What makes us so smart?
The role of symbol systems on the development of analogical reasoning in children and apes

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Abstract
Analogical reasoning is regarded as a core competence of the human species. After a short definition and classification of the concept, the present work examines its influence on human superiority and discusses several theories on the development of analogical reasoning and their empirical validation. It is argued that symbol systems, especially language, play a crucial role in the promotion of analogical reasoning and that therefore reciprocal effects between analogical reasoning and the use of symbol systems are a central determinant of human superiority. Empirical findings regarding analogical reasoning in children and apes that support this statement are presented. Furthermore it is discussed which methodological problems the investigation of analogical reasoning both using apes and children as subjects faces and which approaches have been found to solve these problems. Finally a short outlook on an intervention program that claims it can foster analogical reasoning is given.
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Introduction: Why are we so smart?

Analogical reasoning is known to be a central factor of human intelligence and learning. In order to explain why analogical reasoning makes humans so adaptive towards environmental changes, why it is an important driver of human development, and why it can be difficult to find the right methods to assess analogical thinking, one should first know what exactly “analogical reasoning” is respectively what an “analogy” is. An early but nevertheless established and influential theoretical framework on analogy is the structure-mapping theory (Gentner, 1983): This approach assumes that knowledge is represented in prepositional networks of nodes and predicates. In this model, the nodes represent holistic concepts, whereas the predicates are seen as propositions about the concepts (see fig. 1 for a simple instance).

The theory distinguishes between two types of predicates: Object attributes and relationships. Object attributes are predicates which have only one argument, e.g. SMALL (x), whereas relationships take at least two arguments, e.g. PREDATOR (x, y). Relationships in turn can also be differentiated into two types: First-order relations take objects as arguments, like PREDATOR (x, y). In contrast, second-order relations take other relations as arguments, e.g. CAUSE (HUNGRY (x), HUNTS (x, y)).

Based on these assumptions the theory describes different types of domain comparisons (see tab. 1). All of these domain comparisons share in common that existing knowledge from a base domain is mapped to a target domain, which has to be described or explained. The structure-mapping theory now states that a domain comparison is an analogy if only relations are mapped from the base domain to the target domain and no or at least few object attributes are mapped, i.e. an analogy does not consist in the comparison of superficial features but in the comparison of relational structures. According to the theory an abstraction is a special kind of analogy where the base domain is an abstract relational structure with generalized entities as nodes and a reduced number of predicates so that each predicate of the base domain can be mapped to the target domain.

Figure 1. Simple instance of a prepositional network. Red circles symbolize objects, yellow circles object attributes, and green circles relations.
Table 1. Different kinds of domain comparisons

<table>
<thead>
<tr>
<th></th>
<th>Number of objects mapped to target</th>
<th>Number of relations mapped to target</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Literal similarity</td>
<td>Many</td>
<td>Many</td>
<td>The K5 solar system is like our solar system.</td>
</tr>
<tr>
<td>Featural match</td>
<td>Many</td>
<td>Few</td>
<td>A sunflower is like the sun.</td>
</tr>
<tr>
<td>Analogy</td>
<td>Few</td>
<td>Many</td>
<td>An atom is like the solar system.</td>
</tr>
<tr>
<td>Anomaly</td>
<td>Few</td>
<td>Few</td>
<td>Coffee is like the solar system.</td>
</tr>
</tbody>
</table>

Another central assumption of the structure-mapping theory is the systematicity principle, which states that predicates of the base domain belonging to a system of interconnected relations are more likely to be transferred to the target domain than an isolated predicate. This can easily be illustrated using the often cited analogy “An atom is like a solar system.”: The complex predicate system CAUSE (CAUSE (HEAVIER THAN (sun, planets), ATTRACTS (sun, planets)), REVOLVE AROUND (planets, sun)) is crucial for the analogy while the isolated predicate YELLOW (sun) is negligible. As causal relations usually are embedded within complex predicate systems, the systematicity principle especially promotes predicates that are part of a causal chain. This is especially important because one paradigm to assess analogical thinking, problem solving, is based almost exclusively on causal relational structures, as will be discussed later.

Hence, the term “analogical reasoning” refers to the cognitive ability or the cognitive process to recognize, derive, and create analogies in order to solve problems of different kinds and in different contexts.

The concept of analogical reasoning is of great interest for different research disciplines as it is a central cognitive ability – if not the one cognitive ability – that is characteristic for human species. It enables humans to adapt to rapidly changing environments and thus made the human species to one of the most successful and fastest growing species of the planet – simply spoken – analogical reasoning is what makes us so smart. In a review article named “Why we’re so smart” Gentner (2003) discusses different theories on the nature of human supremacy. She states that there are three different possible explanations for human adaptability and creativity: The first one is a qualitative advantage in innate domain knowledge, the second is a larger processing capacity combined with more effective learning mechanisms, and the third possible explanation is that human language and culture allows us
to increase the limits of our cognitive potential. Gentner contradicts the first explanation approach and claims that humans have, if anything, less innate domain knowledge. Whereas other species are perfectly prepared to live in a certain environment to hunt certain preys and to avoid potential predators, humans do not have that innate preparation. They first have to learn how to live in a given environment, which food can be eaten, and which animals are dangerous. According to Gentner, this unbiased initial state makes humans flexible enough to learn to cope with different environments. Gentner instead proposes a combination of the second and the third possible explanations: The ability to learn by analogy as a powerful learning mechanism and the use of complex symbol systems like language and mathematics are what makes humans so smart. Furthermore these two factors amplify each other because relational language advances the development of analogical reasoning.

