CONVERGENCE OF MULTIPLE FIELDS ON A RELATIONAL APPROACH TO COGNITON

[1]Shane Mcloughlin, [2]Ian Tyndall, & [2]Antonina Pereira

[1]Department of Psychology, Liverpool John Moores University, UK

[2]Department of Psychology, University of Chichester, UK

Convergence of multiple fields on a relational reasoning approach to cognition. Relational reasoning broadly refers to how we assign symbolic meaning to stimuli based on their relationship to other stimuli. For example, the term and concept “tall” can only carry meaning relative to “short”. Charles Spearman referred to *g* as a generic factor of “cognition of relations” (1927, p.165) suggesting that relational reasoning may be central to general cognitive ability. The present article has two main aims. The first aim is to highlight that key researchers across several research traditions have independently converged upon the idea that symbolic cognition involves the ability to relate stimuli for purposes of adaptation, based on both their physical and symbolic properties. There is a large volume of research on relational reasoning of one form or another across several fields, often adopting a diverse range of terminology. For this reason, it is beyond the scope of the current paper to present an exhaustive systematic review of research on relational reasoning. Instead, we focus on key exemplars from each field to highlight a common focus on relational cognition as an opportunity for dialogue across fields when discussing and researching cognitive ability. Secondly, this article then aims to describe a behavioral account of relational reasoning called Relational Frame Theory (RFT) that may prove especially useful for training relational reasoning such that it can be applied across contexts. As such, it might provide a particularly promising avenue of research on far transfer cognitive training effects. Therefore, the overall thesis of this paper is that multiple fields have independently converged upon a relational reasoning account of cognition, but, also that RFT uniquely lends itself to promising training interventions to enhance relational reasoning ability.

Cognitive Psychology

Cognitive psychology, at its core, is an explicitly mechanistic account of psychology (De Houwer, 2018; Pepper, 1942), attempting to describe the mind in terms of inner mental processes, derived through top-down experimentation. That is, with increased experimental rigor and triangulation, cognitive psychologists attempt to derive an increasingly high-resolution picture of the mind and its component processes. Thus, cognitive performance or behavior is "considered to be an indication of processes taking place inside the person…for example, mental processes such as encoding, storage, retrieval, internal computing, decision making, phonemic storage, lexical search, and so on" (Chiesa, 1998, p.355). For example, when we try to explain working memory as being made up of a *phonological loop* and a *visuospatial sketchpad*, these are metaphors used to label how memory behaves by invoking the properties of concrete stimuli (e.g., "memory, which we cannot observe directly, works like a sketchpad, which we can observe directly"), rather than there being anything physically resembling a loop or sketchpad inside somebody's head. Similarly, the *central executive* controlling these components is a metaphor used to fill a gap in knowledge about how resources are allocated to each; there is no observable homunculus operating the gears of the mind, and if there were, we would need to explain how the homunculus is constituted (how does *his* brain work?), and so on, *ad infinitum*. However, breaking cognition up into these processes and modules may nonetheless be *useful* for describing and predicting behavior.

Cognitive scientists have argued that relational reasoning (often referred to as relational schemas) is central to cognition (cf. Halford et al., 2010). One of the core features of relational reasoning is transitive inference. That is, if behavioral event A (hissing sound) is related to B (a slithering creature), and B is related to C (danger), then A is related to C. Here, only the A:B (slithering creature makes a hissing sound) and B:C (slithering creature means danger) relations are directly learned, but the A:C relations (if I hear a hiss, I should run away!) are *derived*. This core feature helps to explain the complexity and generativity of language and cognition. Consider the following: if we learn through direct experience that A is related to B, then we can derive that B is related to A. With the addition of just one more premise, B:C, we can derive C:B, A:C, and C:A. With the addition of a third learned premise, C:D, we can derive several more novel relations: D:C, D:B, B:D, D:A, and A:D.

Another feature of relational reasoning is that the nodal complexity (i.e., number of stimuli and nodal distance of the stimuli) of a relational network within which we can successfully derive relations appears to follow a developmental trajectory (Andrews et al., 2012; Andrews & Halford, 1998; Halford, 1984; Halford et al., 2012), as with other cognitive abilities (Piaget, 1936). The developmental trajectory of relational reasoning abilities appears to be non-linear. Jablansky et al. (2016) coded the use of relational language in a series of semi-structured conversations across three developmental groups (aged 5-10, 11-14, and 15-17). The youngest and oldest groups used relational language less often than expected, while the middle group used relational language more than expected. This, suggests, perhaps, that the acquisition of some forms of relational reasoning in late childhood might accelerate the learning of other forms of relational reasoning in early adolescence before plateauing in mid-late adolescence. These findings suggest that one could compute a "mental age" or an Intelligence Quotient (IQ) score based on how advanced someone's relational repertoire is relative to their peers.

