form a positive feedback cycle. Analogical processes are integral to language learning (Casenhiser & Goldberg 2005; Gentner & Namy 2006; Tomasello 2000), and relational language fosters relational ability. We support this latter contention with four points.

1. *Relational language fosters the development of relational cognition.* Loewenstein and Gentner (2005) found that preschool children were better able to carry out a challenging spatial analogy when spatial relational terms (such as *top middle bottom*) were used to describe three-tiered arrays. We suggest that the relational terms induced a delineated representation of the spatial structure, which facilitated finding relational correspondences between the two arrays (see also Gentner & Rattermann 1991). Further, these representations endured beyond the session: Children retained this insight when retested days later, without further use of the spatial terms. Spelke and colleagues have also demonstrated effects of relational language on children's performance. For example, preschool children who know the terms *left* and *right* outperform their peers in relocating a hidden object placed relative to a landmark (Hermer-Vasquez et al. 2001).

2. *Children who lack conventional language are disadvantaged in some relational tasks.* One example is homesigners – congenitally deaf children of hearing parents who, deprived of a conventional language, invent their own "homesign" symbol systems (Goldin-Meadow 2003). Using the three-tiered arrays described above, we investigated homesigners in Turkey and found that (1) these children appeared not to have invented consistent terms for spatial relations, and (2) they performed substantially worse on the spatial mapping task than did hearing Turkish-speaking children (matched for performance on a simpler spatial task) (Gentner et al. 2007). Likewise, deficits in numerical ability have been found in Nicaraguan homesigners, whose invented language lacks a systematic counting system (Spaepen et al. 2007). Numerical deficits are also reported for the Pirahã people, who possess a *"one, two, many"* number system (Gordon 2004).

3. *Possessing relational symbols facilitates relational reasoning among nonhuman animals.* Research by Thompson et al. (1997) (discussed in Penn et al.'s article, but with an opposite conclusion) provides evidence for this claim. Five chimpanzees were given a relational-match-to-sample (RMTS) task, a notoriously difficult task for nonhuman animals (see Fig. 1):

XX

AA BC

Figure 1 (Gentner & Christie). The relational match-to-sample task.

Four of the chimps had previously had symbolic training – either same/different training or numerical training – and one had not. Only the four symbolically trained chimpanzees succeeded in the RMTS task – a crucial point that is not noted in Penn et al.'s discussion. Instead, Penn et al. link this RMTS task with array-matching tasks that are passed by naive animals (Wassermann et al. 2001). But two large arrays of identical elements (e.g., oooooooo and kkkkkkkk) can be seen as more alike than either is to an array of all-different elements (e.g., vlfxrtdei) on the basis of similar texture (cf. Goldmeier 1972), rather than via relational processing. In contrast, the two-item case does not afford a textural solution. It requires matching the SAME (X,X) relation to the SAME (A,A) relation (instead of to the DIFF (B,C) relation). This kind of relational reasoning is facilitated by relational symbols in chimpanzees just as in humans.

4. *The gap between humans and other apes develops gradually through the influence of language and culture.* Human children do not begin with adult-like relational insight. Rather, children show a relational shift from attention to objects to attention to relations (Gentner 1988; Halford 1987). For example, in the RMTS task with the same triads as described earlier, 3-year-olds respond randomly; they do not spontaneously notice relational similarity. Importantly, however, children show far greater relational responding if known labels (*double*) or even novel labels are used during the task (Christie & Gentner 2007).

Dramatic evidence for the developmental influence of language and culture on relational representation comes from research by Haun et al. (2006). They compared humans from different language communities with the other great apes (chimpanzees, bonobos, gorillas, and orangutans) on a locational encoding task. All four ape species used an allocentric (external) frame of reference. Interestingly, German 4-year-olds showed the same pattern. But older humans diverged in a language-specific way. Dutch 8-year-olds and adults used an egocentric frame of reference, consistent with the dominant spatial frame used in Dutch (and German). In contrast, Namibian 8-year-olds and adults, whose language (Hai||om) uses a geocentric frame of reference, encoded locations allocentrically (specifically, geocentrically). These findings suggest a gradual developmental divergence of humans from great apes; and they further suggest that language is instrumental in this divergence.

Further points. Penn et al. cite the fact that deaf children of hearing parents invent their own homesign systems (Goldin-Meadow 2003) as evidence that external language is not needed. But as discussed earlier, homesign systems fall short precisely where our position would predict: in the invention and systematization of relational terms. Penn et al. also cite aphasics who retain relational cognition despite losing the ability to speak. This is problematic for accounts that hinge on the online use of internal speech. But in our account, the great benefit of relational language is that it fosters the *learning* of relational concepts, which then serve as cognitive representations.

Darwin was not so wrong. We agree with Penn et al. that relational ability is central to the human cognitive advantage. But the possession of language and other symbol systems is equally important. Without linguistic input to suggest relational concepts and combinatorial structures to use in conjoining them, a human child must invent her own verbs and prepositions, not to mention the vast array of relational nouns used in logic (*contradiction, converse*), science (*momentum, limit, contagion*) and everyday life (*gift, deadline*). Thus, whereas Penn et al. argue for a vast discontinuity between humans and nonhuman animals, we see a graded difference that becomes large through human learning and enculturation. Humans are born with the potential for relational thought, but language and culture are required to fully realize this potential.

The missing link: Dynamic, modifiable representations in working memory

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Abstract: We propose that the missing link from nonhuman to human cognition lies with our ability to form, modify, and re-form dynamic bindings between internal representations of world-states. This capacity goes beyond dynamic feature binding in perception and involves a new conception of working memory. We propose two tests for structured knowledge that might alleviate the impasse in empirical research in nonhuman animal cognition.

