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ORIGINAL ARTICLE

Implementation of structure-mapping inference by event-file binding and action planning: a model of tool-improvisation analogies

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Abstract Structure-mapping inferences are generally regarded as dependent upon relational concepts that are understood and expressible in language by subjects capable of analogical reasoning. However, tool-improvisation inferences are executed by members of a variety of non-human primate and other species. Tool improvisation requires correctly inferring the motion and force-transfer affordances of an object; hence tool improvisation requires structure mapping driven by relational properties. Observational and experimental evidences can be interpreted to indicate that structure-mapping analogies in tool improvisation are implemented by multi-step manipulation of event files by binding and action-planning mechanisms that act in a language-independent manner. A functional model of language-independent event-file manipulations that implement structure mapping in the tool-improvisation domain is developed. This model provides a mechanism by which motion and force representations commonly employed in tool-improvisation structure mappings may be sufficiently reinforced to be available to inwardly directed attention and hence conceptualization. Predictions and potential experimental tests of this model are outlined.

Introduction

Analogical inference involves recognizing aspects of a remembered situation that are interesting like aspects of a novel situation, and applying knowledge of relations holding in the remembered situation to explain behavior in or make predictions about the novel situation. Analogies are distinguished by, and their often impressive explanatory power results from, the recognition and inferential use of similarities in relational structure between remembered and novel situations, as opposed to or in addition to similarities in the surface properties of the objects involved in the situations (reviewed by Gentner, 2003; Holyoak, 2005). In conceptual analogies presented in language, the inferential steps of recognizing the structural similarity between a remembered "base" or "source" situation and a novel "target" situation and then mapping the relational structure of the source situation onto the target situation are experimentally separable; the recognition step involves a frontal-parietal working memory (WM) network (Green, Fugelsang, Kraemer, Shamosh, & Dunbar, 2006), while the mapping step involves regions of rostral prefrontal cortex (RPFC; Green et al., 2006; Morrison et al., 2005) that are also implicated in multi-tasking (Dreher, Koechlin, Tierney, & Grafman, 2008; Sigman & Dehaene, 2006) and allocating attention between externally driven perception and internal imaginative processes (Burgess, Simons, Dumontheil, & Gilbert, 2007; Gilbert, Frith, & Burgess, 2005).

Structure-mapping inferences are typically explicated in terms of manipulations of relational concepts expressible in language. Gentner (2003) places relational concepts expressible in language at the center of analogical capability, claiming that "acquisition of relational language is instrumental in the development of analogy" (p. 219). Gentner and Christie (2008) advance the arguably stronger claim that "possession of an elaborated symbol system—such as human language—is necessary to make our relational capacity operational" (p. 136). The dependence of analogical capability on relational language capability is evident in young children, who become progressively more able to recognize analogies between situations as their relational vocabularies increase and the meanings they

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attach to relational terms approach the meanings generally assigned by adults (reviewed by Gentner, 2005). Consistent with the view that recognition of the relational similarities that drive structure mapping depends upon relational concepts expressible in language, analogies presented in language dominate research on the mechanisms of structure mapping. The experimental design employed by Green et al. (2006) to functionally localize the analogical mapping process, for example, depends on the manipulation of language-based semantic relations. When analogies between pictures are used experimentally, for example by Morrison et al. (2005), the interpretation of the results typically relies on the assumption that subjects are retrieving concepts expressible in language to interpret the pictures as structurally analogous.

While non-human animals are clearly capable of recognizing similarities between situations, they are generally regarded as being incapable of recognizing analogies. Penn et al. (2008), for example, argue that non-human animals are incapable of true analogical reasoning, i.e., reasoning in which similarities between relations holding in two situations, not similarities between surface features of objects, provide the basis for an inference that one situation is like another. They attribute this lack of analogical ability to an inability to represent and carry out inferences about relations, concluding that "only humans are able to reason about higher-order relations in a structurally systematic and inferentially productive fashion" (p. 128). Gentner (2003) reviews evidence that chimpanzees are capable of symbolic relation-matching tasks only if given specific training in the use of symbols. She concludes that chimpanzees are capable of relational reasoning, but can perform it "only if they learn relational language" (p. 219). The common denominator between these analyses is the claim that explicit representations of the relations holding in pairs of situations, whether in a natural language (Gentner, 2003) or in a "language of thought" supporting reinterpretation of perceived relations between particular entities as instances of conceptualized abstract relations (Penn et al., 2008), are required for structure mapping driven by relational similarity.

This paper challenges the claim that concepts expressible in language—either a public language or a language of thought—are prerequisites for inference by structure mapping. It focuses on a particular class of inferences from a remembered to a novel situation that are performed by both humans and non-human animals and that appear prima facie to involve relational knowledge: the inferences involved in spontaneous tool improvisation. The improvisation or invention of a novel tool to support a goal-driven activity, previously performed using only parts of an animal's own body, requires the construction of a novel action plan in which the motions and forces required to use the tool replace the motions and forces previously employed. "Introduction" reviews the phenomenology of tool improvisation both in mammalian and in avian species, and shows that tool-improvisation inferences are instances of structure mapping in which the structures being mapped are goal-directed action plan templates that encode both kinematic (specifying motion) and dynamic (specifying force transfer) relations between objects. The broad phylogenetic distribution of tool improvisation suggests that such inferences may be the most ancient instances of structure mapping, and that the highly developed capability for structure mapping observed in humans may be significantly based on an ancient capability broadly shared across species, but restricted in its application, in non-humans, to tool improvisation. "Structure mapping in tool improvisation" reviews data indicating that the structure-mapping inferences supporting tool improvisation are implemented by event-file binding (Hommel, 2004) and pre-motor action planning (Johnson-Frey, Newman-Norland, & Grafton, 2005; Lewis, 2006) networks that are substantially shared by humans and macaques. In contrast, conscious simulation-based evaluation and comparison of action plans, as well as the ability to experience and hence to report that two action plans are analogous, depend on attention-switching functions of RPFC that are evolutionarily recent and probably human-specific (Burgess et al., 2007). A functional model of structure-mapping inferences in the tool-improvisation domain is proposed that requires manipulation of event files and pre-motor action planning, but not conscious conceptual understanding of motions or forces. "Consequences of the event-file manipulation model: functional dependence of motion concepts on structure mapping" shows that in this event-file manipulation model of structure mapping in tool improvisation, the direction of functional dependency is reversed from that claimed by Gentner (2003, 2005) and by Penn et al. (2008): kinematic and dynamic concepts expressible in human language require, instead of being required by, the capability for inference by structure mapping. This proposal is consistent with the hypothesis that human language-based concepts are at least partially derived from pre-existing visuo-motor representations (Barsalou, 2008; Fiebach & Schubotz, 2006; Gallese & Lakoff, 2005). Both anecdotal and experimental evidences supporting this conjecture are discussed. "Testing the proposed model of tool-improvisation structure-mapping inferences" outlines a number of predictions derived from the proposed model of structure-mapping inferences, and reviews observations bearing on them.