Indeed, measuring relational skills appears to function as a useful proxy-measurement of IQ (Colbert et al., 2017). Colbert et al. found that the strength of the relationship between their relational reasoning measure (RAI; relational abilities index) and Wechsler Intelligence Scale for Children-III (WISC-III) full-scale IQ was comparable to the strength of the relationships between WISC-III Full-scale, Performance, and Verbal IQ, the Rey Auditory Verbal Learning Test, the National Adult Reading Test, and the Trail Making Test. These findings are consistent with the idea that relational reasoning and intellectual ability are synonymous, with the ability to derive relations in more complex networks indicative of a higher level of cognitive ability (also cf. Birney et al., 2006).

At higher levels of cognitive complexity, higher-order functions such as hierarchical classification (Goldwater et al., 2018), analogy (Alexander, 2019), and rule-following (Don et al., 2016) can even be conceptualized in relational terms. Moreover, a meta-analysis of 47 functional magnetic resonance imaging studies (Wertheim & Ragni, 2018), suggests that the parieto-frontal regions of the brain are implicated in both inductive relational reasoning tasks (abstracting a pattern to generalize to new stimuli, thereby testing the abstracted premise) and deductive relational reasoning tasks (using established facts as a premise before for deducing other facts). This is consistent with Jung and Haier's (2007) Parieto-Frontal Integration Theory (P-FIT), which suggests that people who perform better on cognitive ability tests have more efficient parieto-frontal interaction during those tasks.

Cognitive Approaches to Education

Staying within the broader cognitive domain, Goldwater and Schalk (2016) suggested that this conceptualization of cognition in relational terms could help to bridge the gap between educational and cognitive research. Within the field of Education, more specifically, Alexander (2019) proposes four forms of relational reasoning, outlined in common-sense terms: analogy, anomaly, antimony, and antithesis. Analogy involves identifying relational similarity between concepts. For example, the poem City Lights by Pie Corbett, opens as follows: "huge round oranges of light ripen against the city sky". Here, the similarity is identified between stars glowing in the sky and oranges ripening on a tree, making one semantic network richer by invoking another. Anomaly involves identifying distinction between concepts. For example, if you ask a child "which one doesn't fit: a dog, a sheep, a cloud, or a cat?", we might expect the child to choose the cloud, as it does not fit into the category "animal". Antinomy is a related concept, allowing one to identify what something is by contrasting it with what it is not. For example, one might say "I did not pass. What did I do" and have someone say "you failed"; we cannot do both at the same time. Antithesis involves identifying an opposing concept. For example, if we ask a child to identify the antithesis of “white” amongst the following array of colors: black, yellow, and red, we might expect them to identify “black” as the correct answer. While red and yellow are different to white, black is a specific kind of different in that it is as far away from white as conceptually possible. That is, we use relational networking processes to compare and contrast stimuli to make sense of them.

Although there are several studies showing an association between relational reasoning and educational outcomes (cf. Dumas, 2017; Dumas et al., 2013, 2014), most of these involve testing relational reasoning/language use as a correlate or predictor. For example, Farrington-Flint et al. (2007) tested 5-8-year-old children’s ability to solve mathematics problems and also administered tests of relational reasoning and found that knowledge of how to solve mathematics problems appeared to be related to domain specific abilities in younger children. Older children employed more domain-general relational reasoning abilities. However, these kinds of studies do not show how to improve relational reasoning as a domain-general ability, and yet, educational researchers often use these studies as a basis for making recommendations for practice (Reinhart et al., 2013). In an applied field like Education, it is imperative to be able to subsequently use this knowledge to design effective interventions, a topic to which we will later return.

Cognitive Linguistics

Language and cognition are often considered to be structurally synonymous and mutually entailed (Lupyan & Bergen, 2016). Everaert et al. (2015) argue that language is a computational cognitive mechanism, defined by its key structural properties, rather than topological properties. For example, we tacitly understand that when we say that a bouncy, spherical object *is called* “a ball”, we behave as if the object and the referent mean the same thing. In other words, if seeing a football elicits memories of a football match we have attended, then saying the word “ball” in the absence of such an object might also elicit the same cognitive response. Of course, the vocal stimulus paired with the object varies across languages, but the way of relating stimuli is constant. Indeed, performance on matrix reasoning tests that require relational reasoning to solve appears to be impaired in those with lesions to the left middle and superior temporal gyri, regions essential for language processing, and the left inferior parietal lobule. It is possible then that relational reasoning might represent the psychological counterpart of what Chomsky called “universal grammar” in linguistics (Goldwater, 2017; Yang et al., 2017). Chomsky’s organicist account of language suggests that language evolves as a function of biological maturation, but how it evolved in the first place (i.e., the selection mechanism) is not well accounted for in evolutionary biology (Nowak et al., 2001) nor in cognitive science (Skinner, 1990).

