Abductive Reasoning by Children

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***Abstract*-Children can link facts and events into integrated beliefs. This ability of the mind to combine facts to form higher-order Gestalts is central to many cognitive activities, including problem solving, analogical reasoning, and creative thought. In fact, it is central to the abduction of meaning: the creation of a self-sustaining pattern of ordered facts that are combined in the larger Gestalt. Abduction has mostly escaped experimental investigation, possibly because it often emerges instantly and non-linearly, and is thus difficult to trace with traditional models of cognition. In the current paper, we take steps towards filling this gap, using ideas from nonlinear dynamics and complexity science. The assumption is that products of abductive reasoning can emerge from competing sources of constraint, namely constraints that favor local facts (and contradict a congruent Gestalt) versus constraints that favor the congruent Gestalt (and override contradictory local facts). The experiments reviewed in this paper exploit situations of such conflicting constraints. The goal is, first, to provide evidence of congruent-Gestalt constraints in young children, and second, to explore the interaction among competing constraints. The outcome is a qualitative evaluation of parameter dynamics, the dynamics of a control parameter of abductive reasoning.**

Keywords*-*Abduction; Reasoning; Nonlinear Dynamics; Constraints; Parameter Dynamics

I. INTRODUCTION

Charles Saunders Pierce coined the term abduction to refer to the essential capacity of a person to form innovative interpretations, to bring together otherwise separate empirical facts or events (cf. [2]). Abduction has been linked to mental phenomena such as insight and the discovery of facts as patterns in data, abstraction of hidden properties, diagnosis of causes of events, and the evaluation of competing explanations (e.g., for reviews see [19, 22,32]). Yet, the empirical study of abduction has focused largely on adult reasoning e.g., [10]), with little explicit investigation of abductive reasoning in children. This is surprising given that children early on can organize facts into coherent ideas (e.g., [7, 9, 13, 20, 38, 39]). For example, they can make causal inferences after only short demonstrations (e.g., see [6], for a review), and they can form beliefs about the behavior of objects in laboratory demonstrations [12, 17]. Even infants appear to abduct ideas about systematic patterns over time, ignoring features that do not fit within those patterns (cf. [1, 5]).

Perhaps these early attempts of children to create meaning are not sufficiently rational to fit the common definition of abduction. They might be based on associative processes with little explicit hypothesis generating on the part of a child (cf., [27]). We nevertheless should not rule them out as abductive reasoning, given that they lead to unified beliefs and causal explanations. In other words, it might not be necessary to tie abductive reasoning to explicit rationality (cf. [30]). Following Pierce's definition, we define abduction instead in terms of its product, not the hypothesized cognitive process that gives rise to abduction. Specifically, abduction is the emergence of a coherent organization among facts and events. Such emergence of coherence could happen instantaneously, analogous to a Gestalt phenomenon [33], or it could involve the piece-meal construction of relations one by one (cf. [3, 4]). And emergent coherence can involve different levels of abstraction, ranging from what we commonly think of perception to what is typically discussed under abstract thought, all the way to explicit comparisons of hypotheses. This necessarily broad view of abduction makes it possible to develop a description of abductive performance without first assuming a particular cognitive process. The hope is to better understand how young children organize separate facts and events into the larger wholes of coherent ideas.

To describe abductive reasoning, we borrow ideas from the framework of nonlinear dynamics and complexity science. This framework has been applied repeatedly to questions of children's development, including motor development (e.g., [34]), the A-not-B error (e.g., [29]), early language development (e.g., [35]), spatial reasoning (e.g., [25]), and problem solving [33]. The general idea is that a qualitative change in performance need not be singly caused, but instead results from changes among multiple sources of constraints favoring one or another performance outcome. We first illustrate what we mean by constraints and then review empirical findings with children to demonstrate how a constraint-based description can capture a large body of findings.

A. *Constraints and Control Parameters*

Our starting point is the assumption that multiple sources of constraint determine the degrees of freedom for behavior, constraints that can be summarized in control parameters. Applied to infant stepping behavior, for example, the sources of constraints pertain to gravity and the mass of an infant's legs on the one hand, and the muscle strength of the legs and the infant's willful control of the legs on the other hand. These constraints can be summarized in a ratio of competing forces to define an idealized control parameter of stepping behavior (cf., [18, 37]). In other words, a control parameter for stepping behavior is concisely summarized by the ratio of the weight of the baby's legs relative to the strength of the baby's legs. Despite being a simplification of the larger system in which control is realized, the data fit this conceptualization: Soon after being born, when the legs are still light, most infants can raise their legs in stepping behaviour (i.e., [lighter legs]/ [strong enough muscles] = [stepping behavior]). However, as the infant grows, the concomitant increases in leg mass may exceed the increase in the legs' muscle strength, eliminating stepping behaviour for a period of time (i.e,. [heavier legs]/ [not strong enough muscles] = [no stepping behavior]). Later, the increasingly stronger leg muscles reach a point wherein the strength of the legs surpasses their mass, allowing the child to step (i.e., [heavier legs]/ [strong enough muscles] = [stepping behavior]).

To understand abduction, we seek a similar ratio of constraints that we envision as a control parameter capturing the tradeoff among constraints that might bring about qualitative changes in a child's thought. As mentioned, abduction brings about congruent Gestalt-like organizations of facts and events. We take this definition to imply the existence of constraints that favor such global or macro-scales of organization and the first experiment corroborates that these constraints exist in young children. We then exploit circumstances in which constraints favoring congruent Gestalts indeed lead to congruent thought, although they do not exist in the facts at hand. We explore manipulations affecting the salience of local facts, which in turn affect children's creation of false Gestalts (i.e., Gestalts that compete with local facts).