The relevance of analogical reasoning as a research subject is given by its importance for human development both in ontogenesis and in phylogenesis: In individual development, analogical reasoning can be regarded as the key to conceptual learning (Gentner, 2003) allowing children to master new problems or to acquire new knowledge based on the structural similarity to problems already solved or knowledge already acquired. In a review article Goswami (2001) states that analogies play a crucial role in the development of knowledge in the so called foundational domains, i.e. naïve psychology, physics, and biology, from early childhood on. Regarding the evolution of human species, analogical reasoning can be seen as a central driver of cultural, technological, and scientific progress: From the invention of simple cutting tools for flesh and fur based on the structural similarity to animal teeth cutting flesh and fur to the highly sophisticated statement that an atom is like a solar system, many achievements of the human species are more or less based on problem-solving by analogical reasoning.

Thus, it is not surprising that analogical reasoning is a good correlate of general intelligence (Goswami, 1991) and subtests measuring this ability, e.g. Raven’s progressive matrices, are part of most modern intelligence tests. Therefore deficits in analogical reasoning on the one hand could cause developmental retardations in children as this learning mechanism influences the acquisition of a broad variety of competences. Hence, the development of diagnostic tools to detect deficits in analogical reasoning and intervention programs to promote analogical reasoning is an important task for developmental psychology. On the other hand, analogical reasoning can lead to extraordinary achievements so that e.g. technological innovation could be controllable if it was possible to evoke spontaneous analogical reasoning.
State of research: Approaches to the development of analogical reasoning

Historical approach: Piaget’s structural competence theory

An early and very influential theory on the development of analogical reasoning was the structural competence theory of Jean Piaget (Goswami, 1991, 2001): Piaget stated that the development of analogical reasoning is based on the development of the overall cognitive structure and that reasoning by analogy is a typical example of a highly sophisticated skill which emerges not until the formal operative stage is reached in early adulthood. Piaget distinguished between lower-order and higher-order relations. In Piaget’s terminology, lower-order relations are relations between objects while higher-order relations are relations between relations, thus corresponding to Gentner’s first-order relations and higher-order relations. But while higher-order relations correspond to true relational similarity in modern approaches, Piaget’s concept of lower-order relations cannot be differentiated from what is called associative similarity or superficial similarity in modern approaches. This can be illustrated by the task used by Piaget: He used a picture based variation of the classical item analogy task – an item analogy task refers to a task of the scheme a:b::c:? (Goswami, 2001). In the first step, children were asked to group the pictures into pairs that go together (e.g. dog – fur). Thus, Piaget wanted to check whether the children were able to correctly relate the a and b terms as well as the c and d terms. Then the children had to organize the pairs to groups of four pictures that go together to check if children were able to abstract the relational structure and find pairs that share the same relational structure (e.g. dog:fur::bird:feathers). In the first stage, the preoperational stage (in the sensorimotor stage children are not able at all to solve classical item analogy tasks due to a lack of speech comprehension and production), children’s responses were very idiosyncratic and variable. Piaget distinguished between stage Ia, in which children were not able to form any kind of relation at all, whereas in stage Ib, children were able to form lower-order relations but failed to form higher-order relations. In the second stage, the concrete operational stage, children were able to construct higher-order relations but failed to resist false counter-suggestions (stage IIa) or at least could not do so consistently (stage IIb). In the third stage, the formal operational stage, children were fully able to construct analogies and able to understand that analogies can be expressed in mathematical functions. Though Piaget built the fundament of the investigation on the development of analogical reasoning with his work, there are at least two shortcomings regarding his theory: First, the inability of children to resist false counter-suggestions in stage two does probably not originate from a deficit in analogical thinking but from a general
suggestibility of children towards adult experimenters. Second, Piaget did not properly control or check whether the children had the necessary knowledge about the crucial lower-order relations because the first step of his experiments, the grouping of single pictures into pairs of two, could also have been based on pure associative similarity. And indeed, in some cases already children of the age of five years (i.e. in the preoperational stage) were able to deduct the correct relational structure like “steering mechanism”, which contradicts the statement of a general inability to draw analogies in that stage. In other studies children already were able at the age of three years to reason by analogy if the children had knowledge about the critical relations (Goswami, 1991).

Knowledge based theories
The observation that already very young children are able to perform analogical reasoning, if they have the knowledge to understand the necessary relations, led to the emergence of two knowledge based approaches: The relational primacy view and the relational shift hypothesis. Though some authors consider these approaches to be independent (Richland, Morrison, & Holyoak, 2004), they at least share in common the claim that knowledge is the developmental driver of analogical reasoning (Ratterman & Gentner, 1998).

