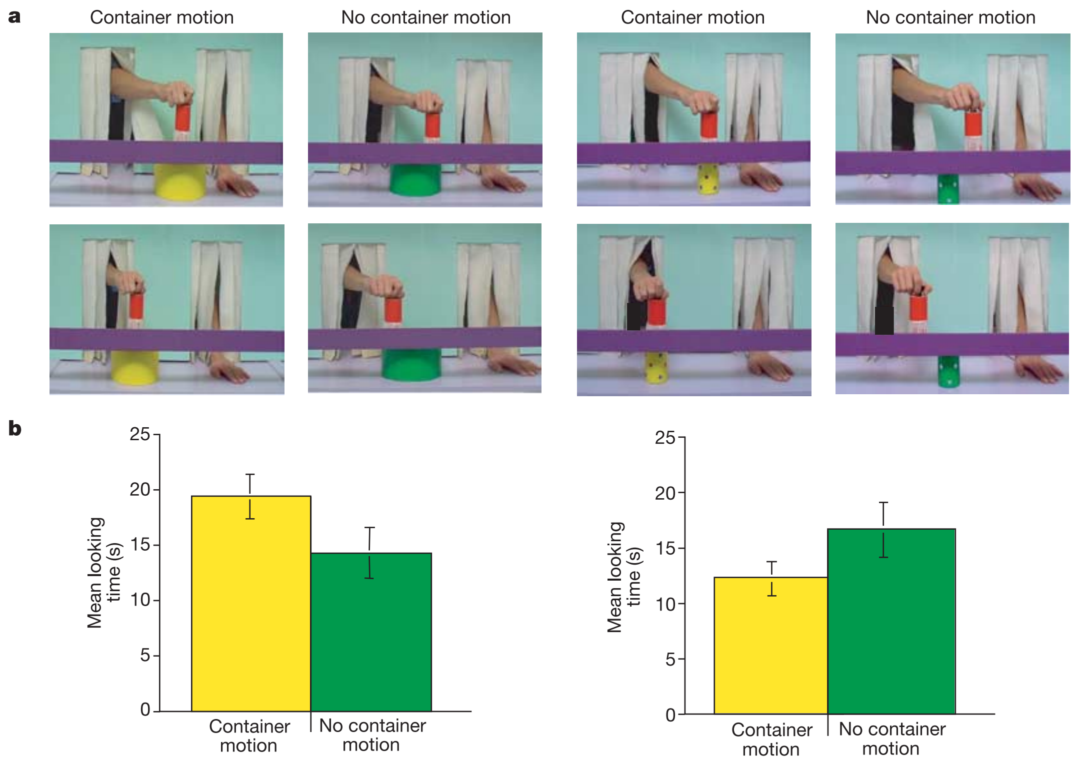

Figure 2 Infants use the tight–loose distinction in predicting object motion. **a**, Test events in experiment 3. **b**, Test trial looking times in experiment 3. Preference for the unnatural motions was significant, both overall and in each condition (each $F_{1,15} > 4.5$, $P < 0.05$). Looking preferences in each test condition differed reliably from those of control conditions presenting the events of the test trials without exposure to the containment events. Error bars represent standard error.

Experiment 2 investigated whether infants in English-speaking families, like Korean adults, generalize the tight–loose distinction across variations in a mechanical distinction that is lexicalized in the closed-class morphology of English but not of Korean: the distinction between containment and support. Five-month-old infants in two conditions were habituated either to a loose-fitting support event, in which a solid object was placed on a pedestal, or to a tight-fitting support event, in which a hollow object was placed on a post (Fig. 1a). Then infants were tested with the same two test events as in experiment 1; that is, events that would be categorized in English as containment and in Korean as a tight or loose fit. Infants looked longer at the test events that presented a change from tight- to loose-fitting or vice versa ($F_{1,30} = 6.422$, $P < 0.02$; Fig. 1b). As with Korean adults, infants exposed only to the English language categorized actions as causing tight- versus loose-fitting contact, even when the actions crosscut the English distinction between 'put in' and 'put on'.