Like stepping behavior, then, abduction may include a competition among mutually exclusive constraints — constraints on different levels of organization that cannot both be met at the same time. The following formula summarizes the tradeoff between such competing constraints as a ratio of a control parameter A:

$$A = \frac{\text{Constraints Sustaining Integrity of Local Facts}}{\text{Constraints toward Global Congruence among Facts}} \quad (1)$$

To make these ideas more concrete, consider a scenario in which the local elementary fact pertains to a person's attitude towards traveling. The person might like to travel, or not – neither attitude by itself inviting a higher-order Gestalt. Now add a second person to the scenario. This second person's attitude towards traveling might match with that of the first person (e.g., both individuals like travelling), or not (e.g., one person likes to travel, while the other person does not). Congruent attitudes arise in the first case, when both people feel the same towards traveling, but not in the second case, when only one of them likes to travel.

To take this scenario one step further, add the attitude of one person towards the other. The two individuals might like each other, or dislike each other. Each of the individual attitudes (i.e., towards each other and towards traveling) can be thought of as local facts. But when combined, an even higher-order congruency becomes possible, namely that of transitive congruence among three attitudes. This congruent Gestalt is present, for example, when the two people like each other and they both like traveling. It is also present when the two people like each other, and they both dislike traveling, or when the two people dislike each other, and they disagree about traveling. Figure 1 shows two congruent attitude examples in schematic form, as well as two incongruent examples, namely when the two people like each other, but have opposite attitudes towards traveling.

The scenario of attitudes illustrates several aspects of what is called a control hierarchy (cf. [36]). First, sources of constraint are nested hierarchically, from the most elementary to the most global. Individual attitudes are treated as local elements, nested within the pattern of two-relation match, nested in turn within the pattern of three-relation congruence. One can even imagine that an isolated attitude is a pattern of some sort, namely one that combines individual instances of travel events into a unified belief. And one can even image that the three-relation congruence is an element of some sort, for example of a higher-order theory of relationships stability. In studying abduction, one may demarcate a particular level of unified facts, with the idea that the same principles should hold when another level is considered in the hierarchy of nested Gestalts.

Second, the scenario of attitudes illustrates how constraints may affect abduction. As long as only one single attitude is considered, constraints toward reproducing that single fact are straightforward, deriving from what we know about remembering single facts. But when two or more facts are to be kept in mind, abduction of higher-level relationships becomes possible, and interactions between facts may shape the abductive outcomes. For example, it is easier to remember congruent facts than facts that create some mismatch among each other (cf., [8]). In fact, constraints toward forming congruent relations among facts may even overwhelm constraints that otherwise sustain elementary facts of the matter, in which case elementary facts are misremembered in favor of a congruent abductive outcome. In this latter scenario, the constraints favoring veridical elementary facts oppose the constraints favoring congruent relations among facts, creating the ratio of opposing constraints illustrated in Formula 1.

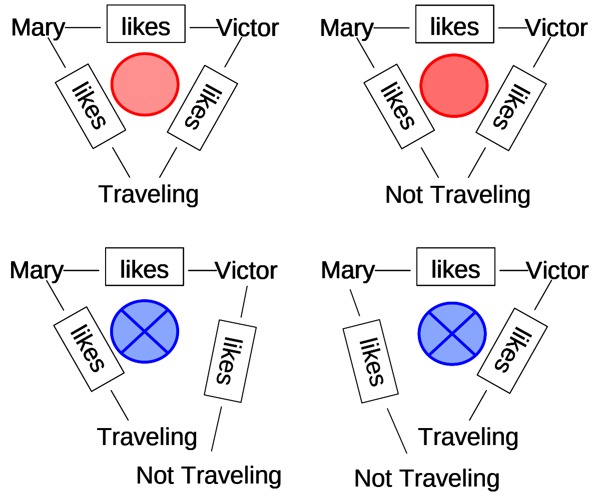

Fig. 1 Schematic representation of attitudes that are either congruent among each other (marked with a red circle) or incongruent (marked with a blue x-ed circle)

'Mary' and 'Victor' stand for two persons who either like or dislike each other, and who each either like or dislike traveling.

B. *Overview of Reviewed Studies*

In what follows, we describe five studies that examined children's capacity to remember correctly the details of local facts[1]. First, by reducing or eliminating constraints that favor the integrity of local facts, we shed light on the constraints that favor abduction of congruent higher-order Gestalts. Second, by pitting weak versus strong local constraints against the constraints that favor congruent Gestalts, we reveal the flexible nature of the child's mind to either abduct the higher-order congruent Gestalt or not.

Instead of attitudes, the reviewed studies use feature correlations as elementary facts. Replace the previous social world of two people and their feelings about travel, with a world of objects that differ in mass, volume, and the rate at which they sink to the bottom of a water tank. A set of plausible local facts about these objects might include a positive correlation between mass and volume (e.g., *heavier is bigger*), a positive correlation between mass and sinking speed (e.g., *heavier is faster*), and a positive correlation between volume and sinking speed (e.g., *bigger is faster*). These three local facts are globally congruent among each other, as shown schematically in Figure 2a. Other examples of

[1] Parts of these findings were published in [14, 15, 26].

congruent facts include *heavier is bigger*, *heavier is slower*, and *bigger is slower* (Figure 2b); or *heavier is smaller*, *heavier is faster*, and *smaller is faster*. But a single change in the facts in evidence can eliminate the globally congruent order. For example, a set of locally possible but globally incongruent facts would be *heavier is bigger*, *heavier is faster*, and *bigger is slower* (see Figure 2c).

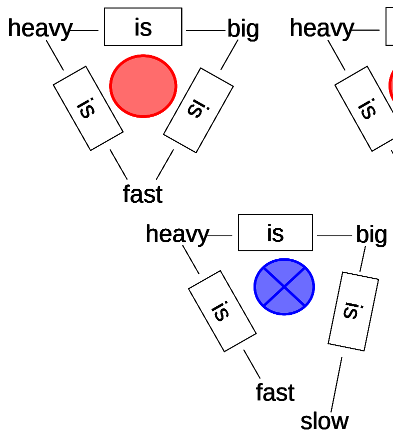

Fig. 2 Schematic representation of feature correlations, each pertaining to a set of objects

The correlations are either congruent among each other (marked with a red circle) or incongruent (marked with a blue x-ed circle).