Lupyan and Dale (2016) argue that linguistic differences can partly be predicted by the environment in which a language is learned and used. This perhaps suggests that the kinds/levels of grammar, or kinds of relational behavior we engage in, might be partially dependent on our sociocultural contexts, not just on biological circumstances. This arguably makes sense as it might help account for how language evolved in the first place, which remains to be explained (cf. Berwick & Chomsky, 2019; Everaert et al., 2017).

Cognitive Psychology and Reinforcement

Referring to cognitive mechanisms (e.g., working memory) is certainly useful for prediction of cognitive/linguistic abilities (e.g., mathematics performance; Bull et al., 2008), but when considered as causal agents, are of limited use as (i) they cannot be directly manipulated and (ii) do not account for how these mechanisms came to be in the first place. Indeed, when it comes to the goal of behavior change, biological and cognitive psychologists often appeal to processes of reinforcement (De Houwer et al., 2017; Pickering & Gray, 2001).

Some cognitive approaches acknowledge the loose conceptual nature of popular cognitive terms. For example, Gladwin et al. (2011) make the point that common cognitive terms like "working memory" are "loose" terms that likely reflect more discrete processes that arise from a history of behavioral reinforcement (Gladwin & Figner, 2014). Cognitive accounts like these allow more room for the study of simpler mechanisms that manifest as what we think of as cognitive constructs. Attempting to manipulate these loosely-defined cognitive processes such as working memory has not been effective in terms of improving general cognitive ability (Melby-Lervåg & Hulme, 2016). A second-order meta-analysis by Sala et al. (2019) suggests that other forms of cognitive training (e.g., chess training, music, video games etc.) have also not been successful to date. Some other cognitive approaches have evoked forms of relational reasoning (cf. Van Hecke et al., 2010), but these approaches were not situated under a unified framework.

Although there are various cognitive theories of syllogistic relational reasoning, Khemlani and Johnson-Laird (2012) consider them to be "inadequate", and indeed, these theories are poorly understood at the level of process (e.g., What are the antecedent and consequential conditions under which one learns how to use syllogisms?). Perhaps this is not surprising, as fractionating a cognitive mechanism derived from common parlance into component mechanisms ad infinitum using top-down experimentation inevitably will become increasingly difficult. An alternative might be to observe micro-behaviors (e.g., basic stimulus discrimination/pairing) that most species can do and try to understand the degree to which these simpler behaviors scale upwards. If indeed they did scale upwards to manifest as complex cognition, this would be consistent with the Process Overlap Theory of Intelligence (Kovacs & Conway, 2019) which suggests that multiple independent but overlapping processes can account for the positive manifold.

A Behavioral Psychology Perspective

Modern behavior analysts also broadly agree with a relational approach to language and cognition. Chomsky is often credited as an instigator of psychology's move away from a behavioral account of language and cognition (Virués-Ortega, 2006), arguing that (i) it is a "blank slate" approach to psychology, and (ii) operant psychology cannot account for the complexity and generativity of language and cognition. It is perhaps surprising, therefore, that modern linguistics converged upon the same broad conclusion as behaviorists that language and cognition involve relational networking of stimuli (Everaert et al., 2015). Moreover, B. F. Skinner was not a blank slate psychologist (cf. Morris et al., 2004), for as he clearly stated, "The organism is, of course, not empty, and it cannot adequately be treated simply as a black box, but we must carefully distinguish between what is known about what is inside and what is merely inferred" (Skinner, 1974, p.233). Furthermore, as Chiesa (1998) put it, the "person in radical behaviorism is the sum of what they do. They are the focal point of a set of complex interacting variables – including genetic endowment and life experience" (p. 357). Indeed, Skinner's successors in this field have been quite consistent on this point (Marr, 2009; D. S. Wilson & Hayes, 2018). Modern behavioral psychology is arguably best conceptualized as applied evolutionary psychology, focusing on the organism's processes of adapting to their environment to satisfy biological and social needs through operant conditioning, as opposed to passive Pavlovian conditioning alone. Thus, behavioral psychology tends to examine individual differences at the level of the individual person rather than at a between-subjects group level and thus approaches the "challenge of variability from a biological rather than statistical perspective" (Chiesa, 1998, p. 355; cf. also Sidman, 1960). For this reason, it is often termed "functional-analytic" psychology; behavior, including perception itself (cf. Simons & Chabris, 1999), is guided by antecedent and consequential functions. It should be acknowledged that on "a deductive-inductive continuum it [behavioral psychology] lies towards the inductive end, encouraging scientists to ask questions of their subject matter without the need for a formal hypothesis" (Chiesa, 1998, p. 355).