What is the source of these action categories? Both human infants and non-human primates represent the mechanical properties of objects by analysing the arrangements and motions of surfaces[11–14,23], and these relationships differ for tight- versus loose-fitting objects. When an object enters a loose-fitting container, it can move independently in the container up to the container's boundaries; however, when an object enters a tight-fitting container, any non-accidental motion of the object will induce a corresponding motion in the container. For infants, therefore, the categorical distinction between tight- and loose-fitting relationships may be a product of a more general, language-independent system for representing object mechanics. As an initial test of this possibility, experiment 3 investigated whether 5-month-old infants make contrasting inferences about the motions of objects in tight- versus loose-fitting containers. Separate groups of 5-month-old infants were habituated to an event in which an object was placed in either a tight-fitting or loose-fitting container. Then both groups of infants were tested with events in which the contained object was moved and the container either moved with it or remained at rest (Fig. 2a). Infants presented with a loose-fitting relationship looked longer when the cylinder and its container moved together; those presented with a tight-fitting relationship showed the reverse preference ($F_{1,30} = 9.108$, $P < 0.01$; Fig. 2b). These findings provide evidence that infants use the tight–loose distinction in predicting object motion: they infer that motion of a contained object will cause a conjoint, rigid motion of the container if, and only if, the object and container fit tightly. Because non-human primates display similar capacities[14], infants' action categories seem to be linked to a language-independent system for representing objects, rather than to any representation specific to the language faculty. When language evolved as a system for linking sounds and concepts, it probably built upon a repertoire of pre-existing conceptual capacities.

Young infants in an English-speaking community are predisposed to parse a continuum of actions at a boundary point that marks a semantic distinction in Korean. Because this capacity is observed well before the acquisition of a natural language in infants whose ambient language does not mark the distinction, this capacity does not depend on language experience. Instead, the capacity seems to be linked to mechanisms for representing objects and their motions that are shared by other animals and therefore evolved before the human language faculty. Finally, infants apply the tight–loose distinction to categorize actions more consistently than do English-speaking adults tested with other materials[16,17], and they seem to apply the distinction more clearly than adults tested with the present materials (Fig. 3). To the extent that language experience influences the prominence of this conceptual distinction, our findings suggest that the influence is selective: language experience reduces sensitivity to conceptual distinctions not marked by the

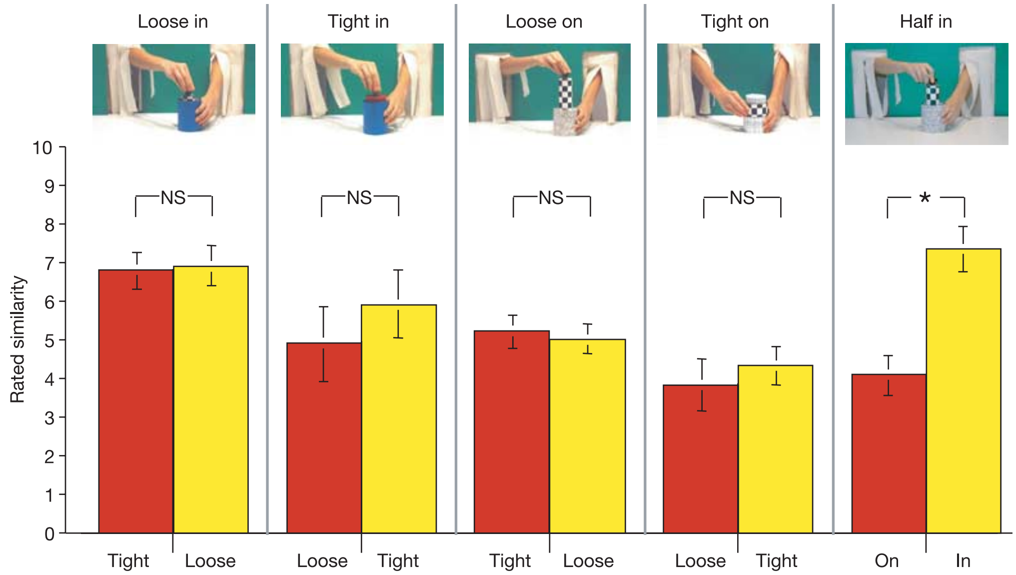

Figure 3 English-speaking adults' sensitivity to the tight-fit–loose-fit and support–containment distinctions. In judging the similarity (where 10 = high similarity) of each of two test events to a standard event (top), adults showed little sensitivity to the tight–loose distinction ($t_{1,15} < 1$ (for all t-values), not significant (NS)) and high sensitivity to the support–containment distinction ($t_{1,15} = 5.74$, $P < 0.001$). After the experiment, subjects were asked whether the actions could be grouped into two categories. All subjects categorized the support–containment actions appropriately, and many categorized the tight–loose actions appropriately, although less consistently. The tight–loose distinction therefore seems to be accessible, on reflection, to many adults whose language does not mark it. Asterisk, $P < 0.001$. Error bars represent standard error.