A general outline of our predictions was derived using Formula 1. The presence of constraints sufficiently strong to sustain local facts yield a numerator greater than its denominator, therefore yielding a value for $A > 1$. In contrast, the presence of weak local constraints, insufficiently strong to sustain local facts, would yield a numerator smaller than the denominator, yielding a value for $A < 1$. The $A = 1$ case reflects either a case in which local and global constraints are aligned together to support veridical performance equivalently. Or it reflects a case in local and global constraints oppose each other, but are exactly equal in strength. Both of these cases are uninteresting for the current purposes. The former one would make it impossible to determine whether children have detected the Global patterns. And the latter case is an unstable, so-called saddle point that degenerates into $A > 1$ or $A < 1$ with the slightest perturbation. It would produce a random pattern of performance respecting neither local nor global constraints overall. We will focus therefore on cases in which $A \neq 1$.

Local constraints can be brought under experimental control in order to test for empirical outcomes consistent with our predictions derived from Formula 1. We review five experiments that implement such manipulations. The first experiment creates a scenario in which local constraints are missing altogether (i.e., children have to make a guess a about a local fact). In the second experiment, local constraints are weak, in that children have to learn two opposite correlations (analogous to learning that two people have opposite attitudes towards travel). The third experiment adds a condition in which local constraints are strong, in that children have to learn two matching correlations (analogous to learning that two people feel the same about travel). Finally, the last two experiments replicate the no-local-constraints and the weak-local-constraints scenarios, respectively, using a new set of facts – ones that are improbable, as a means of minimizing the influence of participants' preconceptions about what they are asked to learn. For each experiment, we first review the method and then describe the findings.

II. Review of Experiments

A. Experiment 1: No Local Constraints

The method includes three main steps, two of which are designed to teach 4 to 5-year-olds about feature correlations, and the third one designed to test their beliefs at the end of the training phase. In particular, in the first step, a preschooler is shown a set of 'submarine' cylinders that differ in mass and volume in such a way that the heavier submarine is also the larger one. The child then engages in activities to learn the fact that *heavier is bigger*. In the second step, the child watches two submarines race to the bottom of a water tank, taking note of the submarine that arrives at the bottom to the tank first. The two cylinders differ only in mass, and they convey the fact that *heavier is faster*. In the final step, the preschooler is invited to play against a submarine man, the fantasy creature who built the submarines. The game is to design a submarine that will sink faster than the submarine of the submarine man. Figure 3a gives a schematic representation of what such a *mass trial* looks like: the submarine of the submarine man is the standard, and the child can choose either a heavier weight (square with more lines) or a lighter weight (square with fewer lines), while the volume of the child's submarine is the same as that of the standard.

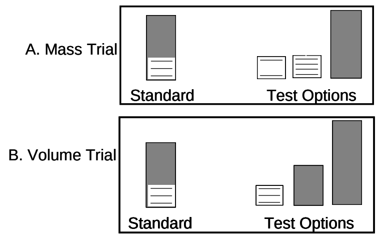

Fig. 3 Schematic representation of the test items presented to children in the third step of Experiments 1 and 2

To create a 'submarine' that would sink faster than the standard, children can either adjust the mass of their submarine (choosing between a heavier and a lighter option; A), or they can adjust the volume of their submarine (choosing between a larger and a smaller options, B).

On the basis of the chosen options across trials, we can ascertain the child's belief of the sinking fact. For example, if the child consistently chooses the heavier option to make faster submarines, the child exhibits the fact that *heavier is faster*. Importantly, the child is also presented with *volume trials* during this third step (Figure 3b), trials in which choices pertain to the volume of the submarine, not mass. In other words, while the child has observed the effect of only one feature (e.g., mass) on sinking speed, testing includes both mass trials and volume trials. And mass trials are intermixed with volume trials, with no explicit instructions about having to make a guess. The child is simply asked to build a submarine that will win against the submarine man's. Nonetheless the absence of demonstrations about the local volume-sinking fact opens the door to a value of $A < 1$, which necessitates the constraints of abductive reasoning toward global congruence.

To establish the existence of these global constraints, children participated in one of four conditions that differed in the mass-volume fact and the demonstrated sinking fact (for a schematic of the conditions, see Figure 4). The demonstrated sinking facts are shown as solid lines in Figure 4. And the to-be-guessed sinking facts are shown as dashed lines with two question marks. The crucial test was whether children's guess about the unknown sinking fact is constrained by the possibility of a global congruence among all three feature correlations. If constrained by congruence, the children who learned that *heavier is bigger* and *heavier is faster* should guess that *bigger is faster* too. And the children who learned that *heavier is bigger* and *bigger is slower* should guess that *heavier is slower* too. Conversely, the children who learned that *heavier is smaller* and *heavier is faster* should guess that *smaller is faster*. And the children who learned that *heavier is smaller* and *smaller is faster* should guess that *heavier is faster*.

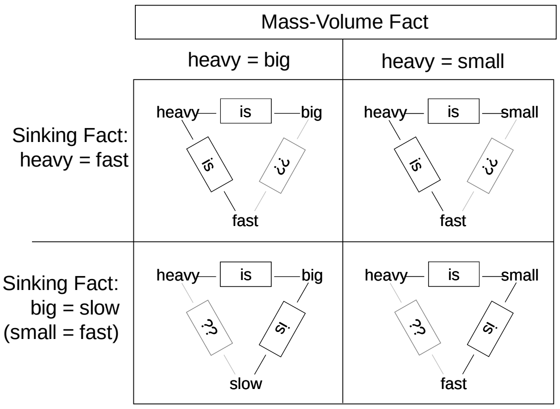

Fig. 4 Schematic representation of the four conditions of Experiment 1

The guessed fact in each condition is marked with question marks. The other two facts are presented to children.