B. F. Skinner's operant psychology conceptualizes cognition as being covert behavior. According to Skinner (1957), there are three main features of any given behavior. The first feature is the antecedent conditions of the behavior. These antecedents include a diverse array of contingencies including the acting organism's biological predisposition and needs, and their learning history. Secondly comes the behavior itself, which may be covert (e.g., thinking) or overt (actions to which the term *behavior* is more commonly applied). Finally, come the consequences of the behavior which refers to the feedback from the environment to let the behaving organism know whether the behavior served its (perhaps tacitly-) intended function (i.e., resulting in positive or negative reinforcement or punishment of the behavior). In turn, the consequence of the behavior informs part of the antecedent conditions of future behaviors. When the behavior achieves its intended function, it becomes more likely in future under similar conditions (termed "behavioral reinforcement"). When it does not achieve its function, that behavior will become less likely in future under similar circumstances. This process of adaptive behavior can be *described* and *predicted* in biological terms (Berridge & Robinson, 1998; Miller & Cohen, 2001), but it is only through manipulating antecedent and consequential functions that practitioners might *change* behavior. On one hand, a behavior analyst may seek to change a specific individual behavior, but on the other, they may try to change/establish 'go to' patterns of behavior that are generally useful in particular contexts. In Skinnerian psychology, these learned patterns of generally-adaptive behavior are known as operants.

Relational Frame Theory (RFT). Skinnerian operants (e.g., "mands" for asking, "tacts" for labelling) are still part and parcel of modern behavioral practice. However, Skinner did not provide experimental procedures that would allow him to demonstrate how complex cognition emerged, and how it could be conceptualized within his behavioral framework. For example, he described metaphorical reasoning as a kind of “extended tact”, which was quite vague and difficult to falsify. RFT (S. C. Hayes et al., 2001) asserts that it is possible to have a multitude of other relational operants (see Table 1), with varying levels of complexity. Indeed, the RFT literature provides several experimental analogues of how this complex operant behavior might be shaped up through schedules of reinforcement. Relational responding, more broadly, means responding to one event in terms of another. For example, “big” only carries meaning relative to “small”.

Table 1.

Studies investigating various patterns of relational framing behavior.

Relational frames	**Study**
Same / Different / Opposite	Steele & Hayes, 1991; McLoughlin & Stewart, 2017
More / Less	Dymond & Barnes, 1995; Munnelly et al., 2010; Munnelly et al., 2019
Before / After	O’Hora et al., 2008; Brassil et al., 2019; Hyland et al., 2012; McGreal et al., 2016
Left of / Right of; Above / Below	May et al., 2017
Member / Class; Part / Whole	Mulhern et al., 2018; Stewart et al., 2018; Slattery et al., 2011; Slattery & Stewart, 2014
I / You; Here / There; Now / Then	McHugh et al., 2004; Guinther, 2017; 2018

Relating equivalence relations	Barnes-Holmes et al., 2005; Stewart & Barnes-Holmes, 2004; Carpentier et al., 2004; Carpentier et al., 2002; Stewart et al., 2001; Barnes et al., 1997; Stewart et al., 2002
Differentiating Same / Different / Opposite relations	McLoughlin & Stewart, 2017; Freeman, 2019

Note. These kinds of relational responding are roughly in order of the complexity of the relations involved.

Simpler forms of relational framing include a symmetrical pattern of response, hence why its first property is termed 'symmetry'. For example, if A is 'the same as' or 'equivalent to' B, then the derived B-A relation will also be one of sameness. However, not all kinds of relations are symmetrical, so RFT broadened these terms to include asymmetrical patterns of relational responding to stimuli, also known as relational framing. The first characteristic of relational framing is mutual entailment: If we directly learn an A-B relation, we can derive the B-A relation. For example, if we learn that A is "more than" B then we can derive that B is "less than" A. The second property is combinatorial entailment: if we know an A-B and a B-C relation, we can derive the respective mutually entailed relations (B-A and C-B), but also the combinatorial A-C and C-A relations. The third property of relational framing is the transformation of function which specifies that functions of the stimuli involved in relational networks change in accordance with the relational networks in which they participate. For example, if a person is already slightly anxious about 'stimulus A' and told that A is less scary than B and B is less scary than C then an individual who had otherwise never encountered C might display symptoms of extreme anxiety in its presence. According to RFT, patterns of derived relational responding are the key generalized operants underlying the complexity and generativity of symbolic language and cognition (Dymond & Roche, 2013).