native language, but it does not produce the relevant concepts. In all the above respects, the early development of semantic categories parallels the development of phonological categories and suggests that natural language semantics, like natural language phonology, evolved so as to capitalize on pre-existing representational capacities[24]. Nevertheless, intuition suggests a difference between mature auditory and conceptual capacities. In studies of speech perception, adults' recognition of non-native phonological categories may improve with training but rarely attains native facility[25]. In contrast, mature English speakers have little difficulty distinguishing tight-fit from loose-fit categories once these are pointed out, and many English speakers discover the categories on their own. The effects of language experience therefore may be more dramatic at the interface of audition and phonology than at the interface of conceptual structure and semantics. □

Methods

In each experiment with infants, 32 participants aged 4.5–5.5 months (16 per condition) viewed habituation and test events. Looking time was recorded from a live video by observers blind to the condition (inter-observer agreement = 92%). Each habituation or test trial continued until the infant looked away for 2 s continuously; the habituation series ended when mean looking times over triplets of trials declined by half (maximum, nine trials). Habituation trials presented a single tight- or loose-fitting event repeatedly (see Supplementary Information). Test trials presented two alternating events with initial order counterbalanced (six trials total). Test trial looking times were analysed via 2 by 3 by 2 (condition by test trial pair by test event) analyses of variance. In experiments 1 and 2, infants viewed a hand-held cylinder entering a middle-sized container that fit it either loosely or tightly (experiment 1), or placed on a support that was either loose- or tight-fitting (experiment 2). After habituation to one repeated event, all infants viewed the same tight- and loose-fitting test events with narrow and wide containers. In experiment 3, separate groups of infants viewed tight or loose containment events behind a horizontal screen that occluded the top of the container. After habituation, they viewed alternating events in which the contained object was moved and the container either moved with it or remained at rest. The unnatural tight-fit/no container motion event was produced by detaching the top half of the contained object behind the occluder. The unnatural loose-fit/container motion event was produced by securing the contained object in a concealed narrow collar within the container.

In the experiment with adults, 80 English-speaking volunteers with no knowledge of Korean, aged 18–33 yr (16 per condition), viewed one habituation event repeated six times and two test events as in the experiments with infants, and they rated the similarity of each test event to the habituation event on a ten-point scale. Four conditions presented the habituation and test events of experiments 1 and 2; a fifth condition presented a partial containment event for habituation, in which the narrow cylinder was inserted halfway into the narrow container, and a full containment and a support event for the test, in which the same cylinder was inserted fully into or placed on top of the containing object. If adults categorize events as do infants, they should give higher similarity ratings to the same-category test event. Similarity ratings for the same-relation versus different-relation test event were compared by t-tests.

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Correspondence and requests for materials should be addressed to S.H. (s.hespos@vanderbilt.edu).

Comparison of population coherence of place cells in hippocampal subfields CA1 and CA3

Inah Lee*, D. Yoganarasimha, Geeta Rao & James J. Knierim

Department of Neurobiology and Anatomy, W.M. Keck Center for the Neurobiology of Learning and Memory, University of Texas Medical School at Houston, PO Box 20708, Houston, Texas 77225, USA

* Present address: Center for Memory and Brain, Boston University, 2 Cummington Street, Boston, Massachusetts 02215, USA

The hippocampus, a critical brain structure for navigation, context-dependent learning and episodic memory[1–3], is composed of anatomically heterogeneous subregions. These regions differ in their anatomical inputs as well as in their internal circuitry[4]. A major feature of the CA3 region is its recurrent collateral circuitry, by which the CA3 pyramidal cells make excitatory synaptic contacts on each other[4,5]. In contrast, pyramidal cells in the CA1 region are not extensively interconnected[4]. Although these differences have inspired numerous theoretical models of differential processing capacities of these two regions[6–13], there have been few reports of robust differences in the firing properties of CA1 and CA3 neurons in behaving animals. The most extensively studied of these properties is the spatially selective firing of hippocampal 'place cells'[1,14]. Here we report that in a dynamically changing environment, in which familiar landmarks on the behavioural track and along the wall are rotated relative to each other[15,16], the population representation of the environment is more coherent between the original and cue-altered environments in CA3 than in CA1. These results demonstrate a functional heterogeneity between the place cells of CA3 and CA1 at the level of neural population representations.