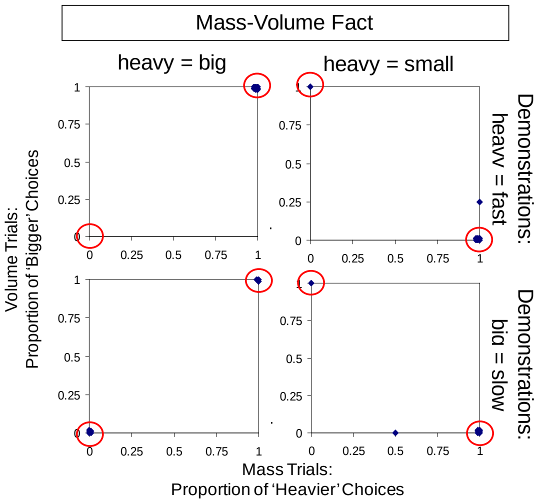

Fig. 5 Scatterplots of individual children's responses in Experiment 1 (N = 8 per cell), measured in proportion of 'heavier' choices on mass trials and proportion of 'bigger' choices on volume trials, separated by condition

The red circles denote the corners of the scatterplot that correspond to congruent facts.

In line with the predictions of weak local constraints, preschoolers were highly likely to abduct a globally congruent set of facts. Figure 5 shows scatterplots of children's choices for the sinking facts, separated by condition. The individual points of each scatterplot correspond to individual children (N = 8 per condition) and portray the proportion of "heavier" choices on mass trials (X-axis) and the proportion of "bigger" choices on the volume trials (Y-axis). Red circles mark the corners of the scatterplot where a child's choices would be 100% globally congruent. As can be seen in the figure, almost all of the children's performance fell within the red circles (30 out of 32). In other words, almost all of the children made systematic choices consistent with globally congruent facts anticipated from $A < 1$.

In sum, guessed sinking facts were almost always congruent with the other two facts, bringing *mass-volume*, *mass-speed* and *volume-speed* into Gestalt-like global congruence. Given that children were open to guess one of the facts, the local constraints of that fact were weak. Yet, children did not produce a random dispersion of choice responses; they did not guess blindly. Instead their choices were systematic consistent with constraints favoring abductions toward global congruence. This finding establishes the very existence of this higher-order constraint in preschool children. The next two experiments expand on this result by manipulating the relative strength of local constraints.

B. *Experiment 2: Weak Local Constraints*

Children between 4 and 7 years of age participated in a three-phase procedure that closely mimicked Experiment 1. They were first shown a set of submarines that differ in mass and volume (to convey a mass-volume fact). And they were then shown a series of submarines, racing in pairs to the bottom of the water tank (to convey sinking facts). Finally, their inductions were assessed in mass trials and volume trials, presented in random order. The difference from Experiment 1 was that sinking demonstrations conveyed facts about mass (while volume was held constant) *and* volume (while mass was held constant). That is to say, children saw pairs of submarines in which the heavier one sank fastest (i.e., *heavier is faster*); and they saw pairs of submarines in which the bigger one sank more slowly (or the smaller one sank faster; *smaller is faster*).

Note that the two demonstrated sinking facts are feature correlations with opposite signs. Mass and sinking speed follow a more-is-more (positive) relation, while volume and sinking speed follow a less-is-more (negative) relation. Given the heightened cognitive demand for learning opposite facts, we predicted that this scenario could yield weaker local constraints, and thus we should see children's choices during mass trials and volume trials to be constrained by global congruence.

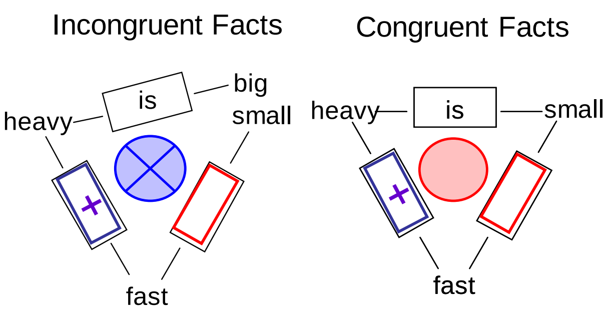

Fig. 6 Schematic representation of the two conditions of Experiment 2 (incongruent-facts vs. congruent-facts condition)

The conditions differ in whether the same two sinking facts (*heavier is faster* and *smaller is faster*) are congruent with the mass-volume fact (congruent-facts condition) or not (incongruent-facts condition). Given that children are asked to remember two sinking facts of opposite relations (one being positive and one being negative), they are expected to be constrained by higher-order congruence.

To test this prediction explicitly, children participated in one of two conditions. The conditions were identical in the demonstrated sinking facts, but differed in whether the two sinking facts were congruent with the mass-volume fact presented to children in the first phase. Figure 6 shows a schematic of the two conditions. Specifically, in the globally *incongruent-facts* condition, the facts were incongruent (i.e., *heavier is bigger*, *heavier is faster* and *smaller is faster*). And in the globally *congruent-facts* condition, the facts were congruent (*heavier is smaller*, *heavier is faster*, and *smaller is faster*). If children attend to the higher-order pattern of global congruence, they should make systematic mistakes in the incongruent-facts condition (because local facts conflict here with higher-order congruence, yielding $A < 1$). And they should be able to learn the (same) local facts in the congruent-facts condition (because here local facts are aligned with higher-order congruence, yielding $A = 1$).