Relating stimuli based on physical/non-arbitrary properties is easier as these relations can be directly perceived, even by young children (termed, “non-arbitrarily applicable relational responding”; NAARR). For example, if I learn that a yellow, spherical, bouncy object is called a ball and a red, spherical, bouncy object is called a ball, then I can derive that a novel blue, spherical, bouncy object is called a ball; all the particular kinds of balls have the common physical property of being spherical and bouncy. At more advanced levels, stimuli are related not based on their physical properties, but based on their socially reinforced, arbitrary properties (termed “arbitrarily applicable relational responding”; AARR). This is a more difficult behavioral repertoire to master, as arbitrary and non-arbitrary properties may not always align. For example, a 10p British sterling coin is “more than” a £1 sterling coin physically (i.e., it is a larger piece of metal), but “less than” in the context of wanting to buy something. So, if told that one “Bleg” is greater than one “Jumb”, and that one Jumb is greater than £1, most people, having never seen a Bleg or a Jumb before, will choose a Bleg over £1 if offered one or the other.

RFT hypothesizes that relational framing abilities are synonymous with symbolic cognition. In particular, Cassidy, Roche, and O’Hora (2010) argue that items on IQ tests can be conceptualized as being proxy-tests of relational framing abilities. So, from an RFT point of view, a person with “higher intelligence” is someone who can derive relations (i) based on more abstract properties of stimuli (ii) across longer nodal distances (iii) using a larger array of relational patterns (e.g., symmetrical Same/Opposite versus asymmetrical More/Less). Therefore, a person with higher IQ, from an RFT perspective has better developed relational framing abilities relative to others their age.

Manipulating Complex Language and Cognition

Many cognitive neuroscientists agree, in principle, that complex cognitive repertoires might be comprised of more discrete overlapping processes (Kovacs & Conway, 2019). Some neuroscientists also argue that complex cognition is shaped up through organism-environment interaction wherein simple patterns of reinforced behavior combine to produce what appears to be complex behavior under increasingly subtle contextual control. For example, Miller and Cohen (2001, p. 172) stated the following: "When a behavior meets with success, reinforcement signals augment the corresponding pattern of activity by strengthening connections between the PFC [pre-frontal cortex] neurons activated by that behavior. This process also strengthens connections between these neurons and those whose activity represents the situation in which the behavior was useful, establishing an association between these circumstances and the PFC pattern that supports the correct behavior. With time (and repeated iterations of this process), the PFC representation can be further elaborated as subtler combinations of events and contingencies between them and the requisite actions are learned[…] brainstem neuromodulatory systems may provide the relevant reinforcement signals, allowing the system to 'bootstrap' in this way." We also understand that it is the dopaminergic system maintains incentive salience in reinforcement learning (Berridge & Robinson, 1998). Similarly, a core tenet of RFT is that simple behaviors can be shaped up through reinforcement to manifest as complex cognition.

RFT: Learning Deductive Reasoning Through Induction

Symmetrical relations. The first empirical RFT study by Steele and Hayes (1991) helps to demonstrate how relations of similarity, distinction, and opposition can be shaped up through reinforcing particular patterns of behavior. For instance, in a match-to-sample procedure, a "sample" stimulus might appear at the top of the screen, followed by two "comparison" stimuli at the bottom from which a participant must choose, one of which is the same as the sample. If and when the participant chooses the comparison stimulus that is the same as the sample, the experimenter (or computer program) can provide a reward (e.g., “correct!”). Across several such trials in which the stimuli are varied and the “correct” comparisons are counterbalanced, the participant will learn matching behavior. In a new block of trials, the participant’s matching behavior might be reinforced but only in the presence of a particular stimulus (e.g., a nonsense word, “Bleg”). Across multiple trials, Bleg acquires the stimulus function “same”. In the same way, an experimenter could reinforce choosing the non-matching comparison stimulus in the presence of another word (e.g., “Blod”). Eventually we have two contextual cues meaning “same” and “different” that govern the pattern of behavior we apply in any given context. Importantly, the contextual cue remains constant and not the stimuli to which the associated pattern of behavior is applied.

This basic paradigm can be extended further towards more complex relations, such as opposition. For example, by including three comparison stimuli in a match to sample procedure, one might reinforce choosing the stimulus that is least like the sample stimulus in the presence of a new stimulus (e.g., “Glep”). Across several more trials, the participant will become fluent at choosing the “least similar” (we might also call this “opposite” or “antithesis”) in the context of the previously meaningless stimulus. By the end of such an experiment, we have three stimuli meaning “same”, “different”, and “opposite” respectively.

It is, of course, cognitively effortful to abstract the commonalities across multiple exemplars in in a context-sensitive manner. However, after one has become fluent in first receptively and then expressively applying the previously learned functions of a contextual cue, it should become less effortful to “think relationally” when confronted with novel stimuli in the presence of the same contextual cue. This is theoretically consistent with both the Neural Efficiency Hypothesis (Neubauer & Fink, 2009) and the bifactor theory of intelligence (Horn & Cattell, 1967); a smarter person can apply complex patterns of behavior less effortfully as they are employing well-rehearsed operant patterns of behavior.