Structure mapping in tool improvisation

Humans, chimpanzees (Whiten et al., 2001), orangutans (van Schaik et al., 2003), gorillas (Breuer, Ndoundou-

Hockemba, & Fishlock, 2005), capuchin monkeys (Ottoni, Dogo de Resende, & Izar, 2005), bottlenose dolphins (Krutzen, Mann, Heithaus, Connor, Bejder, & Sherwin, 2005), elephants (Byrne, Bates, & Moss, 2009), crows (Hunt & Grey, 2003, 2004) and finches (Tebbich & Bshary, 2004) exhibit tool improvisation in the wild. The most familiar tools of any animal are its own limbs, and the most fundamental cases of tool improvisation involve using an object common to the animal's environment to augment the reach or force of an animal's limbs. New Caledonian crows employ manufactured hooks to extend the reach of their beaks (Hunt & Grey, 2003, 2004), modifying them as needed for particular tasks (Weir & Kacelnik, 2006). Woodpecker finches use cactus spines and sticks as probing tools (Tebbich & Bshary, 2004). Bottlenose dolphins adapt sponges as head-mounted fishing tools (Krutzen et al., 2005; Mann et al., 2008). Elephants manufacture and employ tools for personal hygiene (Byrne et al., 2009). Capuchin monkeys use stones to crack nuts (Ottoni et al., 2005; Visalberghi, Fragaszy, Ottoni, Izar, de Olviera, & Andrade, 2007). Gorillas use stout sticks as walking sticks, canes and bridges (Breuer et al., 2005). Chimpanzees and orangutans use many kinds of objects as tools, modifying them as needed (Sanz & Morgan, 2007; van Schaik et al., 2003; Whiten et al., 2001); distinct choices of objects to employ as tools and distinct methods and objectives of tool use among these primates are among the principal markers of community-specific cultures in wild primate communities (reviewed by Whiten & van Schaik, 2007), as they are among humans. Paleo-anthropological evidence indicates proto-human use of modified stone tools from at least 2.5 million years ago (Plummer, 2004; Wynn, 2002). Modern humans immersed in a tool-rich technological culture continue to practice tool improvisation, from the cobbling together of prototypes of new technologically sophisticated tools to meet novel requirements to the casual use of screwdriver handles, crowbars or suitable stones in the place of forgotten hammers.

The inference that a novel object A can functionally substitute for a more familiar object B in the context of a goal-directed action is non-trivial. Consider the case of capuchins (Ottoni et al., 2005; Visalberghi et al., 2007) or chimpanzees (Biro, Inoue-Nakamura, Tonooka, Yamakoshi, Sousa, & Matsuzawa, 2003; Carvalho, Cunha, Sousa, & Matsuzawa, 2008) using stones to crack nuts. Both species are familiar with food sources with husks and peels, and with the removal of these coverings with the hands, but their hands are not capable of removing the hard shells of nuts. Some individuals of both species are observed to select stones from the local environment and use them as tools to crack nuts so that the shells can be removed. Tool-using individuals are capable of selecting from among multiple stones those that are appropriate for use as tools (Carvalho et al., 2008; Schrauf, Huber, & Visalberghi, 2008; Visalberghi et al., 2007, 2009). Young individuals of both species learn, through a combination of observation of older stone-using conspecifics and practice, to select stones appropriate for use in cracking nuts from a variety of available candidates, and to execute the positioning and striking motions necessary to crack nuts with the selected stones. Tool-using individuals do not merely learn that specific stones are useful as tools, but rather that stones with particular properties, including size, shape, weight and hardness, are useful as tools (Carvalho et al., 2008; Schrauf et al., 2008; Visalberghi et al., 2009). While these primates do not modify stones used for nut cracking, chimpanzees do modify other tools (Whiten et al., 2001) including pointed sticks used as spears (Pruetz & Bertolani, 2007) and concrete disks used as projectiles (Osvath, 2009). Orangutans (van Schaik et al., 2003), gorillas (Breuer et al., 2005), elephants (Byrne et al., 2009) and crows (Hunt & Grey, 2004; Weir & Kacelnik, 2006) also modify tools. Selection of potential tools using general and functionally relevant criteria, modification of selected objects to better satisfy functionally relevant criteria and learning of group-specific tool selection and use practices (Whiten & van Schaik, 2007) all indicate that non-human animal tool use involves non-trivial causal inferences as opposed to simple associations (Penn & Povinelli, 2007). Hence while available evidence does not support the claim that non-human animals understand concepts, such as applied force in the abstract (Penn, Holyoak & Povinelli, 2008; Penn & Povinelli, 2007), it does support the claim that, at least in tool-improvisation contexts, they execute inferences that require representations of physical parameters, such as size, weight, flexibility, tensile strength and sharpness that are relevant to the functioning of tools.