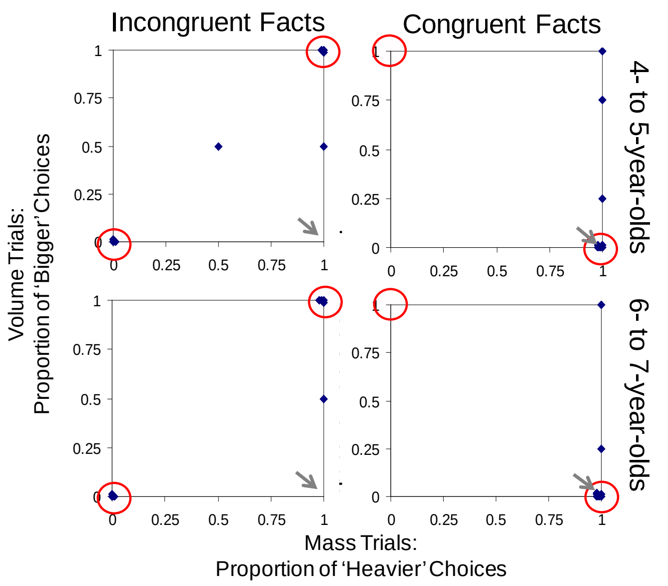

Fig. 7 Scatterplots of individual children's responses in Experiment 2 (N = 8 per cell), measured in proportion of 'heavier' choices on mass trials and proportion of 'bigger' choices on volume trials, separated by condition

The red circles denote the corners of the scatterplot that correspond to congruent facts. And the grey arrows denote the corners of the scatterplot that correspond to correct facts.

Figure 7 shows the scatterplots of children's individual performance, separated by condition (incongruent-facts, congruent-facts) and age group (4-5 vs. 6-7) (N = 8 per cell). Like before, the scatterplots portray the proportion of "heavier" choices on mass trials (X-axis) and the proportion of "bigger" choices on the volume trials (Y-axis). Red circles mark the corners of the scatterplot where choices would be 100% globally congruent. And gray arrows mark the corners of the scatterplot where choices would be 100% correct, reflecting the demonstrated sinking facts. As can be seen in the figure, most children produced choices that were congruent. This means that a majority of children in the congruent-facts condition produced choices that were factually correct (62% of 4-5 year-olds and 75% of the 6-7 year-olds), while none of the children did so in the incongruent-facts condition. Most children in this latter condition were misled to create globally congruent facts instead (69% of 4-5 year-olds and 88% of 6-7 year-olds).

In sum, findings from this second experiment agree with the findings from Experiment 1. Under weak local constraints, children made the predicted systematic choices to establish congruent facts in the incongruent fact condition.

C. *Experiment 3: Strong Local Constraints*

So far we have shown that young children are biased toward congruent facts when local constraints were either absent (Experiment 1) or weakened (Experiment 2). In the next experiment we add a condition in which constraints towards local facts were strong. The general procedure mimics the three-phase procedure of Experiment 2: Participants were first shown a set of submarines that differ in mass and volume (to convey a mass-volume fact). And they were then shown a series of submarines racing in pairs to the bottom of the water tank (to convey sinking facts). Finally, their abductions were assessed in mass trials and volume trials, presented in random order in the final phase.

Different from Experiment 2, the details of the facts about sinking relations were manipulated, as a means of manipulating the strength of local constraints. In particular, the two sinking facts had opposite direction in the weak-local-constraints condition (*heavier is faster* and *small is faster*; identical to Experiment 2), and the two sinking facts matched in direction in the strong-local-constraints condition (*heavier is slower* and *bigger is slower*). Figure 8 presents a schematic of these two conditions.

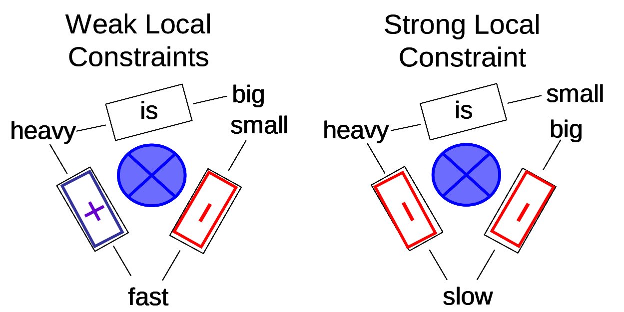

Fig. 8 Schematic representation of the two conditions of Experiment 3 (weak-local-constraints vs. strong-local-constraints condition)

Both conditions involved incongruent facts. The difference pertained to whether participants had to learn two sinking facts of opposite directions (left graph) or of matching directions (right graph).

Note that the two sinking facts were incongruent with the mass-volume fact in both conditions in both conditions. However, local constraints were pitted against global constraint. Thus, learning two sinking facts of matching directions increase the ratio of constraints such that $A > 1$, while learning two sinking facts of opposite relations decrease the ratio of constraints to $A < 1$. We should therefore expect to see systematically mistaken choices to create global congruence in the weak-local-constraints condition, but less so in the strong-local-constraints condition. Participants included children between 5 and 9 years of age, as well as adults. Figure 9 shows the scatterplots of individual participants' performance (again plotting mass-trials performance against volume-trials performance), separated by condition (weak- vs. strong-local-constraints) and age group (5-9-year-olds vs. adults).

Red circles mark the corners of the scatterplot where choices would be 100% globally congruent; and gray arrows mark the corners of the scatterplot where choices would be 100% correct with the demonstrated sinking facts. Note first the patterns of responses of the children (top row), focusing on the correct versus congruent corners of the graph (gray arrows vs. red circles). Confirming our prediction, children in the weak-local-constraints condition were more likely to create congruent facts than children in the strong-local-constraints condition. And vice versa, children in the weak-local-constraints condition were less likely to produce correct facts than children in the strong-local constraints condition.