Asymmetrical relations. In the same vein as in Steele and Hayes (1991), people can be trained to respond in accordance with comparative relations like "more than" and "less than" (Dymond & Barnes, 1995), spatial relations like "to the right of", "to the left of", "above", and "below" (May et al., 2017), or temporal relations like "before" and "after" (cf. Brassil et al., 2019). What is common to these studies is that they involve multiple exemplars of physical relations (e.g., we can see that A is the same as B as they are the same shape/color) across which we abstract a pattern of behavior that allows us to satisfy a need (e.g., a need for reward) efficiently. We subsequently know when to apply these patterns of behavior based on the contextual cues. Contextual cues can also be related (e.g., "Bleg" is the same as "Wekt") in this kind of experimental paradigm (McLoughlin & Stewart, 2017; Perez et al., 2017) such that the functions of a conditioned contextual cue (e.g., "Bleg") change the functions of an arbitrary stimulus ("Wekt"). This might reflect a process of learning synonyms or perhaps even a new language. Here, we can see that by implementing certain schedules of reinforcement, we can shape up relatively complex pattern of behavior that can be applied across multiple environments.

Of course, in the real world, we respond even more efficiently to networks of stimuli by also providing evaluative responses like "true", "false", "yes", and "no", which can also be learned through abstraction from multiple exemplars. For example, the experimental setup (cf. McLoughlin & Stewart, 2017; Stewart et al., 2004) might include either a congruent relational network (e.g., "A1 is the same as B1"; where A1 and B1 are the same stimulus) or an incongruent relational network (e.g., "A1 is the same as B2"; where A1 and B2 are not the same stimulus). Two arbitrary stimuli (say, "Kef" and "Jup") serve as response options. When the relational network is congruent, the participant is reinforced for choosing "Kef". When the relation is incongruent, the participant is reinforced for choosing "Jup". In this way, across multiple trials, the stimulus “Kef” acquires the function “Yes/True” and “Jup” acquires the function “No/False”.

This *Relational Evaluation Procedure* (J. Hayes et al., 2017) allows participants to respond to increasingly complex presentations of relational networks in this bottom-up, natural-language-free manner. By “natural-language-free”, in this case, we mean that the stimuli involved are arbitrary nonsense syllables and were not part of any participants’ learning histories. Similarly, we know that response options such as “yes” and “no” that *are* likely to have been part of an individual’s learning history *can* be shaped up by reinforcing simple patterns of behavior in the presence of arbitrary stimuli (Stewart et al., 2004).

RFT also lends itself to training and testing complex relational networking processes (cf. Stewart, 2016) that are normally conceptualized as higher-order cognitive functions that are too complex to be accounted for by behavioral psychology. While it is beyond the scope of the present paper to outline all of this research in detail, we will provide some examples from the RFT literature on analogy to highlight but one RFT account of complex cognition: analogical reasoning.

Cognitive and behavioral approaches to analogy. Cognitive approaches to explaining analogical reasoning such as Structure Mapping Theory (SMT; Gentner, 1983) and the Incremental Analogy Machine (IAM; Keane, 1997) typically refer to “matching” stimulus isomorphs, or the expressive “mapping” of one isomorphic structure onto another. For example, if the relationship between Karen and Janice is one of sisterhood, then the relation “sister” operates upon the two arguments, “Karen, Janice” (sometimes written *operator-sister[Karen, Janice]*). Another stimulus relation might be *operator-sister(Hillary, Michelle)*. Noticing the structural similarity of instances of *operator-sister(X, Y)* then allows one to draw the analogy “Karen is to Janice as Hillary is to Michelle”. This was demonstrated in a series of experiments by Halford et al. (1998) adopting a broader cognitive approach to relational reasoning called *Relational Schema Theory* (RST), which is in many ways the cognitive counterpart of RFT, only adopting a mechanistic rather than pragmatic approach. One core difference between the cognitive and behavioral approaches to analogy is the criterion by which we assess our theories, and this has manifested in the respective research programs on analogy.

The truth criterion for mechanistic/cognitive theories is "correspondence" between the theory and ontological reality (Barnes-Holmes, 2000; Pepper, 1942), using a mind-as-computer metaphor (cf. Cobb, 2020 for a detailed historical overview of metaphors of the mind). It is not surprising that this language appears in cognitive theories of analogy too. For example, Hummel and Holyoak (1997) modelled analogy using a computer program that learned to map structural representations. However, in this case, it may be more accurate to say that the computer was taught to behave as if stimuli were related by its Creator, rather than there being literal ontological relationships between stimuli to be represented. In human cognition, the behavior of relating stimuli is a functional adaptation rather than discovery of some kind of pre-programmed relationship that exists in ontological terms.