The existence of distinct tool-use cultures in neighboring bands of chimpanzees (Biro et al., 2003; Sanz & Morgan, 2007) indicates that tool improvisation by individual chimpanzees is not uncommon. The first, "discovery" instance of using a novel tool need not involve a structure-mapping inference: a lucky capuchin or chimpanzee might, for example, fortuitously drop a rock onto a nut and crack it, revealing a food source inside. Positive affective tags associated with food discovery would be expected to increase the likelihood that such an event would be remembered. However, incorporating the remembered event into the repertoire of food-seeking action patterns requires inference; in the nut cracking case, it requires linking the goal of obtaining food to both the novel source and to the sequential actions of searching for an appropriate stone to use as a cracking tool and manipulating it in an appropriate way. While some experiments have been interpreted as indicating planning based on experienced episodic memories in chimpanzees and orangutans (Osvath & Osvath, 2008), most observations do not support such capabilities in non-human animals (Suddendorf & Coraballis, 2007; Suddendorf, Coraballis, & Collier-Baker, 2009). Inference from a chance discovery, or from observation of tool use by a mentor, is probably unconscious and automated, in capuchins even if not in chimpanzees. That such inferences are non-trivial is indicated by the fact that multiple demonstrations are typically required for learning behaviors, such as nut cracking in both species (Biro et al., 2003; Marshall-Pescini & Whiten, 2009; Ottoni et al., 2005). The primary hypothesis of this paper is that the construction of novel goal-directed action patterns involving tool use is accomplished by a particular kind of unconscious, but non-trivial inference: structure mapping.

From a phenomenological perspective, tool-improvisation inferences satisfy the definitional criteria of structure mapping. Nut-cracking capuchins or chimpanzees, for example, appear to execute a structure-mapping analogy stone:nut::hand:fruit. The source case for this analogy is an action plan—hold the fruit so that it does not move and remove the covering of the fruit by movements of the hand—that has a specific goal, obtaining the food inside the fruit. The target case is a similar action plan—secure the nut so that it does not move and remove the covering by movements of the hand holding the stone—with a similar specific goal, obtaining the food inside the nut. When the action encoded by either of these action plans is executed successfully, the food that was previously hidden is exposed and visible. Thus, source and target cases share (1) their application to objects containing food; (2) their encodings as action plans that involve visually coordinated forceful hand movements; (3) their goals of obtaining the hidden food contained in the objects to which they are applied; and (4) their observable successful outcomes of making visible what was previously invisible. They differ in the details of the objects to which they are applied, the hand movements that are employed, and what the dominant hand is holding: nothing in one case and a stone in the other. In the context of the action plan, this last difference is encoded by differences in muscle configurations and movements and by two parameters: the felt weight of the hand grasping the stone, and the force required to move that weighted hand with sufficient velocity to crack the nut (Brill, Dietrich, Foucart, Fuwa, & Hirata, 2009). Mappings between source and target cases that preserve long-range organizing relations, such as goals or outcomes while allowing variations in the superficial details of objects and motions and in the values of properties and parameters are structure mappings (Gentner, 2003; Holyoak, 2005). Tool-improvisation analogies in general share these defining characteristics of structure mappings.

Non-trivial analogies are not just structure-mapping inferences, but structure-mapping inferences in which relations, not surface similarities, carry the inferential weight (Gentner, 2003; Holyoak, 2005). Thus, it might be objected that tool-improvisation inferences, while qualifying as structure mappings, fail to qualify as analogies because they are driven by surface similarities, not relational similarities. This is not, however, the case. Stones, for example, have few surface similarities with hands, and do not functionally substitute for hands in contexts involving grasping, manipulating, climbing, grooming or locomotion. Stones only functionally substitute for hands in contexts that call for a tool or a weapon, i.e., contexts that involve the application of mechanical force to another object. Utility for the application of mechanical force is a relational criterion. While there is no evidence that primates other than humans understand this criterion in the abstract (Penn et al., 2008), the marked preferences of both chimpanzees (Carvalho et al., 2008) and capuchins (Schrauf et al., 2008; Visalberghi et al., 2009) for stones with shapes, weights and hardness suitable to the dynamic requirements of nut cracking indicates that they are sensitive to this relational requirement. The centrality of relational requirements involving force (i.e., weight), tensile strength, rigidity and particular details of shape is a general feature of tool-improvisation structure mappings. Non-human animals, like humans, select objects for use as tools that satisfy functional criteria, not objects that merely share surface features. Gorillas, for example, test branches or sticks for strength before using them as supports (Breuer et al., 2005). Crows modify twigs so that the final shape differs from the original shape in ways that contribute to function (Hunt & Grey, 2004). Chimpanzees sharpen sticks to be used as spears with their teeth, achieving impressive points (Pruetz & Bertolani, 2007). Tamarin monkeys, although they apparently do not use tools in the wild, differentiate functionally relevant from functionally irrelevant features of candidate tools in captivity, even in infancy (Hauser, Pearson, & Seelig, 2002). The objects that are selected as satisfying tool-improvisation structure mappings are thus selected, or selected and then modified, on the basis of criteria directly relevant to the principle organizing relation of the structure mapping, the utility of the object employed as a tool in achieving the result that motivates the structure-mapping inference. Tool-improvisation structure mappings therefore qualify as analogies in the strict sense of inferences driven by relational similarities, not surface similarities. As discussed above, selection and modification on the basis of functional, relational criteria do not imply conscious understanding of these criteria, or of the concepts of force or of utility to achieve an end in the abstract, but do imply at least an implicit representation of such criteria, and do require that these criteria trump functionally irrelevant surface similarities in the selection process.

Tool-improvisation analogies executed by non-human, and therefore language-lacking animals pose both a difficulty and an opportunity for functional models of structure mapping. The difficulty is that existing models of structure mapping depend on the manipulation of concepts expressible in language, either a public natural language or an internal, comprehended language of thought. The opportunity is that the representation of tool use in the primate brain is considerably better understood than the representation of abstract conceptual reasoning; hence tool-improvisation analogies may provide insights into how brains implement structure mappings, at least those structure mappings that depend on kinematic and dynamic relations between objects.