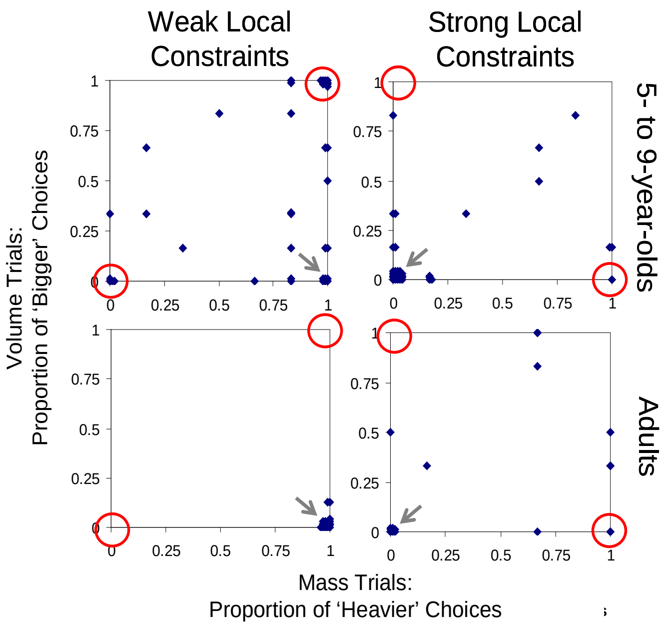

Fig. 9 Scatterplots of individual participants' responses in Experiment 3, measured in proportion of 'heavier' choices on mass trials and proportion of 'bigger' choices on volume trials, separated by condition and age group

The red circles denote the corners of the scatterplot that correspond to congruent facts. And the grey arrows denote the corners of the scatterplot that correspond to correct facts.

Adults, by contrast, were not affected by constraints toward congruence in either of the conditions (bottom row of Figure 9). Their choices correctly reproduced the demonstrated sinking facts even when these facts were sustained by weak local constraints. It is possible that opposite facts did not increase cognitive demand sufficiently to weaken local constraints in adults. Surprisingly, adults had difficulty remembering the local facts in the strong-local-constraints condition. This might stem from adults' stable belief that heavier objects cannot possibly sink more slowly than lighter objects. Watching demonstrations in which this belief was contradicted (strong-local-constraints condition) might have weakened local constraints. It remains to be seen why such weakened local constraints did not yield a susceptibility to creating global congruence.

To sum up, the goal of Experiment 3 was to test for changes in performance due to the strength of local constraints, and we confirmed the expected interplay between local and global constraints in children. Experiment 3 also included a direct replication of findings from Experiment 2 across a wider age range: 5 to 9-year-olds made choices creating higher-order congruence, in the face of weak local constraints. Lastly, adults differed from children, making choices consistent with demonstrated facts in all cases. The final two experiments are conceptual replications using arbitrary relations as facts.

D. Experiment 4: Conceptual Replication I

"A transformer was found on a far-away planet. If you put something in on one end, something different will come out on the other end." This cover story justified local facts that combine completely arbitrary features. The specific features, chosen to have little or nothing in common, pertained to (1) the size of a cartoon mouse, (2) the darkness of a cloud, and (3) the depth of a bowl (with no change in volume). Note that these features have dimensional properties, in that they have a 'more' pole (big; dark; deep), and a 'less' pole (small; light; shallow)[2]. As such we could create the fact of a 'positive' correlation (e.g., *bigger is darker*) or the fact of a 'negative' correlation (e.g., *bigger is lighter*). These facts were demonstrated to preschoolers and adults through a series of movies, showing, for example, a big and a small mouse entering the transformer and emerging as a dark and a light cloud, respectively.

The design was a combination of Experiment 1 (when participants had to guess a fact) and Experiment 3 (when they were presented with two facts that either matched in direction (strong-local-constraints condition) or had opposite directions (weak-local-constraints condition). The general procedure consisted of a demonstration phase and a testing phase. During demonstrations, participants were presented with movies conveying two separate facts. For example, participants learned a size-darkness fact and a depth-darkness fact. In the strong-local-constraints condition, these two facts matched in direction (e.g., *bigger is lighter*; *deeper is lighter*[3]). And in the weak-local-constraints condition, these two facts had opposite directions (e.g., *bigger is darker*; *deeper is lighter*). Analogous to Experiment 3, the idea was that opposite facts yield weaker local constraints than matching facts. As a result, the matching-facts scenario yields a ratio of constraints $A > 1$, while the opposite-facts scenario yields a ratio of $A < 1$. We therefore expected to see more choices creating congruent facts in the weak-local-constraints condition (when children are exposed to opposite facts) than in the strong-local-constraints condition (when children are exposed to matching facts).

During testing, participants were presented with choices to decide on a particular fact. For example, they were presented with a dark-grey cloud and a light-grey cloud and asked: "Which cloud will the big mouse turn into?" Importantly, while only two facts were demonstrated to participants, beliefs about all three facts were assessed, requiring that one fact be guessed. Using the example from above, participants who saw the size-darkness fact and the depth-darkness fact in demonstrations were not only asked about these two facts during testing, but also asked about the size-depth fact, which was not demonstrated beforehand.

We again created scatterplots displaying the proportion of 'more' ('darker,' 'deeper,' or 'bigger') choices made by a participant (see Figure 10). Red circles represent choices

[2] Note that the identified 'more' pole is somewhat arbitrary in the case of darkness and depth. For achromatic color, for example, one could easily imagine the 'more' pole to refer to *more white*,, rather than to *more grey* (cf., [28]). And for depth, the deepest bowl was less wide than the shallowest bowl, meaning that the identified 'more' pole (for depth) corresponded to a 'less' pole (for width). To circumvent the arbitrariness of what we considered to be the 'more' vs. 'less' pole of a feature, the direction of the poles of each dimension were explicitly taught to children.