In her relational familiarity hypothesis Goswami (2001) states that children’s performance in analogical reasoning depends on their knowledge about the required relations. Goswami (2001) extended this statement to the relational primacy hypothesis, in which she claims that children are able to establish prototypes via categorization from early childhood on and that therefore relational processing is available from early childhood on. And indeed there is empirical support for this hypothesis: For instance, already infants of 13 months, whom Piaget considered to be in the sensomotor stage, which is characterized by an egocentric and purely perceptual view of the environment, are able to succeed in a problem solving task consisting of several steps to be taken to get an attractive toy out of reach if the children had seen their parents solving a structural similar problem before. There is even empirical support for the hypothesis that the ability to reason by analogy is innate: Experiments using the habituation-dishabituation paradigm with infants of seven and eight months showed that infants were able to discriminate between the relational structures of acoustic material consisting of different syllable patterns (Gentner, 2003).

The relational shift hypothesis (Ratterman & Gentner, 1998) agrees with the relational primacy hypothesis regarding its central proposition: Children from very early age on are able to learn by analogy if the domain knowledge of the base domain is available and limitations in
analogical reasoning are caused by a lack of knowledge about the crucial relations. Thus, it states that the mechanism underlying this development is not maturational but rather epistemological.

However, both hypotheses contradict each other regarding certain errors that are made by children when confronted with classical analogy item tasks: The relational shift hypothesis claims that children first turn their attention to common object properties, i.e. they try to establish superficial similarity, and then to common relational structure. The early concentration on object properties is considered to be a necessary developmental step for the emergence of true analogical reasoning by common relational structure. The career of similarity hypothesis, an expansion of the relational shift hypothesis, characterizes the usual and necessary development as three successive steps: From holistic (overall) similarity to object similarity, e.g. a round, red apple and a round, red ball, and finally to relational similarity, e.g. sun MELTS snow CAUSES snow CHANGE TO puddle and flame MELTS candle CAUSES candle CHANGE TO mound. In contrast, the relational primacy hypothesis does not consider object similarity to be a crucial step in the development of true analogical reasoning; in fact it regards object similarity as a performance factor that can impede children’s ability to perform on the basis of relational similarity. Thus, both hypotheses make different predictions about the errors children make during their development solving classical analogy item tasks: The relational shift hypotheses predicts that children should predominantly make errors based on featural similarity (so called “mere-appearance matches”), whereas the relational primacy hypothesis predicts that children should make no mistakes once the critical knowledge is available and otherwise make a variety of errors, which follow no systematic principle.

Empirical studies rather support the relational shift hypothesis than the relational primacy hypothesis: Richland, Morrison, and Holyoak (2004) e.g. stated that children are able to attend to and map relations by the age of three to four but that they nevertheless make disproportionately many errors based on featural similarity even if the children know about the critical relations. Furthermore Ratterman and Gentner (1998) showed that earlier empirical support for the relational primacy hypothesis arose from confounding distractors regarding their featural similarity.

**Approaches based on information processing**

Information processing approaches to analogical reasoning concentrate on superordinate cognitive systems and processes and their influence on analogical reasoning. Two approaches
are discussed in the present work: Sternberg’s componential theory of analogical reasoning and Halford’s relational complexity theory.

The rather descriptive componential theory of Sternberg claims that six different processes are involved in analogical reasoning (Goswami, 1991): First, the terms of the analogy have to be encoded. Second, the relation between a and b has to be inferred. Third, the relation between the a and the c term has to be mapped. A relation analogous to that then has to be applied to the b term to produce the d term. The goodness of match of this d term then has to be justified. At last a response has to be given.

Sternberg tried to test the use of different components by the age levels of eight, ten, and twelve years but few qualitative changes occurred except eight-year-olds not mapping the relation between a and c. However, the eight-year-olds made very few mistakes which led Sternberg to infer the association hypothesis claiming that younger children do not reason analogically but purely associative. Goswami (1991) contradicts the assumption mentioning empirical studies in which children of the age of four were able to reason by higher order relations and to resist the wrong associative distractors.

Another approach based on information processing is Halford’s relational complexity hypothesis (Ratterman & Gentner, 1998). He claims that limitations of children’s working memory affect their ability to represent and process multiple relations simultaneously. Richland et al. (2004) showed that children’s ability to reason analogically at higher levels of complexity, which means that multiple relations have to be processed at one time, increases with age and related enhancements in working memory.

The authors of this study also interpreted the findings that young children make many errors due to featural similarity in a information processing manner: According to the authors these errors do not only reflect an epistemological deficit but a maturational deficit in inhibitory control. Thus, children are not always able to resist the tendencies to choose the featural similar distractors.

**Summary of the empirical support for different approaches**

As mentioned above, Piaget’s general structural view on the development of analogies is disproven by many empirical findings showing that already very young children are able to reason analogically.