On the other hand, behaviorists adopt a pragmatic truth criterion; something is "true" or not depending on whether it is useful. According to RFT, analogical responding involves identifying a relation of equivalence between two stimulus relations. For example, if I use the analogy "he is to his brother as chalk is to cheese", what I am really saying is "the relationship between Person A and Person B is the same kind of relation that holds between chalk and cheese". This is practically useful in that if I know that chalk and cheese are opposite one another, then Person A is also characteristically opposite Person B. Then, if we know what Person A is like (e.g., Person A is outgoing), we can infer something about Person B (We might expect Person B to be introverted) whom we have never met. RFT studies on analogy have so far been characterized not primarily by making predictions in line with theory and testing those predictions, but more so by demonstrating how schedules of reinforcement can be used to shape-up this complex behavior.

Stewart et al. (2004) demonstrate how such a complex cognitive repertoire could be trained in a culturally unbiased manner. In their experimental paradigm, they first established contextual cue functions (“Same” and “Different”) in arbitrary stimuli, and then evaluative functions (“Yes and “No”) in two more arbitrary stimuli using the aforementioned paradigms. Next, they provided blocks of trials in which a whole relational network served as the sample stimulus: two relational statements (e.g., “A is the same as B” and “C is different to D”) along with a contextual cue (e.g., “is the same as”) between these statements. These were followed by two response options, “Yes” and “No”. That is, the participants were presented with an entire relational network meaning “A is to B as C is to D; true or false?”. Selecting “false” in the presence of an incongruent network, and “true” in the presence of a congruent network were reinforced. In this way, across multiple trials, analogical responding, traditionally thought of as a form of complex cognition, could be trained as a conditioned response that can be applied to arbitrary stimuli given the appropriate contextual cues.

Complex cognition such as analogical responding, when conceptualized in RFT terms, can be shaped up through schedules of reinforcement, making it a promising avenue of research in cognitive training. For instance, Carpentier et al. (2002) tested for the ability to relate simple stimulus relations in 5-year-olds, 9-year-olds, and adults, finding that the 5-year-olds could not relate stimulus relations successfully. However, it was possible to facilitate the ability to relate stimulus relations by first introducing simpler relational tasks. While it is not yet clear whether RFT’s conceptualization of analogical responding is correct, Ruiz and Luciano (2011) found that those who needed fewer training trials to pass an analogical relational test tended to score higher on a traditional analogical reasoning test (r = -.78 and r = -.74) of the sort typically found as an IQ subtest.

Going Beyond "Matching" and "Mapping"

One of the main differences between a cognitive/mechanistic approach to a problem such as analogy (RST) and its behavioral/pragmatic counterpart (RFT) is that behavioral psychology puts greater emphasis on the functional aspect of cognition in its methods. Behavior is explicitly conceptualized as a process of environmental adaptation; it is arbitrarily applicable, but functionally and contextually applied. That is, one will treat two potential isomorphs as being analogous depending on whether it achieves a desirable outcome (e.g., reward, in an experimental context). This implies that it should be possible to get analogical responding under contextual control using schedules of reinforcement.

This was achieved by Stewart et al. (2001) who first trained participants to relate relational isomorphs formed based on their association with a common physical property of color, instead of their shape. This involves a matching to sample procedure where nonsense words where participants were reinforced for selecting a particular nonsense syllable (A) in the presence of shapes of a certain color, while selecting other nonsense syllables (B) in the presence of new shapes of that same color, thereby being able to derive that the A:B relation is one of equivalence (based on the common color). In a similar way, other stimuli were trained as being equivalent, based on color, creating new derived equivalence relations (C:D). Finally, participants were trained such that other stimulus relations were non-equivalent (e.g., E:F; G:H). Therefore, some derived relations were isomorphic (e.g., A is to B as C is to D; E is to F as G is to H), while others were not (A is to B is different from E is to F; C is to D is different from G is to H). The probe test tested whether participants would treat only the relational isomorphs as being equivalent. Participants responded in accordance with their history of reinforcement (relating derived stimulus relations based on color) rather than in accordance with shape, which was not reinforced. In their second experiment, the same general pattern was demonstrated using larger relational networks. In their third experiment, they trained participants to relate isomorphs based on a more abstract property of age, a more ecologically valid version of the first to experiments.

This study was expanded in a series of experiments by Stewart et al. (2002). The same basic paradigm was used for the se experiments. In Experiment 1, participants were taught to relate stimuli either based on the formal property of color (i.e., two nonsense syllables, A and B, were equivalent if participants were taught to select A in the presence of a green triangle and B in the presence of a green circle, but neither in the presence of a red triangle or circle), while other participants were trained to relate stimuli based on shape (i.e., two nonsense syllables, C and D, were equivalent if participants were taught to select C in the presence of a red triangle and D in the presence of a green triangle, but neither in the presence of a red or green circle). Control participants were reinforced for matching stimuli based on both color and shape. In probe tests for relating stimulus relations, experimental participants responded in accordance with the predicted analogical meta-relations reflecting their history of reinforcement, while the control participants showed no consistent matching pattern. In a further experiment, they found that symbolic meaning transferred across these kinds of relational networks.

