frontal damage should have relatively little impact on analogical reasoning when explicit mapping is not central to performance, and that more temporal damage should severely reduce relational priming and consequent analogical reasoning.

One interesting prediction from the model that also suggests a dissociation of analogy and mapping concerns a developmental asymmetry in analogy completion when base and target are reversed. For each analogy, it is predicted that there will be a period when the model can complete an analogy one way but fails to complete its reverse. For example, apple:cut apple::bread:cut bread at a given point in development may be easier than the reverse analogy: bread:cut bread::apple:cut apple. This phenomenon arises in the model because pattern completion is differentially constrained in the base domain and the target domain. The base domain involves greater external constraint (i.e., both the $a$ and $b$ terms) than the target domain (just the $c$ term). Consequently, the model is more likely to appropriately complete an analogy if the less well learnt relation is in the more highly constrained base domain than if it is in the less constrained target domain. This prediction is hard to reconcile with structure-mapping accounts and so constitutes a further strong test of the validity of analogy as relational priming model.

5.5. Development revisited

One of the principal lessons from this work is that it is vital to place development squarely at the heart of any account of cognition. This is not a new proposal (e.g., see Karmiloff-Smith 1998; Mareschal et al. 2007; Piaget 1970; Thelen & Smith 1994) but one that is often overlooked by investigators of adult cognition. Many models of adult cognition have become very complex, often positing a myriad of specialist mechanisms, but are also very powerful at explaining many different aspects of adult performance on a range of complex tasks. However, in many cases, these models make no attempt to explain how the complex structures assumed to be part of adult cognition emerged. In contrast to this, we have emphasized the need to explain how cognitive mechanisms emerge over time with experience of the world. The result is that a very different kind of model is arrived at. As discussed in sections 4 and 5.4, our current account still has a substantial way to go to capture the complexity and richness of adult analogical reasoning. Indeed, in section 4 we sketch one possible way forward. That objection notwithstanding, it still remains for adult-level models to make contact with the developmental constraint: namely, that all proposed mechanisms must have a developmental origin in order to be plausible. Thus, while the developmental model does not reach adult levels of competence, the adult model does not make sufficient contact with its developmental origins. A complete explanation of analogical reasoning must breach this gap.

In summary, relational priming has been presented as a developmentally viable account of early analogical completion. We have shown that the account, implemented in a connectionist model, captures a broad range of developmental phenomena, including seven detailed developmental markers of analogical ability. Our final simulation demonstrates how the simple relational priming mechanism can be applied iteratively to traverse complex analogies. This approach promises to provide a fuller developmental picture of the mechanisms underlying the gradual transition from simple to more complex reasoning.

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NOTES

1. Unless otherwise stated, all figures shown in this section portray the raw network data after fitting by 15 b-spline functions with a lambda smoothing coefficient of 0.5 using the Functional Data Analysis MatLab toolbox (Ramsay & Silverman 2002). This results in much clearer trajectories that can be interpreted in terms of higher derivatives (see Shultz [2003] for a full discussion of the benefits of using this method of presenting network data for estimating developmental trajectories). This smoothing process does not change the essence of the results we present nor the arguments that we make based on these network simulations. We thank Tom Shultz for suggesting this additional analysis.

2. It is important to note that the sum of squared error at output is calculated for the network appropriately producing either a transformational or auto-associative response (which it is being trained on) – not analogical completion (which it is never trained on). As such, sum of squared error and percentage analogies correctly completed are logically independent, and non-parametric correlation is an appropriate statistical test to assess their relationship.
C is to . . . ?" (denoted as "A:B::C:?" in what follows) analogy, which is customarily handled thus:

map A onto C
map B onto D (this is the unknown term to occupy the . . . position)
transfer across the relation between A and B to C and D (so as to correctly determine D)

Their conjecture is that relational priming accomplishes this task neatly. To wit, exposure to A and B primes a relation R that then biases C to show the way to the appropriate D. To give an example from the simple causal domains of childhood, after seeing the triple “cake, slice of cake (i.e., cut cake), pizza,” the analogically appropriate response would be “slice of pizza” (i.e., cut pizza). Here, the terms “cake” and “slice of cake” prime a relation (“cutting”) that then biases “pizza” to produce the appropriate response “slice of pizza.”

Relational priming is a commonsense notion, and its relatives are widespread. Estes and Jones (2006, p. 89) define relation [sic] priming as a phenomenon in which grasp of a word pair (“plastic spoon”) is facilitated by the past presentation of another (“wooden plate”) that instantiates the same conceptual relation (“made of”). Recanati (2004, pp. 148–51), inspired by Wittgenstein, elucidates how someone learns a predicate P – a central concern in cognitive linguistics. The learner observes the application of P in a particular context (situation) K and associates P and K. In another context K', the learner will assume that P applies in case she discerns that K' is “similar” to K (Aksen 2007). If her judgment regarding the resemblance of K and K’ is flawed (in other words, K and K’ are similar in a way not pertinent for the application of P), then communal help would come and correct the learner. The learning phase of the learner boils down to noting enough contexts in which P is reasonably applicable. In some sense, we can say that P and K cause a “legitimate context of application” to be primed.