Theories which consider domain knowledge to be the central driver of analogical reasoning however seem more promising. Thus, three-year-old children have been shown to be able to solve classical item analogy tasks attending to and mapping relational structures if they had
knowledge about the crucial relations (Richland et al., 2004). Furthermore, empirical studies rather support the relational shift hypothesis, which suggests that despite knowledge about the critical relations children tend to make errors due to object similarity (Ratterman & Gentner, 1998). However, one limitation can be attested to knowledge based approaches: Especially in problem solving tasks with little surface similarity between the base and the target problem, most of the children did not reason by analogy spontaneously and had to be instructed to think about the base problem or had to receive other hints to solve the target problem. These observations however can be explained by deficits in knowledge about the own knowledge and strategies how to use the own knowledge, the so called meta-knowledge (Goswami, 1991).

Empirical studies also gave support to the hypothesis that limitations in children’s information processing cause their errors in analogy tasks. For example Halford’s theory of relational complexity, which states that limitations in working memory cause problems for children to represent and process multiple relations simultaneously, is supported by empirical studies (Richland et al., 2004).

Special focus: Analogy and symbol systems

As already mentioned, Gentner (2003) assumes that human superiority is due to the ability to acquire new knowledge by analogical reasoning, the use of complex symbol systems, and, what is especially important to the present work, a mutual interaction of both concepts. According to Gentner (2003) the most important symbol system for the development of analogical reasoning is language. She states that relational terms, i.e. propositions which have two or more arguments, have a large variety ranging from causal to numerical to logical relatedness, etc. These relational terms invite and preserve analogical patterns that were otherwise unremarkable. As relational concepts are not part of perceptual nature but are culturally and linguistically shaped, Gentner states, verbs and prepositions are learned later by children than concrete nouns. Furthermore children very often use actually relational nouns as object reference terms at first until they understand the relational meaning of these words. A good example of words used by children not understanding their relational characters are the words usually learned first: For infants the words “mommy” and “daddy” initially only refer to these two special persons. An understanding of the relational meaning CAUSE (GAVE BIRTH (x , y), MOMMY (x, y)) occurs considerably later. However, the difficulties of learning relational language are outweighed by its many benefits: First, naming a relational structure helps to extract it from its initial context thus making it more probable that the
relational structure is recognized in other contexts. Furthermore initially registering a relational term in a specific situation encourages children to store the situation so that it can be compared to later situations in which the relational term is also heard. In addition, relational terms can direct children’s attention to special aspects or relations of a situation. Moreover a relational term can reify an entire complex pattern and thus reducing its complexity so that superordinate assertions about it can be made. Therefore using relational terms can be cognitively and linguistically economic. Finally a habitual use of a given set of relational terms promotes uniform relational encoding thereby reducing the difficulty and increasing the probability of transfer between situations, which share the same relational structure (relational reminding). The latter aspect is especially important as the transfer of mapping relations from one domain to another is the crucial process of analogy but relational transfer is generally poor, even in adults.

Experimental evidence for the role of symbol systems on the development of analogical reasoning in children

The impact of relational terms on analogical transfer in children was assessed in several studies (Gentner, 2003). In one study the impact of relational language on analogical transfer in the context of relative size and position was assessed. Children of three, four, and five years were presented two triads of objects, one in front of the experimenter and one in front of themselves, both in monotonically increasing order regarding size. The experimenter then put a sticker under one of the objects of his triad and asked the child to find another sticker by looking for it under the object in the same place of the own triad. When both triads were literally similar, children succeeded in this task, but when featural and relational information were inconsistent (so called cross-mapped patterns), children of three and four years performed very poorly. Especially when the objects were very complex, the children performed only at chance level. So the children of the experimental group took part in a training, in which they learned to use the labels “daddy”, “mommy”, and “baby” for the objects in the triad – these labels are known to be used by children of that age spontaneously to indicate monotonic differences in size. After the training even three-year-old children performed at the level of five-year-old children solving 89% (simple objects) and 79% (complex objects) of the items via analogical transfer. Unfortunately, in this study relative height and relative position of the objects confounded so that it is not clear whether correct responses of children in the control group based upon size relations or upon positional relations.
In another study the effects of spatial terms like “on”, “in”, “under”, “top”, “middle”, and “bottom” were assessed. Children were presented two boxes with a shelf in the middle so that each box had three positions in which three cards were put. The experimenter then put a card in his hiding box and the child was asked to find the corresponding card in his finding box. In the experimental group the experimenter used relational language like “I’m putting it on the box.”, whereas in the control group the experimenter just said “I’m putting it here.” It was shown that children of 3;6 years significantly benefited from the use of relational language (the performance of the control group was just above chance), whereas children of 4;0 years and older did not need the use of relational language to solve the task probably because they already had internalized the relational system. However, when the difficulty of the task was increased by using cross mapped objects, (i.e. the featural structure of the objects is inconsistent to the relational structure) even 5;2 year old children could benefit from the use of relational language.