Neurocognitive implementation of structure mappings for tool use: evidence and functional model

Non-human animals lack human language; they must therefore implement tool-improvisation analogies with neurocognitive mechanisms that do not rely on human language. This requirement has two parts: first, non-human animals must have non-language-based representations of the goals, objects and action plans involved both in the source and in the target cases; second, they must have a non-language-dependent inferential mechanism capable of executing structure-mapping inferences, at least for source and target cases in the tool-use domain. Humans do have human language, and clearly execute analogies, such as the political analogies described by Holyoak (2005), that appear to be explicable only in terms of language-dependent inferences. One can, however, ask also in the case of humans how goals, objects and action plans involved specifically in tool use are represented, and how structure-mapping inferences specifically involving tool improvisation are executed.

To develop a language-independent model of tool-improvisation inferences, it is useful to consider the neurocognitive implementation of tool-use actions and action planning. A considerable body of experimental evidence indicates that humans represent actions involving tools in a left-hemisphere-dominated praxis network that includes posterior-parietal multi-modal binding areas, somatosensory areas and premotor areas (reviewed by Culham & Valyear, 2006; Johnson-Frey et al., 2005; Lewis, 2006; Martin, 2007). This frontoparietal network is activated not only by performing actions with tools, but also by pantomiming actions with tools and imagining actions with tools. It overlaps significantly with the mirror-neuron system (MNS) that maps observations of others performing motor acts onto motor plans (reviewed by Puce & Perrett, 2003; Rizzolatti & Craighero, 2004). Mirror neurons respond to non-biological motions that are kinematically similar to biological motions, such as motions of reaching or pounding tools, as well as to biological motions (Engel, Burke, Fiehler, Bien, & Rosler, 2007; Schubotz & van Cramon, 2004); rigid tool motions are represented separately within the praxis network (Martin, 2007). Planning tool use couples this frontoparietal action representation to areas of lateral prefrontal cortex involved in learning motor responses to visual stimuli (Boettiger & D'Esposito, 2005), maintaining representations of task requirements as motions are executed (Cole & Schneider, 2007; Courtney, 2004; Tanji & Hoshi, 2008), and associating task requirements with premotor-encoded information about movement capabilities (Johnson-Frey et al., 2005). Increasing the complexity of tool-use actions increases activation of more rostral areas of prefrontal cortex, as demonstrated in experiments in which novices (Stout & Chaminade, 2007) and experts (Stout et al., 2008) manufactured replicas of early stone-age tools. Relatively simple motions used by novices to construct relatively simple stone tools activated the frontoparietal network supporting perceptual control of motor actions, but not prefrontal executive areas (Stout & Chaminade, 2007), while the more complex sequences of motions used by experts to construct more sophisticated tools activated both lateral and rostral prefrontal areas, including language-production areas (Stout et al., 2008; Stout & Chaminade, 2009).

Comparative studies of human and non-human primate tool use indicate broad similarities in the encoding of tool-use actions across primates. Tool use both in macaque monkeys and in humans leads to specificity changes in interparietal sulcus (IPS) neurons implementing visual to somatosensory binding that effectively extend the body to incorporate the tool (reviewed by Maravita & Iriki, 2004), while maintaining a body-tool distinction (Povinelli, Reaux, & Frey, 2009). Monkey and human IPS are highly anatomically and functionally homologous, implementing multi-modal sensory binding to construct spatial layouts, binding action plans to the representations of such layouts, and controlling motions relevant to objects in a layout (reviewed by Grefkes & Fink, 2005). Mirror neurons specific to observations of tool use have been identified in macaque monkeys (Ferrari, Rozzi, & Fogassi, 2005). The specificities of these tool-use-specific mirror neurons develop slowly over months of training and experience with tool-like objects, consistent with both the time course of tool-use learning in wild primates (Biro et al., 2003; Ottoni et al., 2005) and the general plasticity of mirror-neuron specificities observed in humans (Catmur, Gillmeister, Bird, Liepelt, Brass, & Heyes, 2008; Catmur, Walsh, & Heyes, 2007). Multi-step actions are planned, sequenced and controlled by areas of lateral prefrontal cortex in macaques as they are in humans (reviewed by Hoshi, 2006); in macaques lateral prefrontal cortex appears to encode control for all action sequences regardless of complexity (reviewed by Tanji & Hoshi, 2008) with more rostral prefrontal cortex reserved to decision-making based on affective and sensory (primarily olfactory) cues (Averbach & Seo, 2008).

While activation of the frontoparietal praxis network by tool-improvisation inferences has not been observed directly, the involvement of this network in imagining and planning tool use (Lewis, 2006) indicates that it would be active in tool-improvisation inferences if they involve either imagining or planning tool use. The overlapping, multimodal nature of the representation of tool-use actions and tool-use planning in the frontoparietal praxis network indeed suggests that this network itself may implement structure-mapping inferences in the tool-use domain. A functional model of the implementation of two structure-mapping inferences, the stone:nut::hand:fruit analogy discussed above and the common human backpacker's tool-improvisation analogy stone:tent-stake::hammer:nail, based on their implementation by the praxis network is shown in Fig. 1. This model proposes that (1) the representational structures that are mapped in tool-improvisation analogies are event files (Hommel, 2004) implemented as activation patterns centered on IPS; and (2) mapping of event files is executed in two phases by two distinct binding processes. The first of these processes involves retrieval of an action instance or minimally abstracted action schema that serves as the source case, and induces mapping of the object and motion components of the task environment into a source-case-based action plan. The second process involves the embedding of additional action components into the partially mapped action plan, and induces mapping of the tool components of the task environment to create a fully mapped target-case action plan. In the final step of this second process, the fully mapped target-case action plan is executed, confirming or disconfirming the adequacy of the structure mapping.

In the model shown in Fig. 1, the task environment explicitly specifies the current layout of task-relevant objects and implicitly specifies a goal layout in which the position or orientation of one or more objects has changed. This task environment is represented by an event file (Hommel, 2004) binding the current layout, the goal layout and the motion(s) required to resolve the spatial discrepancy between the two layouts. Such event files are constructed hierarchically from lower-level object-motion bindings, in a process that is sensitive to priming by long-term memory (LTM) resident representations encoding relationships between objects or features in the current perceived situation (Colzato, Raffone, & Hommel, 2006). Event files, thus, provide a level of representation at which relational priming could drive implicit analogical inference, as proposed by Leech, Mareshal and Cooper (2008) for analogies between concepts expressible in language. Construction of a task-environment event file requires representation of the goal layout as a manipulable image, and inference of the required motion(s) from the spatial discrepancy between the perceived current layout and an imagined goal layout. It is important to emphasize that neither the goal layout nor the inferences of motion need be consciously experienced. Even in humans, such representations and inferences are not experienced during expert "flow-like" performance of familiar tasks (Dietrich, 2004; Ericsson & Lehmann, 1996).