[3] Relations of matching directions could be both positive, and both negative. However, we again only focused on the two-negative-relations case – to be consistent with what was done in Experiment 3 with sinking objects.

yielding 100% congruent facts[4]. As can be seen in the figure, preschoolers were rather overwhelmed by having to learn arbitrary relations: many of them did not make consistent choices across trials of a fact. Nevertheless, the effect of condition was still visible: There were more ‘congruent’ participants in the weak-local-constraints condition (80% of adults, 30% of preschoolers) than in the strong-local-constraints condition (70% of adults, 15% of preschoolers). And this finding might mask the true effect of condition, given that participants – to be congruent – had to guess a negative correlation in the weak-local-constraints condition (and a positive correlation in the strong-local-constraints condition). Young children rarely produce negative correlations spontaneously (e.g., [11, 16, 28]). If such directional bias could have been balanced out, the effect of condition might have been even stronger.

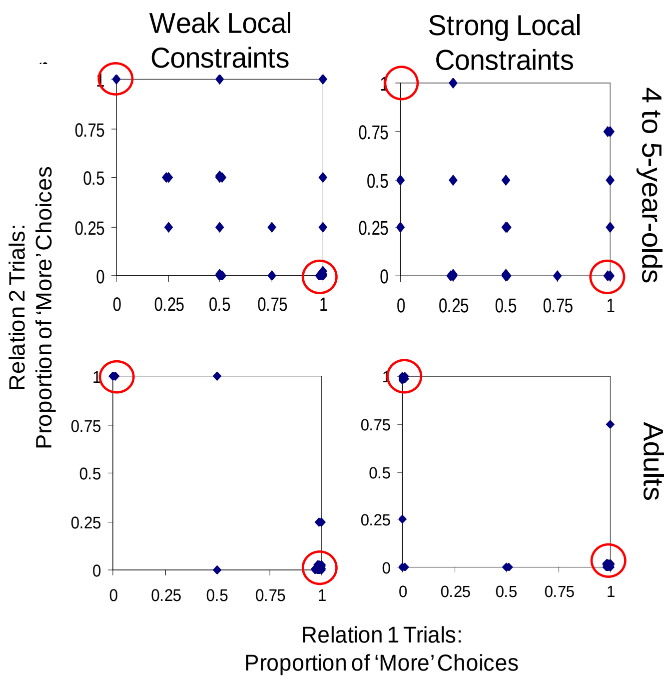

Fig. 10 Scatterplots of individual participants’ responses in Experiment 4, measured in proportion of ‘more’ choices for two of the three facts (referred to as Relations 1 and 2), separated by condition and age group

Performance on the third fact is not displayed here. It was the fact that a participant believed to be a negative relation. Given that the direction of the third fact was fixed, we are able to denote the corners of the scatterplot that correspond to congruent facts (marked with red circles).

In sum, the findings of this experiment provide further support for our conceptualization of abduction. In a context in which feature correlations were arbitrary, and participants had to guess one of the facts – one that was not presented during training – we found a stronger bias toward congruent facts in the weak-local-constraints condition than the strong-local-constraints condition for both preschoolers and adults. Children’s bias towards congruent facts was weaker overall (possibly because they had difficulty with the arbitrariness of the facts), while adults were biased by congruence in both conditions.

E. Experiment 5: Conceptual Replication II

In this final experiment, we return to a domain of plausible facts to strengthen the manipulation of weak versus strong local constraints. The goal was to replicate the findings of Experiment 3 with a set of feature correlations for which children are unlikely to have strong a-priori beliefs. Rather than using sinking objects that differ in mass and volume, we used composite objects that differed in two measures of extension, each of which affected the size of the shadow cast by the object. Facts about how the size of an object affects the size of its shadow are physically meaningful, yet preschoolers are unlikely to have strong beliefs about these facts.

The left side of Figure 11 shows schematics of the two settings used in this experiment. In both settings, the outcome feature pertains to the size of the shadow cast by a disc (represented with an arrow on the projection screen in Figure 11). And in both settings, the size of the shadow was affected by the sizes of two shapes, attached perpendicularly to each other. In the setting shown in the top row of Figure 11, the two shapes pertained to the projected disc and a ‘base’ (which determined the distance between disc and light source). And in the setting shown in the bottom row of Figure 11, the two shapes pertained to the base (which again determined the distance between disc and light source) and a ‘tower’ (which determined the height of the light source). The arrows on these shapes, shown in Figure 11, represent how their size varied. The sizes of the two shapes affect shadow size either in opposite ways (weak local constraints, top row of Figure 11), or in matching ways (strong local constraints; bottom row of Figure 11).

The method was conceptually similar to that of Experiment 3: A demonstration phase showed preschoolers how the composite shapes affect the size of the projected shadow. Preschoolers were shown a set of composite shapes for which the sizes of the two component shapes were correlated. In particular, the sizes correlated either positively (e.g., *more disc is more base*) or negatively (e.g., *more disc is less base*). The correlation was chosen to be either congruent or incongruent with the two shadow facts. For example, in the incongruent-facts weak-local-constraints condition (top left quadrant of Figure 11), the three facts were: *more disc is more base*, *more disc is more shadow*, and *more base is less shadow*. And in the congruent-facts strong-local-constraints condition (bottom right quadrant of Figure 11), the three facts were: *more base is more tower*, *more base is less shadow*, and *more tower is less shadow*.

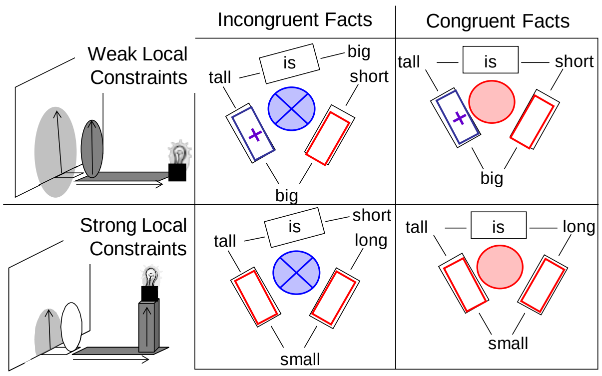

Fig. 11 Schematic representation of the conditions in Experiment 5

Conditions differ in whether children are asked to learn two opposite facts (yielding weak local constraints; top row) or two matching facts (yielding strong local constraints; bottom row). And they differ in whether the facts are congruent among each other (right column) or incongruent (left column).