Unfortunately, the notion of relational priming is fairly problematic. It is true that an analogy problem such as “puppy:dog::kitten:?“ can be solved rather easily with relational priming. Basic-aly, exposure to “puppy” and “dog” primes the relation “offspring,” which then biases “kitten” to produce “cat” as the D term. But the question arises: Why not the relation “younger than”? Let me borrow the notion of situation theory for a second (Barwise & Perry 1983) and say that if B is a binary relation and A, B are objects appropriate for the respective argument places of R, then we shall write << R, A, B, 1>> to denote the informational item that A, B stand in the relation R. My point is that exposure to “puppy,” “dog” could potentially prime several candidate relations, and it is no easy feat to decide which one of these is to be preferred. (It is a different matter to inquire whether this would affect the correct solution of the analogy problem.) In a nutshell, <<offspring, puppy, dog, 1>> and <<younger than, puppy, dog, 1>> and <<younger than, puppy, dog, 1>> are, <<younger than, puppy, dog, 1>>, <<younger than, puppy, dog, 1>> are, <<younger than, puppy, dog, 1>> and so on, are all possible informational items, not to mention the more theoretical <<isa, puppy, dog, 1>>. Presumably, this problem does not arise in the aforementioned cake example because of the implicit presence of a causal agent (e.g., a knife), but even that is suspect. Surely, the primed relation could have been “larger than” in that example. (Or “more expensive than,” if you truly want to make life difficult for a fan of relational priming.)

It is also crucial to observe that R has two argument roles, yet these “slots” into which appropriate objects can be placed are not ordered in any way – and “certainly not linearly ordered as a finite sequence” (Devlin 1991, p. 116). In the case of the relation “offspring,” the argument roles can be termed as “ascendant” and “descendant.” Accordingly, one apparent objection has to do with the “direction” of the relationship. Maybe “ancestry” (rather than “offspring”) should be the primed relation as it does the job equally well; after all, one of the informational items <<ancestry, descendant; dog, descendant; puppy, 1>> and <<offspring, descendant; puppy, ascendant; dog, 1>> is redundant given the other. In all likelihood, young children would never use these abstract relations anyway; they would prefer a tangible relation such as “mother of.” At least this is what my 5-year-old consistently does. Whenever she sees a lonely cat in the backyard, she says that the animal is seeking “the mom” (and never “the dad” or “the parents”).

To make things more complicated, it is not clear whether other examples superficially similar to “puppy:dog:kitten:?“ can be solved effortlessly. Take “rake:leaves:magnet:?“ In this case, exposure to the first pair should presumably prime the relation “conveniently collects in one place (location).” Then the answer “paper clips” would be apparent. However, I trust that this must be a tough one for a child of five.

Finally, take the celebrated line attributed to Groucho Marx: “Military justice is to justice as military music is to music.” When this is formulated as “military justice:justice::military music:?” it is straightforward to say that the first two terms prime the theoretical relation “ako” – representing one class being a subset of another – and hence the D term can be trivially worked out as “music.” However, and I say this somewhat hesitantly, the correct understanding here starts from the reverse direction. In other words, what makes the analogy a striking one (one that works) is that we are supposed to know that military music is invariably dreadful as a harmonious experience and that military justice should fail in the same vein. Maybe another Groucho quip is in order: “A child of five would understand this. Send someone to fetch a child of five.”

A neural-symbolic perspective on analogy

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Abstract: The target article criticises neural-symbolic systems as inadequate for analogical reasoning and proposes a model of analogy as transformation (i.e., learning). We accept the importance of learning, but we argue that, instead of conflicting, integrated reasoning and learning would model analogy much more adequately. In this new perspective, modern neural-symbolic systems become the natural candidates for modelling analogy.

The target article identifies two different stages as important for analogical reasoning: the learning of transformations (or relations) between objects, and the application of the acquired knowledge. The importance of learning, building a knowledge base, is highlighted in the article, as the analogy performance improves when more expertise is acquired. In what regards the application of knowledge for analogy, the process can be divided into two steps: (1) the recognition of the context, exemplified by the search for the most appropriate relation to be considered, and (2) the further reasoning over a different object, which might be seen either as a search for the most relevant target, or as the application of a transformation (as advocated in the article).

Among other works, the authors mention Shastri and Ajjagadde (1993), an important reference for the research on the integration of neural and symbolic artificial intelligence approaches. Since then, the research on neural-symbolic systems has evolved considerably with a strong focus on the integration