The first phase of structure mapping is initiated by activation of an LTM resident representation of a previously executed or observed action instance or minimally abstracted action schema that encodes both a result and a motion sufficiently similar to the goal and motion encoded by the task-environment representation. This retrieved action instance is thus both a goal-result and a kinematic match to the event file representing the task environment. On the basis of this goal-motion alignment, the retrieved instance is bound to the event file representing the task environment. This binding step replaces the object and motion representations of the retrieved action instance with those of the task-environment event file to produce a partially mapped, partially instantiated action plan that shares the goal of and satisfies the kinematic requirements of the task environment, but still encodes the dynamic, i.e., force-application, parameters of the retrieved action instance. Such non-intentional—in fact fully unconscious—replacement of components of retrieved representations by components of current perceptual representations by structure-mapping mechanisms has been observed in verbal analogies (Day & Gentner, 2007).

The appropriate application of force is critical to successful tool improvisation; as discussed above, it is only in the context of such dynamic constraints that a tool can be said to be analogous to a part of the body. The proposed model requires that LTM-resident action instances encode applied force in two ways: as a reproducible sensation of muscular effort and as a parametric representation of the resulting motion. Choice of and use of tools by chimpanzees indicate that they are sensitive to these representations of force (Brill et al., 2009). Calibration of these two representations to achieve expert ability in fine motor control requires extensive practice (Ericsson & Lehmann, 1996). Studies of expert athletes indicate that fine adjustments in motor control driven by representations of muscular force are performed unconsciously in response to unconscious perceptions of movement requirements (Kibele, 2006), consistent both with their common encoding at the event-file level and the independence of force-motion inferences from deliberate conceptual processing. In the model shown in Fig. 1, applied force is represented parametrically with respect to the object to which force is applied, while motion

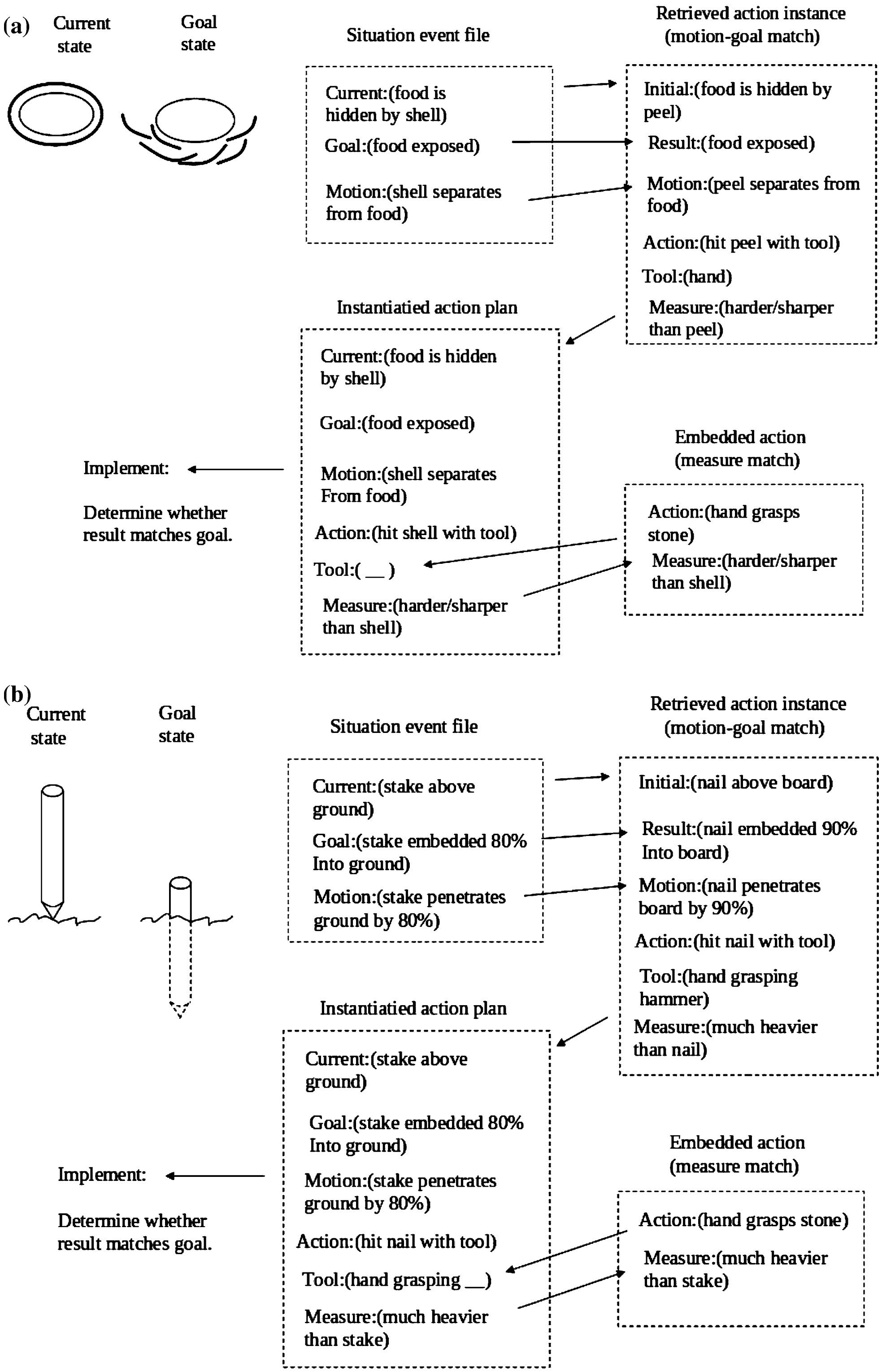

Fig. 1 Frame-based representation of structure-mapping steps in tool-improvisation analogies: **a** the stone:nut::hand:fruit analogy and **b** the stone:tent-stake::hammer:nail analogy. *Arrows* indicate retrieval and mapping steps. The use of frames is heuristic only and is not meant to imply that the representations implemented by the praxis system encode concepts expressible in either public language or an internally comprehended language of thought

is represented qualitatively in terms of the final dispositions of relevant objects.