In a recent study, Gentner, Angorro, and Klibanoff (2011) showed that the use of relational syntactic structure helped children to learn novel relational categories. In a first experiment three, four, five, and six-year-old children were first presented two pictures of objects, one served as an entity the other as an operator, to exemplify a novel relational structure (e.g. a knife and a watermelon to exemplify the structure CUTTER FOR). In the relational language group (the experimental group), relational syntactic support was given to the children, e.g. “The knife is the dax for the watermelon.”, whereas in the no label group (the control group) the experimenter did not use relational language, e.g. “The knife goes with the watermelon.”. In the test phase children then were presented another entity, for example a sheet of paper and were asked to choose the right operator from three alternatives, the correct relational match (scissors), a thematic associate (pencil), and an object match (pieces of paper). In the relational language group children then were asked “Which one of these is the dax for the paper?” and in the no label condition “Which one of these goes with the paper in the same way?” The results showed that four to five-year-old children only learned the relational structure when it was labeled with a relational term, whereas the three-year-old children could not learn the relational structure at all and the six-year-old children also were able to infer the relational structure without support by relational terms. To ensure that children did not just learn an abstract superordinate category based on object similarities like reptiles or vegetables or in the case mentioned above “dax” as a superordinate category for sharp objects a second experiment with a third control group was conducted with four and five-year-old children. In this label superordinate condition children just were shown the operator object (e.g. the knife).
and told “Do you know what this is? This is a knife. This knife is a dax.”, and afterwards in the test phase they were asked “Which one of these is also a dax?”. Furthermore a novel distractor was used which showed an object that matched the operator card very closely at a perceptual level (similar color and similar shape). The results of this second experiment showed that children of the superordinate label group were less likely to choose the correct relational match and more likely to choose the perceptual match than children of the relational language group. Therefore the children of the relational language group must have learned true relational categories and not just abstract superordinate categories.

In a third experiment the authors investigated whether relational language in combination with comparison processes enables also three-year-old children to learn relational categories. Therefore the authors repeated experiment one with one crucial change in the learning phase. Instead of just one operator-entity pair, the children were shown two pairs, e.g. a melon and a knife and a tree and an axe, which were commented by the experimenter either using relational language or using non-relational language. The results of the third experiment showed that either relational language or comparison processes are sufficient for four to five-year-olds to infer relational categories but that even both of them are not sufficient to enable three-year-olds to infer those categories.

As the inability of three-year-old children to form relational categories under these circumstances can be explained by a lack of domain knowledge, which impedes a sufficiently firm encoding of the domain relations to be able to map the common relational structure, the authors further investigated whether progressive alignment in combination with relational language enables children of three years to map the relational structure. In order to activate progressive alignment, the authors presented four entity-operator pairs in the learning phase of a fourth variant of the experiment: Two close pairs, which do not only share relational similarity but also object similarity (e.g. knife one – watermelon, knife two – orange) and two far pairs, which only share relational similarity (e.g. tree – axe, piece of wood – saw). Three-year-old children then were again assigned to a relational language group and a no label group. The results of this experiment showed that the combination of relational language and progressive alignment even enables three-year-old children to form relational categories.

Experimental evidence for the role of symbol systems on the development of analogical reasoning in apes

But as Gentner (2003) states, there is especially one limitation to the investigation of symbol systems’ influence on analogical reasoning: There normally are no humans who do not use at
least one symbol system: Language. So, in order to really control the use of symbol systems, there is only an indirect approach: Non-human primates who have been taught symbol systems can be compared to conspecifics that have not.

Boysen, Bernston, Hannan, and Cacioppo (1996) for example made an astonishing observation with common chimpanzees (Pan troglodytes), who had been taught the Arabic numerical system at least from zero to six. In this study the chimpanzees were presented two plates. They contained either two different amounts of candies, two different amounts of rocks or two different Arabic numbers. The chimpanzees then pointed to one of the plates and received the other plate. Thus, the best strategy was to point to the plate containing the smaller amount. When the plates contained candies, the chimpanzees consistently (in 70% of all cases) failed to point to the smaller amount of candies. The performance rate was even lower the more conspicuous the difference between the two amounts was (i.e. the larger the term “difference between both amounts / sum of both amounts” was. The authors argued that the highly incentive character of the candies might have hindered the chimpanzees to inhibit the first impulse and thus make the more favorable choice. But the same pattern of results also occurred when rocks were used instead of candies and the chimpanzees received the amount of candies that corresponded to the amount of rocks on the plate not chosen. Hence, the inability of making the more favorable choice cannot completely be attributed to the highly incentive character of candies. The authors discuss that the rocks might have gained incentive value by stimulus generalization. However, when Arabic numbers were used instead of concrete objects, the chimpanzees were able to consistently choose the smaller number to get the higher amount of candies. Furthermore the results with numbers differed qualitatively from the results with rocks and candies in a second way: The relation between the conspicuity of the difference and the performance was reasonably weaker in trials with numbers than in trials with rocks and candies. This result suggests that the apes indeed were able to understand the implicit rule structure but that only the use of a symbol system enabled them to map it to different problems of that kind.

Chimpanzees generally seem to be predisposed for analogical reasoning. Thus, infant chimpanzees dishabituate to a pair of nonidentical objects when they have been habituated to pairs of identical objects before and vice versa, whereas infant macaques do not show this ability (Gentner, 2003).