[4] The content of the third fact differed from participant to participant. It was the fact for which participants consistently picked the ‘less’ options.

Testing consisted of asking preschoolers to design a composite object that would make a bigger shadow than a standard. As was done in Experiment 3, preschoolers were given a choice for only one of the shape sizes, while the other shape size was held constant (analogous to mass trials and volume trials).

The manipulation resulted in a 2x2 design, with cells differing in weak versus strong local constraints (shadow facts had either opposite or matching directions, respectively), and cells differing in congruent versus incongruent triads of facts. In the incongruent case, when local facts are pitted against global congruence, the prediction was that the strong-local-constraints conditions yield $A > 1$, while the weak-local-constraints conditions yield $A < 1$. In the congruent case, when local facts agreed with global congruence, both conditions yield $A = 1$, thus serving as control conditions to establish whether preschoolers can learn the shadow facts presented to them.

Figure 12 shows children's performance in scatter plots corresponding to weak versus strong local constraints and globally congruent versus incongruent facts. Red circles indicate performance consistent with congruent facts, and gray arrows indicate correct performance, consistent with demonstrations. Note that red circles coincide with gray arrows in the congruent-facts cases, but not in the incongruent-facts cases. As can be seen in the figure, many preschoolers performed correctly in strong-local constraints settings (68%), but not in the weak-local-constraints settings (19%). More importantly, and in line with our predictions, performance in the incongruent-facts conditions reflected a bias toward globally congruent facts in the weak-local-constraints condition (for 62% of preschoolers), but not in the strong-local-constraints condition (0% of preschoolers).

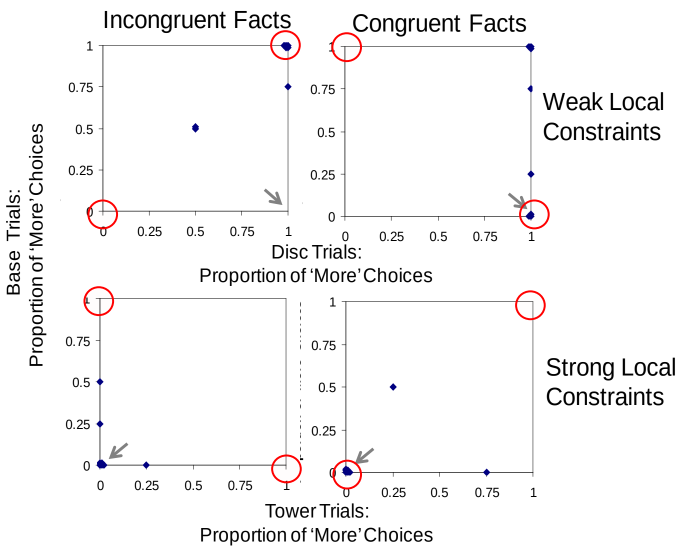

Fig. 12 Scatterplots of individual children's responses in Exp. 5, measured in proportion of 'more' choices on each trial type

The red circles denote the corners of the scatterplot that correspond to congruent facts. And the grey arrows denote the corners of the scatterplot that correspond to correct facts.

Taken together, this series of five experiments reveals that a bias exists toward higher-order congruence that can be captured by changes in a ratio of constraints (values of a control parameter) toward local versus global order. Overall, this ratio predicted and organized the performance of children and adults, to cause-effect facts as well as to arbitrary feature correlations in several task contexts.

III. CONCLUSION

Previous findings attest to a curious interplay between a child's ability to abstract a higher-order pattern of Gestalt and the detection of elements that compose those higher-order patterns. Quinn et al. [23] for example, found that infants who could attend to the higher-order pattern also remembered the individual shapes better (Experiment 3). This Ying-Yang of attention to local and global patterns – though far from what is traditionally referred to as abduction – has an important relation to abduction. It reflects the interdependence between constraints on a local level and constraints on a more abstract level. The current paper exploited this interplay in defining a ratio of constraints that could capture the emergent outcomes of abduction.

Changes in constraints have been shown to capture systemic changes in systems of very different material composition, ranging from physical models of fluids and solids, to chemical substances, to the bodily interactions as an infant is learning to walk (for a review, see [18]). Here we applied it to the most cognitive of human activities: abductive reasoning. As such, we adapted an established method from nonlinear dynamics to a system that has traditionally been explained by mental constructs alone. Such mental constructs, say the hierarchical representation of a knowledge domain, or the mental process of analogy, are intuitive. But they fail to capture what one might consider the essence of systemic order: the nature of compromise among competing forces (cf. [21]). The idea of a control hierarchy and its entailed control parameters fills this gap. It reveals abduction as the results of competing sources of constraint, favoring one or another hypothesis.

The empirical studies reviewed here illustrate how children's abductive hypotheses about the physics of a laboratory world can motivate a nonlinear dynamical description of abduction. The description centers on demonstrated local constraints that may increase or decrease the degrees of freedom for choices – which in turn open the possibility of observed choices reflecting the bias of induction toward globally congruent facts (cf., [24]). Though merely a starting point, our review could provide a common umbrella for notorious context dependence of abductive inferences. It emphasizes the precarious balance of sources of knowledge that determine whether induction will result in a reliable or spurious higher-order Gestalt in thought and behavior. As such, our proposal may show the promise to reconcile conflicting findings about children's higher-order reasoning.

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