A partially mapped action plan may be executed, but will fail in cases requiring tool improvisation. In the stone:nut::hand:fruit case, implementation of the partially mapped plan fails because hands are not hard and sharp enough to open nuts, as some, but not all wild chimpanzees eventually comprehend (Biro et al., 2003). In the stone:tent-stake::hammer:nail case, the partially mapped plan typically fails because the backpacker has not brought a hammer. In either case, failure of the partially mapped action plan initiates the second phase of structure mapping.

In this phase, one or more LTM-resident action instances are activated that encode force measures similar to that of the partially mapped action plan. Similarities in applied force are relational, not surface, similarities. The retrieved action plan is embedded into the partially mapped action plan, inducing replacement of the insufficient tool with the object of the embedded action. The result of this embedding is a fully mapped action plan incorporating the objects and motions of the task environment and the alternative tool retrieved for its ability to meet the force requirements of the task environment. This model of action embedding as a method of action-plan generation is similar to that employed in some robotic action planners (e.g., Beaudry et al., 2005). Action plan embedding involves holding at least two action plans in WM simultaneously, a form of multitasking; hence capability in action-plan embedding and therefore in tool improvisation would be expected to increase with increased development of rostral prefrontal cortex, which supports multitasking (Dreher et al., 2008; Green et al., 2006), consistent with the observed capability gradients from simians to great apes to humans and from children to adults. Interestingly, young chimpanzees are more efficient learners of some tool-use tasks than are human children (Horner & Whiten, 2005), suggesting that they may be more efficient tool improvisers as well.

Instantiation of the fully mapped action plan provides the criteria necessary for a visual and tactile search for an object to serve as the alternative tool followed by dynamic testing of the object to determine whether it actually meets the force-application requirements of the action plan. Hefting a stone to assess its weight or bending a stick to assess its rigidity are dynamic tests of this kind. Tool modification may follow testing. The fully mapped action plan is then executed and its results observed. Successful plans are those for which the result of execution matches the goal.

The binding and memory-access steps proposed by this model of structure mapping would be expected to engage areas of the temporal-parietal junction (binding), pre-motor cortex (mirror-neuron action representation and motor planning), anterior cingulate cortex (process monitoring and conflict detection), dorso-lateral prefrontal cortex (goal maintenance and WM management) and rostral prefrontal cortex (attentional control). Left-hemisphere activation would be expected to dominate, consistent with the left-hemisphere specialization for sequential actions (Fiebach & Schubotz, 2006) and tool-related actions in particular (Lewis, 2006). Such activation would contrast with the right-hemisphere activation associated with general semantic representations (Bar, 2008), which is observed specifically when subjects solve word-association problems involving distant semantic connections (Bowden et al., 2006; Sandkühler & Bhattacharya, 2008; Jung-Beeman et al., 2004; Kounios & Beeman, 2009). Specific tests of this model would require either imaging or magnetic deactivation of specific praxis-network areas while subjects performed tool-use relevant analogies not presented in, and hence not potentially confounded by, language. Activity patterns generated while subjects performed analogies presented in language involving tool use, tools but no tool-use motions, bodily motions but no tools and neither motions nor tools would be suitable comparisons. Testing these latter conditions separately would provide a more sensitive analysis than that of Green et al. (2006), who employed some analogy problems involving descriptions of physical motions.

Consequences of the event-file manipulation model: functional dependence of motion concepts on structure mapping

The functional model outlined above and illustrated in Fig. 1 describes tool improvisation as structure mapping at three levels. First, the objects in the task environment are mapped to objects in the retrieved action instance using motion and goals or results as structuring relations. Second, tools in the retrieved action instance are mapped to tools in the embedded action by using a force measure as the structuring relation. Finally, the observed result of executing a successful fully mapped action plan is related, in practice, to the result of the original retrieved action instance by the functional composition of the two previous structure mappings. Thus, the criterion of systematicity that characterizes good analogies (Gentner, 2005; Holyoak, 2005) can be rigorously defined in the case of tool improvisation as coherent scaling of both the kinematic and dynamic requirements between source and target cases. An "analogy" in which the forces applied cannot produce the motion required to achieve the goal is not a good analogy; applying too much force—swatting a fly with an axe—generally produces bad results as well.

If this model of tool improvisation is correct, two prominent claims regarding analogical inference require revision. First, the claim that structure-mapping analogy is a uniquely human capability, which has been based on the poor performance of animals on abstract and conceptual analogy tasks (Gentner, 2003; Penn et al., 2008) must be rejected in the case of tool-improvisation analogies, which members of many non-human species perform with facility in the wild. Second, the claim that structure-mapping analogy is dependent on relational language (Gentner, 2003) or on explicit access to relational concepts in a language of thought (Penn et al., 2008) must also be rejected in the case of tool-improvisation analogies, both for animals lacking such language, and for humans who may implement such analogies using language-independent, event-file-based

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binding and action-planning mechanisms. Indeed, the model predicts exactly the reverse functional dependency: that a natural class of motion and force concepts expressible in language are functionally dependent on the structure-mapping capabilities of the event-file manipulation and action-planning systems.