Oden, Thompson, and Premack (2001) found surprising results testing the ability of a chimpanzee called Sarah to complete and construct analogies based on geometrical forms. The authors state that simple same / different tokens as a substitute for relational language
enable the chimpanzee to express its otherwise implicit conceptual knowledge about relational structures. They further explicate that the facilitating effects of an external symbol system provide apes with the necessary representational scaffolding that is necessary to solve problems involving the comparison of relational structures.

**Practical part: Methodological difficulties in assessing true analogical reasoning in children and apes**

The following chapter of the present work aims to point out some methodological weaknesses that the presented paradigms to assess analogical reasoning in children and apes show and how insights of one scientific discipline can be used in the other one. As Oden et al. (2001) claim when investigating such highly sophisticated skills like analogical reasoning one has to be aware not to make the psychologist’s fallacy. I.e. that outcome behavior that is compatible to the researchers’ predictions does not automatically mean that it is based on the underlying cognitive processes that are suggested by the researchers.

When methodological weaknesses of assessing analogical reasoning are discussed, one should keep in mind that there are two principle paradigms that can be used and that differ regarding some aspects: Classical item analogy tasks and problem solving tasks. A classical item analogy task is, as mentioned before, a task of the scheme a:b::c:? Normally, the d term is not given and has to be found. Therefore the relation between a and b has to be abstracted and established on the right side of the equation. This can only be achieved by forming a proper relation about the relations on the left and on the right side of the term. In problem solving tasks the analogy depends on the relational structure of a target problem to be solved and an already solved base problem. Thus, the analogy underlying problem solving tasks can be equated as problem$_a$:solution$_a$:problem$_b$:solution$_b$. An example would be Duncker’s radiation problem: The target problem is the task to irradiate a brain tumor without damaging healthy body tissue too much, whereas the base problem is to conquer a hostile fortress without sending heavy armies on mined approaching roads. The solution to both problems is to approach the aim by using weaker forces from different directions (Goswami, 2001; Oden et al., 2001).

The first difference between those two paradigms is that in classical item analogy tasks the instructions are rather concrete, whereas in problem solving tasks the solution to the problem is totally committed to the participants and they are supposed to recognize the relational similarity to a previous problem encountered before. The second difference is the kind of relations underlying the used analogies. Whereas in problem solving tasks the relations are
always causal, in classical item analogy tasks the relations are arbitrarily ranging from functional relations to class memberships to numerical relations, etc. (Goswami, 1991). Having demonstrated the principle differences between these two paradigms, they will be discussed separately regarding their application in research with children and apes.

Problem solving tasks

The study of Boysen et al. (1996) described above can be regarded as an example of problem solving tasks in research with apes. The chimpanzees are supposed to solve a problem, pointing to the smaller amount of candies / rocks or to the lower number, based on their experiences with prior problems of that kind. Here can be argued that the base problem(s) and the target problem(s) can be seen as almost the same differing only in the amounts presented on the plates. And indeed these problems share very high surface similarity (at least within the same trial condition). Nevertheless, the chimpanzees’ performance in the condition with Arabic numbers as stimuli can be regarded as analogical reasoning in the first place, as the relational structure CAUSE (AND (LOWER THAN (x, y), CHOOSE (x), more candies)) has to be mapped to each new trial. Unfortunately, the authors do only describe very scarcely how the chimpanzees learned the numerical concepts and they do not describe how stable the chimpanzees’ representations of the numerical concepts were. Thus, it theoretically could also have happened that the chimpanzees simply attributed new meanings like “few candies” or “more candies” to these symbols that simply “overwrote” the former meanings.

Another limitation that can be stated concerning this study is that compared to humans the apes’ performance was very inconsistent. The performance of apes when they finally managed to solve the task was only 66% with a chance rate of 50%. In studies with human subjects one would expect rates differing more clearly from chance rate. This is probably due to qualitative differences in motivation and information processing between apes and humans. One possibility to avoid this limitation would be to present more choice alternatives to the apes but then the task demands might be too hard for the apes’ information processing abilities.

The objection of high surface similarity given in the study of Boysen et al. (1996) can also be made to many works investigating analogical reasoning in children. As mentioned above, children normally only show analogical transfer when high surface similarity is given, too (Goswami, 1991). Otherwise explicit instructions of thinking about the base problem have to be given or the analogical transfer cannot be made in most cases. But these limitations are actually not problematical as they are predicted at least by the relational shift hypothesis
stating that object similarity enhances children to reason analogically and that object similarity matching is a necessary step in developing analogical reasoning (Gentner, 2003; Ratterman & Gentner, 1998).

More detrimental to problem solving tasks in research with humans are the sometimes weak conceptualized control groups. In order to make clear that the solution to a problem is found by analogical reasoning and not by spontaneous realization of situational aspects, sometimes two groups are used. The experimental group receives a base problem and its solution whereas the control group does not receive a treatment at all (Goswami, 2001). This is problematical for two reasons: First, the poorer performance of the control group might also be due to less attention received by the children from the experimenter. Second, without having seen a base problem, instructions to the target problem sometimes do not make sense at all. For example instructions like “give the doll a ride” and “help the bird fly” (Goswami, 2001) are very vague and could even overcharge adults when they have not seen in a previous problem what these instructions mean.