Five rats implanted with multiple recording probes in CA3 and CA1 were trained to circle clockwise (CW) on a circular track in a controlled, stable environment ('standard session'; STD in Fig. 1). Twelve tetrodes were lowered to CA3 and 6 tetrodes were lowered to CA1 (Fig. 2b). On each day of recording, three standard sessions were interleaved with two mismatch (MIS in Fig. 1) sessions, in which the local cues on the circular track were rotated anticlockwise (ACW) and the set of distal cues was rotated clockwise (CW) by an equal amount (Fig. 1). Total mismatch angles between the local and distal cue sets varied between 45°, 90°, 135° or 180°, and each rat received 4 sets of each rotation mismatch over 8 days.

Approximately 36% of the complex spike cells in CA1 (range 26–62%) and 26% of the complex spike cells in CA3 (range 22–33%) had place fields in the first standard session of the day; other cells were isolated in pre-session sleep periods but were silent or fired sparsely with no spatial selectivity. To first describe the heterogeneity of single-unit responses to the cue rotations, we categorized the individual place field responses into 5 groups (Fig. 2a). In some cases, the place cells rotated their preferred firing locations either CW or ACW, following in the direction of the distal or local cue sets, respectively. In other cases, place fields in standard sessions disappeared in mismatch sessions ('Disappear') or appeared only in the mismatch sessions ('Appear'). Some place fields could not be decisively categorized into the 4 response types described above, and were categorized as 'Ambiguous' (for example, when a cell had a single place field in one session and multiple place fields in the other session).

There were notable differences between CA1 and CA3 in the proportions of response types (Fig. 2c; $\chi^2 = 130.8$, $P < 0.0001$). The majority of CA3 place fields (~60%) rotated on the track (ACW, $n = 221/429$; CW, $n = 33/429$), whereas only ~27% of CA1 cells responded similarly (ACW, $n = 50/349$; CW, $n = 45/349$). In contrast, most CA1 cells altered their place fields (~73%), either showing ambiguous responses ($n = 128/349$) to the changed environments or having a robust place field in only one of the two sessions (Disappear, 98/349; Appear, 28/349). Only ~40% of CA3 cells altered their place fields in these ways. These general patterns between CA1 and CA3 were observed across all rats (Supplementary Fig. 1).

To validate objectively the categorical analysis described above, a population correlation analysis was performed. The firing rate of each cell was calculated for each 1° bin of the track, thus constructing a population firing rate vector for each of the 360 bins. The firing rate vector for each bin of the standard session was then correlated with the firing rate vector for each bin of the mismatch session to produce a STD versus MIS correlation matrix (Fig. 3; Supplementary Fig. 2). For the 45° mismatch sessions, the STD versus MIS matrices for both CA1 and CA3 showed a large correlation on the diagonal, indicating that both regions maintained strong coherence in their representations between the standard and mismatch sessions with the smallest mismatch angle tested (compare with the correlation matrices between the standard 1 and standard 2 sessions). When the mismatch angles were greater than 45°, the CA1 representations lost their coherence between the standard and mismatch sessions, as the diagonal band of high correlation disappeared. In contrast, CA3 maintained a structured, diagonal band of highly correlated activity in all mismatch types. As the mismatch angle increased, the band of high correlation shifted downward, consistent with the observation that the majority of CA3 place fields rotated ACW with the local cues.

We used circular statistics[17] to analyse the subgroup of cells that maintained place fields in both the standard and mismatch sessions. Figure 4a shows the amount that each place field rotated between

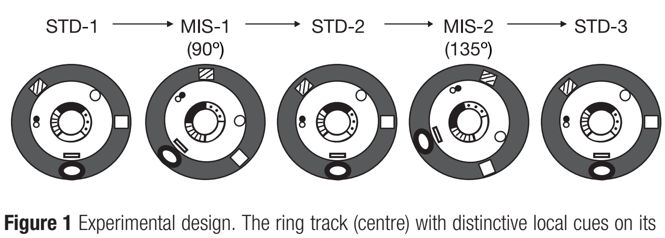

Figure 1 Experimental design. The ring track (centre) with distinctive local cues on its surface was positioned in a curtained environment (black outer circle). Distal cues were positioned along the curtained wall. Each day, the standard session (STD) was repeated three times, interleaved with cue-mismatch sessions (MIS) of different mismatch amounts (90° and 135° in this example).