The neurocognitive representation of abstract concepts, such as “tool”, “motion” or “force” is not well understood (Martin, 2007). However, humans can clearly focus sufficient attention on the representations of such concepts, in the absence of relevant perceptual input, to activate overt behaviors including speech. Alert attentional focus on internal representations in the absence of perceptual input is managed by an area of medial rostral prefrontal cortex proximal to areas implementing the self-other distinction and hence the capacity for autonoetic episodic memory (Simons, Henson, Gilbert, & Fletcher, 2008; Turner, Simons, Gilbert, Frith, & Burgess, 2008); the apparent human-specificity of both experienced abstract conceptual understanding (Penn et al., 2008) and experienced autonoetic memory (Suddendorf & Coraballis, 2007) may result from the evolutionarily recent elaboration of this region of cortex (Burgess et al., 2007). Not all possible abstractions of motions and forces, however, are expressed by abstract concepts in natural languages: most such abstractions are expressible only in the artificial, technical languages of analytical mathematics and physics. The unconscious execution of structure-mapping inferences by the binding and premotor systems provides a mechanism by which some particular motion and force abstractions, those activated in tool use and in recognizing the utility of objects as tools, would be sufficiently selectively reinforced by everyday life to make them available for attentional amplification even in the absence of relevant perceptual input. An expectation of the model outlined here is, therefore, that the force and motion concepts expressible in natural languages, and hence those employed in “folk physics,” will be those that would be activated in unconscious structure mappings involving tool use.

It is well known that children naturally develop (Karmaloff-Smith, 1995) and adults routinely employ (Gentner, 2002) a “folk physics” with essentially Aristotelian concepts of force and motion. These concepts include the notion that motion continues only as long as force is applied and the notion that the shapes of curvilinear trajectories are preserved by “curvilinear momentum”. These concepts conflict with classical Newtonian mechanics, but are easily understood from the perspective of tool manipulation. Using tools requires applying force, force that is felt as feedback from the muscles. Hence, tool use would tend to reinforce the Aristotelian and folk-physics notion that continuing motion requires continuing application of force. Hand-held tools that move in curvilinear trajectories do so because they are swung by arms moving forcefully on fixed pivots, the shoulders. Hence, forceful curvilinear motions with tools would tend to reinforce the notion of curvilinear momentum, and as well as the intuitive notion of centrifugal force. Such felt muscular forces and typical resulting trajectories and force-application capabilities are the relations that drive tool-improvisation structure mappings of the kind illustrated in Fig. 1. The folk physics concepts of continuing force for continuing motion, curvilinear momentum and centrifugal force are, therefore, the very concepts that would be expected if the human paradigms of physical motions are tool-use motions and the paradigms of forces are the muscular forces employed to assess whether an object is suitable as a tool, and then to use it as such. These folk physics concepts of motion and force are routinely employed to solve practical problems in contexts in which subjects cannot later fully enunciate either a complete and correct description of the task environment or of the rules being employed, suggesting that problem solving is being performed by visuo-motor simulation, not explicit conceptual reasoning (Hegarty, 2004; Wolff, 2007), consistent with a functional dependence of the concepts as consciously understood and expressed in language on underlying pre-motor capabilities. Children identify situations in which hidden mechanisms cause unexpected behavior unattributable to animate agency at around 4 years of age (Sobel, Yoachim, Gopnik, Meltzoff, & Blumenthal, 2007), well before they possess a conceptual understanding of mechanical systems, suggesting that they are capable of an implicit analysis of motions and implied forces. Activation of the praxis system in qualitative numerosity judgments (Cantlon, Brannon, Carter, & Pelphrey, 2006) and in algebraic equation-solving (Qin et al., 2004) provides additional suggestive evidence for the involvement of motor simulation in what on the surface appears to be purely conceptual problem solving.

Even in formalized, mathematical physics, analogies and metaphorical representations that directly conflict with established theory and hence with conceptual understanding are routinely relied upon and employed both practically and pedagogically. Perhaps, the best-known example is the Rutherford atom analogy electrons:nucleus::planets:sun, which was employed by Green et al. (2006) as a canonical test case for analogical reasoning. Ernest Rutherford’s (1911) model of the atom as consisting of a small, heavy central nucleus orbited by much lighter electrons was proposed to account for the results of experiments in which gold atoms were bombarded by high-energy alpha particles. Most of the alpha particles passed straight through the gold foil target, but others were deflected backwards, suggesting collisions with a small heavy object and thoroughly contradicting the then-dominant Thompson or “plum pudding” model of atoms as spheres containing a uniform mixture of positively charged material and electrons (Rutherford, 1911 and Randall, 2005 briefly review the relevant history from a physicist's perspective; Mehra and Rechenberg (1982) provide a more detailed historical review). Rutherford's model was revolutionary in that it proposed an atom consisting mostly of empty space, in which the positive charges were concentrated in the center and the negative charges (the electrons) occupied the distant periphery. However, while the Thompson model with its statically embedded electrons was consistent with classical electrodynamics, the Rutherford orbital model directly contradicted existing theory: classical electrons moving in the electric field of the positively charged nucleus would radiate away their kinetic energy in much less than a second, and the Rutherford atom would explosively collapse. This tension was resolved by Bohr's (1913) proposal of quantized electron orbits, but at the price of altogether removing the classical concept of motion from the physical description of events at atomic scales.

The staying power of the Rutherford atom with orbiting electrons, an image so ubiquitous as to be iconic, is prima facie evidence that experienced motions and forces are central to the understanding of even such abstract concepts as atoms. The popularity of Feynman diagrams as illustrations of elementary particle interactions provides further such evidence. Physicists greatly prefer Feynman diagrams to the complex path integrals that they represent, employing them in professional publications and pedagogy; Randall (2005) is a case in point. Such diagrams are, however, grossly misleading if taken literally. They depict particles as having well-defined trajectories, and depict the "virtual" particles that carry forces in quantum field theory as being emitted and absorbed at well-defined locations along these trajectories. Both of these depictions are flatly inconsistent with quantum mechanics. As in the case of the Rutherford atom, depictions consistent with the motions and forces of everyday tool use and folk physics are maintained as cognitive aids, even when they are inconsistent with conceptual knowledge. Pedagogical research in physics indicates that such graphic aids and the manipulations that they invoke nonetheless significantly aid conceptual learning (Lasry & Aulls, 2007). The utility of manipulations in conceptual learning is corroborated by recent experiments in which activation of components of the praxis network is directly measured. Subjects briefly trained to manipulate novel objects as if they were tools later classify them as tools, as indicated by activation of tool-specific areas of left-hemisphere TPJ and pre-motor cortex (Martin, 2007; Weisberg, van Turennout, & Martin, 2007). Manipulating tools and other common objects facilitates verbal descriptions of their shapes in the absence of visual input, again accompanied by activation of tool-use relevant areas of TPJ (Oliver, Geiger, Lewandowski, & Thompson-Schill, 2009). In both of these cases, as apparently in the cases of atoms and elementary-particle interactions, learning and use of object concepts is facilitated by the kinds of manipulations that provide input to pre-motor structure-mapping inferences.