**Classical item analogy tasks**

In their research with the chimpanzee Sarah, Oden et al. (2001) argue very cautious to avoid making the psychologist’s fallacy. Therefore they gave Sarah a variety of different tasks to assess different cognitive processes to solve them and carefully noticed Sarah’s errors to get propositions about the strategies she used.

Sarah’s and other chimpanzees’ ability to reason analogically first was recognized using a matching to sample task: A pair of identical or nonidentical objects served as sample and the choice alternatives consisted of two pairs of objects, one identical and the other nonidentical. Matching pairs consisting of same and different objects does not seem like a task that requires analogical reasoning but rather like a task that can be solved solely by perceptual matching. However, this task indeed requires analogical reasoning as in a first step the relations within the pairs have to be abstracted. After that the relations between those relations within the pairs have to be mapped to decide which choice alternative shares the same relation with the sample. Due to the fact that both steps require the same relation (identical or nonidentical) the task can be considered to be a very simple form of analogy but it nevertheless is analogy in principle. Sarah furthermore was reported to be able to solve analogies based on geometric forms and on functional relations. Critics however stated that Sarah’s performance in these tasks could also be due to associative matching. The handling of this critic by the authors however was exemplary as they tried to separate the processes and strategies adopted by
Sarah using different tasks and error analyses. So, in order to investigate the boundary conditions of Sarah’s analogical reasoning and to investigate whether Sarah was not only able to complete but also able to construct analogies, the researchers used four different tasks. All tasks were conducted using a blue cardboard which was separated into four quadrants by a white cross. Sarah’s token, which symbolized the concept "same", was placed at the intersection of the board’s arms. Sarah now had to solve analogical problems based on geometric forms. The following rules were used to select items for the analogies: a and b differed regarding a single dimension (size, color, shape, or fill). c and d also differed in this single dimension. a differed from c (and thus b differed from d) on two dimensions, both different from the feature distinguishing a and b. In the first task three geometric forms were put on three quadrants of the cardboard and Sarah had to choose from two alternatives which geometric form had to be put on the fourth quadrant to build a correct analogy. Hence, this task was a classical a:b::c:? task. In a second task only two geometric forms were put on the cardboard and the other half of the analogy had to be completed by first choosing two out of three alternatives and then putting them in the right order onto the quadrants. In task three and four, Sarah only received an empty cardboard with the same token in the middle and four (task three) or five (task four) geometric forms. Sarah then had to construct the whole analogy by herself by putting four forms in the right order onto the cardboard. In task three the featural similarity between the geometric forms was varied systematically: In half of the trials items were selected following the item construction rules described above whereas in the other half of the trials items were selected in a way that a and c (and thus b and d) only differed in one featural dimension so that featural similarity of the items was generally higher. Sarah’s performance was significantly above chance in all conditions ranging from 21% correct with a chance level of 7% in task five to a correct rate from 89% with a chance level of 50% in task one. Thus, Sarah was able to solve tasks which required the completion of an analogy as well as tasks which required the construction of an analogy. To ensure that Sarah did not solve the problems by producing maximal relational similarity on the board, i.e. minimizing the total amount of featural differences on the board, the authors analyzed the frequency of errors which probably would have occurred if Sarah had adopted this strategy. The analysis of the error patterns showed that Sarah did not just adopt an object matching strategy. Furthermore the authors checked whether Sarah adopted a simpler strategy than analogical reasoning in task four which included first sorting out one item and then constructing an analogy with the remaining four items. Sarah could also have managed the step of sorting out one item by sorting out the item with a feature not shared by any other item. Further
analyses of Sarah’s performance on task four indicated that this interpretation had to be accepted at first sight. But analyses of the temporal patterns in which Sarah placed the four items lend support to another interpretation of these results: Sarah did not construct analogies in the way the experimenters expected her to do but by equating the number of featural differences within the pairs of the analogy, independently of the physical nature of those differences. This strategy however can also be considered as analogical reasoning as it is based on an understanding of the relations between relations: EQUAL (NUMBER OF FEATURAL DIFFERENCES BETWEEN (a, b), NUMBER OF FEATURAL DIFFERENCES BETWEEN (c, d)). This strategy can even be regarded as more sophisticated than the strategy supposed by the authors as Sarah totally abstracted from the superficial features of the items and based her solution only on the abstract number of featural differences. Thus, Oden et al. (2001) demonstrated how important it can be to inquire the own interpretation of outcome behavior in the context of analogical reasoning.

How can now be assessed in research with children whether they reason analogically or whether they just compare object similarities? A good way to distinguish purely perceptual or associative answer strategies from analogical reasoning is to construct perceptual or associative choice alternatives. For example Gentner et al. (2011) used for the item “The knife is the dax for the watermelon. Which one of these is the dax for the paper?” a baseball bat which shared the same color and shape with the knife as a perceptual choice alternative and a pencil as an associative choice alternative (the correct answer were the scissors). How important it is to choose proper perceptual or so called mere appearance distractors shows the study by Rattermann and Gentner (1998). In this study the authors showed that the choice alternatives of a prior study of Goswami and Brown were not chosen properly as their mere appearance matches actually were less similar to the c term than other alternatives. Thus, the children could also solve some of the items by purely perceptual matching.