We agree with Penn et al. that the ability to recognise structural correspondences between relational representations accounts for many distinctive properties of higher cognition. We propose to take this argument further by defining both a conceptual and a methodological link between animal and human cognition. The conceptual link is to treat relational processing (Halford et al. 1998a) as dynamic bindings of chunks to a coordinate system in working memory (Oberauer et al. 2007). Such a coordinate system consists of slots and relations between them, and includes relational schemas (Halford & Busby 2007). Dynamic bindings are defined structurally, the governing factor being structural correspondence, which gives the flexibility that characterises higher cognition. It enables bindings to be modified, and it permits representations to be combined, giving the property of compositionality that is essential to higher cognition. It also permits premise integration, the core process of reasoning. Dynamic bindings involve the prefrontal cortex as well, which is late evolving and late developing (Wood & Grafman 2003), and is characterised by the sort of sustained activations needed to maintain a representation of task structure across different task instances. Working memory is at the core of higher cognitive processes, being the best single predictor of reasoning performance, accounting for more than 60% of the variance (Kane et al. 2004). We propose that dynamic binding to a coordinate system in working memory is a prerequisite for relational representations and therefore well worth studying in humans and nonhuman animals.

Humans' dynamic binding ability can be tested by briefly presenting words in separate slots, such as frames on a computer screen, then testing for recognition of the frame to which a word belonged (Oberauer 2005). This ability underlies the capacity for relational processing because the explicit representation of relational information requires binding to slots (the relation "larger than" comprises sets of ordered pairs in which the larger and smaller elements are bound to specific slots). We need a test for mapping to coordinate schemas that can be used with inarticulate participants. The delayed response task could be adapted for this purpose. For example, animals could see food hidden in one of two boxes, placed one above the other; then the boxes would be moved to a different location to remove environmental cues, and, after a delay, the animals could attempt to retrieve the food from one box. This requires dynamic binding of the food to a box, where the correct box is defined by its relation, above or below, to the other box. Thus, the spatial relationships within the set of boxes provide a coordinate system. There are potentially many variations on this paradigm, once the significance of dynamic binding to a coordinate system is recognised.

Another paradigm is the generativity test. A relational schema is induced by training on sets of isomorphic problems. Then elements of a new problem can be predicted by mapping into the schema. This is a form of analogical inference, and provides a good test for relational knowledge in humans (Halford & Busby 2007). The test can be applied to nonhuman animals using the learning set paradigm (Harlow 1949) comprising series of two-object discrimination tasks, in which the choice of one object is rewarded and the other is not. At the asymptote of training, typically after hundreds of isomorphic problems, discrimination between a new pair of objects is very rapid. In some higher primates it is close to perfect after one information trial (Hayes et al. 1953).

To illustrate, consider a new pair of objects. If A is chosen on the first trial and the response is rewarded (A+), A will continue to be chosen on a very high proportion of subsequent trials. If, however, B is chosen on the first trial, resulting in no reward (B−), there will be a reliable shift to A on subsequent trials (win-stay, lose-shift). This paradigm has not been widely interpreted as inducing relational knowledge, but it does have potential for that purpose (Halford 1993). At the asymptote of inter-problem learning, participants could acquire a representation of a relation between slots, one rewarded and the other not. When a new pair is encountered, following an information trial when one object is found not to be rewarded (B−) it will be mapped to the non-rewarded slot, and the other (A) will be mapped to the rewarded slot of the relation (by structural correspondence rules which provide, inter alia, that each object will be mapped to one and only one slot). This inference can be made before the participant has any experience with the second object (A) and is a form of analogical inference. This interpretation of learning set acquisition is supported by findings that participants learn less about specific objects near the asymptote of learning set acquisition than early in acquisition (Bessemer & Stollnitz 1971). This suggests a switch to a different mode of learning late in acquisition, consistent with our proposal that the ability to process relational schemas is acquired near the asymptote of learning set acquisition. This paradigm can be used with inarticulate species, because the types of stimuli presented and responses required remain the same as in simple discrimination learning. We propose that this paradigm has been under-utilised as a measure of relational knowledge in inarticulate species. It can also be applied to more complex concepts such as oddity and conditional discrimination (Halford 1993), as well as to structures based on mathematical groups (Halford & Busby 2007).

The difficulty in resolving controversies in animal cognition is partly attributable to limitations in the power of empirical methods, as Penn et al. note. The two paradigms that we propose might break this impasse. The generativity test is adaptable for inarticulate subjects and can be used to assess induction of relational schemas. Dynamic binding in the context of a coordinate system (relational schema) can be assessed with nonhuman animals, and it affords the missing conceptual link between externally driven, perceptually grounded representations and internally driven, structurally reinterpreted representations.

Ontogeny, phylogeny, and the relational reinterpretation hypothesis

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Abstract: If our knowledge of human cognition were based solely on research with participants younger than the age of 2 years, there would be no basis for the relational reinterpretation hypothesis, and Darwin's continuity theory would be safe as houses. Because many of the shortcomings cited apply to human infants, we propose how a consideration of cognitive development would inform the relational reinterpretation hypothesis.

Penn et al. propose a pervasive domain-general cognitive discontinuity that defines the difference between "us and them." In doing so, we believe Penn et al. have inadvertently argued something akin to cognitive recapitulation. In many ways, human ontogeny of the cognitive abilities they discuss appears to recapitulate phylogeny, as young human children seem to display the same lack of relational insight that the authors identify in nonhuman