Additionally, albeit highly indirect evidence for the dependence of motion and force concepts on a small number of abstractions of experienced motions and forces is provided by the relative paucity of words for motions and mechanical forces in the vocabularies of natural languages. Natural languages typically include words naming high-level abstractions: "move" for physical motion, "push" and "pull" for mechanical force, "put" and "take" for manipulations involving force-transferring actions. However, precise specifications of motions, even of the human body, tend to be specialized technical names or descriptive phrases. Reproducibly and correctly identifying the referents of such specialized terms typically requires extensive specialized training and practice; they are not "natural" parts of human languages. Two of the oldest such specialized vocabularies available for study are those of yoga and chi-gung. Both vocabularies employ richly descriptive metaphorical language to name precisely specified motions and postures, i.e., particular proprioceptive images. Both require extensive physical training and practice to correctly identify the referents of the these terms; specialized phrases such as "chaturanga" (a motion) or "downward dog" (a posture) name concepts that are learned by learning to recognize particular dynamic or static proprioceptive images. Posture names are far more common than motion names in the vocabularies of yoga and chi-gung, as they are in natural languages. Why are there not ubiquitous, natural concepts and hence names for many if not most of the motions available to the human body, including those practiced in ancient disciplines, such as yoga and chi-gung? Perhaps, because these motions and the forces felt while performing them do not play common roles in pre-motor structure mappings, and hence are not sufficiently reinforced to be available to the internally directed attention required for conceptualization.

Testing the proposed model of tool-improvisation structure-mapping inferences

The event-file manipulation model of structure-mapping inference in tool improvisation proposed here generates a number of experimentally testable predictions in addition to the predicted praxis-network activations discussed above. Additional evidence relevant to any of these would serve to confirm or disconfirm the model as presented.

A primary prediction of the model is dissociability of conceptual comprehension of tool-improvisation analogies from their implementation. Patients exhibiting motor-imagery apraxias that spare semantic memory would be expected to be capable of comprehending verbal explanations of tool-improvisation analogies, but not of executing such analogies if they are presented in modalities other than language. Functional dissociation of tool-use abilities from conceptual knowledge of tools and their uses in human apraxias (reviewed by Johnson-Frey, 2004; Petreska, Adriani, Blanke, & Billard, 2007) provides support for this prediction. Conversely, patients exhibiting aphasias disrupting semantic memory for tools and tool uses, but not apraxia, would be expected to be incapable of understanding verbal descriptions of tool-improvisation analogies, but capable of executing them if presented graphically or with actual candidate tools. The practical intelligence displayed by Susan Schaller's language-less subject Ildefonso, who appears to have lacked conscious conceptual knowledge (Schaller, 1995), is consistent with this prediction.

The event-file manipulation model of structure mapping also predicts that cognitively normal subjects would complete tool-improvisation analogy tasks more rapidly and if time-limited, more accurately if the analogy problems were presented graphically, visually or tactilely as compared to verbally. It predicts that chimpanzees and possibly orangutans may exhibit higher-than-expected analogical ability if presented with tasks requiring the analogical transfer of causal knowledge from one context to another, as compared with the symbolic analogy tasks reviewed by Gentner (2003). The performance of young chimpanzees, which used the same tools and methods to extract a food reward from an opaque box as they had used to extract a similar reward from a similar transparent box (Horner & Whiten, 2005) is consistent with this prediction.

The mechanism of action embedding postulated by the model predicts that RPFC activation in tool-improvisation tasks will scale with the number of independent motions, and hence the number of independent embedded actions, required to complete the task. It similarly predicts enhanced RPFC activation in analogy tasks in which multiple embeddable actions conflict, compared to tasks in which action-embedding conflict is minimal.

The model would also predict that individuals scoring in the low range on tests of systemizing bias (Baron-Cohen, 2002; Baron-Cohen et al., 2003) will exhibit worse performance on tool-improvisation analogies than individuals with matched total or verbal IQ, but with higher systemizing bias. This prediction is consistent with general observations of correlations between sex, gender orientation, systemizing bias and mechanical skills (Goldenfeld, Baron-Cohen, & Wheelwright, 2006; Nettle, 2007; Baron-Cohen, 2008).

Finally, the considerations outlined in the previous section suggest that the above predictions may extend to other or even all analogies involving motion and mechanical forces as organizing relations, whether or not they involve tool improvisation.

Conclusions

Structure-mapping analogy is a fundamental inferential and learning mechanism. It has been regarded as concept-dependent and human-specific (Gentner, 2003; Penn et al., 2008). The model developed here is based on the hypothesis that structure-mapping analogies in tool improvisation are implemented by manipulations of event files (Hommel, 2004) and do not require awareness or understanding of relational concepts expressible in language. Considerable observational and experimental evidences support this event-file manipulation model, suggesting that tool-improvisation analogies are neither concept-dependent nor human-specific. This result renders human analogical capabilities continuous with those of other species, and provides an evolutionary path from higher-primate tool-improvisation capability through proto-human tool-improvisation capability to modern-human tool-improvisation and possibly more general motion-and-force-involving analogy capabilities. It moreover suggests that at least some concepts common to natural languages, those referring to experienced motions and forces, are functionally dependent on structure-mapping capabilities of the event-file binding and pre-motor planning systems. If correct, this functional dependence provides a mechanistic basis for proposals, such as that of Gallese and Lakoff (2005): visuo-motor simulation underlies language abilities, and raises the possibility that the human ability to focus attention on internally generated representations (Burgess et al., 2007), not a human-specific inferential capacity, is primarily responsible for the impressive analogical abilities of *Homo sapiens*.

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