As in Sarah’s case, children’s principle ability to solve analogy tasks does not mean that they do it the way the experimenters expect. To get insights on the processes and strategies that are adopted by children one should always check which errors the children make disproportionally frequently and if necessary change the design of the items so that non analogical strategies lead to incorrect choices. Of course, in contrast to apes, one can always ask children how they found the solution but one also has to be aware of the fact that especially very young children are not always able to verbalize their strategies.

Summing up one can state that several methodological difficulties must be regarded in order to properly assess analogical reasoning in children and apes. However, both approaches have
found solutions to frequently discussed problems and both approaches can learn from each other’s insights.

Discussion: Recapitulation and outlook
The present work discussed that the ability to reason by analogy can be regarded as a core competence of the human species. Analogical reasoning is defined as mapping relations from a base domain to a target domain. It enables humans to acquire new knowledge based on existing knowledge and to solve problems based on experiences with prior problems of a similar relational structure. Thus, analogical reasoning makes humans that flexible and successful as a species.

Different approaches to the development of analogical reasoning in children were discussed. Empirically most supported are the relational shift hypothesis, an approach which states that domain knowledge is the central driver for the development of analogical reasoning and that featural similarity can enhance analogical reasoning (Gentner, 2003; Ratterman & Gentner, 1998) and the relational complexity theory, which states that developing capacities of the working memory are crucial to the development of analogical reasoning (Richland et al., 2004).

It was stated that symbol systems have an important promotional effect on the development of analogical reasoning. Empirical studies showing this effect in children and apes were described. Thus, Gentner’s (2003) view that the ability to reason by analogy, the use of symbol systems, and mutual interactions of analogical reasoning and symbol systems make humans so smart is supported by the present work.

Further some methodological difficulties of assessing analogical reasoning in children and apes were discussed. It could be shown that research with children and research with apes face some similar problems but that both approaches have found ways coping with them and that both approaches could benefit from the insights of the other.

An intervention to train analogical reasoning: The cognitive training for children
As the ability to reason by analogy has a crucial effect on the individual development of children, one might wonder if there are intervention programs to foster children’s ability to reason analogically. One training program that states it can promote reasoning abilities is the cognitive training for children (Klauer, 2001), available for children from five to eight years, for children from ten to thirteen years and for adolescents from fourteen to seventeen years with special educational needs. Klauer claims that his program can promote inductive
reasoning. Inductive reasoning means the detection of regularities and legalities that leads to more or less helpful hypotheses. Inductive reasoning is thought to crucially determine the general intelligence and analogies are assumed to be an aspect of inductive reasoning. The processes involved in inductive reasoning according to Klauer are the detection of equality and / or discrepancy between features or relations in materials of different kinds. I.e. that inductive reasoning consists of object matching and relational mapping according to Gentner’s (1983) terminology. Based on all combinations of the definition of inductive reasoning, Klauer describes six core variants of inductive reasoning. As can be seen in tab. 2, especially the last three of them correspond to analogical reasoning. The aim of the training is that the trainee establishes problem schemes for these six problems. Via repetitive experience with these problems the paradigms (the underlying structures) of these problems are supposed to get familiar and to be recognized by the trainee. Therefore many examples of the paradigms with different surface structures have to be encountered so that the paradigms can be abstracted from the surface structures.

<table>
<thead>
<tr>
<th>Name</th>
<th>Typical Items</th>
<th>Detection of …</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generalization</td>
<td>Constructing / completing classes, finding commonalities</td>
<td>Equality of features</td>
</tr>
<tr>
<td>Discrimination</td>
<td>Eliminating improper elements</td>
<td>Differences between features</td>
</tr>
<tr>
<td>Cross classification</td>
<td>Pivot tables</td>
<td>Equality of and differences between features</td>
</tr>
<tr>
<td>Comprehension of relationships</td>
<td>Completing sequences, simple analogies</td>
<td>Equality of relations</td>
</tr>
<tr>
<td>Differentiation of relationships</td>
<td>Disrupted sequences</td>
<td>Differences between relations</td>
</tr>
<tr>
<td>System construction</td>
<td>Matrices, complex analogies</td>
<td>Equality of and differences between relations</td>
</tr>
</tbody>
</table>

However, the training is discussed controversially (Hager & Hasselhorn, 1998). Whereas it is undisputed that the training is effective (the effect-size on outcome variables is $d=.5$ on average), it is contended why and by what the training is effective. Klauer himself states that the training is effective because the transfer of declarative knowledge about the problems
increases inductive reasoning in terms of the detection of regularities and legalities. His critics however claim that the tasks per se are the central procedural component of the training’s effectiveness and that the training’s effects are based on an increase in speed and accuracy of visual perception.

It is not the aim of the present work to discuss the empirical results regarding the cognitive training for children en detail but it can be concluded that the relevance of analogical reasoning is recognized so that trainings are developed that try to promote its development and prevent deficits in analogical reasoning and that these trainings are discussed and evaluated in terms of their effectiveness.
Reference List