These studies used small sample sizes, as is typical in behavioral experiments, which might raise concern over power and the possibility of Type 1 error. However, to pass any given training stage, participants were required to answer 4/5 probe trials correctly, meaning that there was a .156 probability of passing the first training block of each study by chance. As passing subsequent blocks depended on mastery on the previous blocks, the cumulative error rate for the second test is $.156^2$ for the second test, $.156^3$ for the third, and so on. In sum, the probability of even a single participant demonstrating the predicted pattern of analogical responding by chance in these experiments was quite low. Across both studies, Stewart et al. showed that the behavior of treating what started out as arbitrary stimulus pairings as being relationally isomorphic or not can come under contextual control depending on the schedules of reinforcement implemented. This shows how analogy is driven by its function and context, which is emphasized in RFT, and not merely structure, which is emphasized more in cognitive/mechanistic accounts like the SMT and IAM. Moreover, this pattern of behavior is subject to reinforcement contingencies (i.e., systematic environmental influence).

Some later experiments by Halford and Busby (2007) mention that relational schemas are meaningful, emphasizing goal states in their Relational Schema Induction Paradigm. However, the goal state is only reached in logical/structural terms rather than based on reinforcement contingencies. For example, when presented with a hexagon with numbers 1-6 written in the corners in clockwise order, a problem might be posed as follows: *anti-clockwise(3, ?)*, testing whether a participant will correctly respond "2". Here the goal state is completing the relational statement, meaning that the behavior is functional, but not under contextual control of reinforcement contingencies. In contrast, RFT studies of analogy emphasize manipulating schedules of reinforcement to bring analogical responding under contextual control of the experimenter, as in Stewart et al. (2001) above (cf. also Stewart et al., 2002).

Other RFT studies focus on training/facilitating other advanced forms of cognition (cf. Stewart et al., 2020) such as class containment/categorization (Ming et al., 2018; Mulhern et al., 2017, 2018), hierarchical responding (Slattery et al., 2011; Slattery & Stewart, 2014; Stewart et al., 2018), perspective-taking (Guinther, 2017, 2018) and rule-governed behavior (O'Hora et al., 2004; Tarbox et al., 2011). Such studies condition these particular relational responses to arbitrary stimuli in the presence of particular contextual cues using targeted schedules of reinforcement. The use of arbitrary stimuli within these reinforcement schedules is important because it helps us to account for (i) how we might have evolved to perform these adaptive patterns of cognition before establishing natural language, and importantly, (ii) how established patterns of relational framing might be expected to transfer across stimulus sets (cf. McLoughlin et al., 2020).

Applications of RFT: The example of the SMART program. There is some promising initial data from RFT on how relational operants can be shaped up through schedules of reinforcement. One such program called Strengthening Mental Abilities with Relational Training (SMART; Cassidy et al., 2016) uses simple schedules of reinforcement to train the ability to use both symmetrical (same/opposite) and asymmetrical (more/less) relational operants. Users can make progress incrementally with small increases in complexity across 70 stages. For example, Stage 1 might provide a statement like, "WEK is the same as JUB" and ask a question about it like "Is WEK the same as JUB?" to which one can respond with "Yes" or "No". Across trials, no nonsense syllable (e.g., WEK, JUB) appears more than once, meaning that users are trained to respond in accordance with the operator "same as" in a simple two-argument relational network. More advanced stages might provide a similar relational premise, but ask the question "Is JUB the same as WEK". This kind of stage teaches users that "same as" is symmetrical (i.e., *operator-same[X, Y] = operator-same[Y, X]*). Once users learn how to use "same as", they can practice using it in increasingly complex networks, perhaps in combination with other stimulus relations:

WEK is the same as JUB

HAL is the same as JUB

Is HAL opposite to WEK?

YES NO

Other symmetrical relations might be more complex. For example, the opposite of an opposite relation is a sameness relation:

WEK is opposite JUB

HAL is the same as JUB

HAL is opposite LAK

Is LAK opposite to WEK?

NO YES

Asymmetrical relations add even more complexity, as for the first time, an A:B relation will not be the same as a B:A relation (e.g., *operator-more[X, Y]* != *operator-more[Y, X]*). Instead, we need a new contextual cue, “less than”, which can also be trained up. Sometimes it may even be possible to train contextual cues by relating them to previously learned contextual cues (e.g., *operator-opposite[more, less]*), a sort of meta-relational response (McLoughlin & Stewart, 2017; Perez et al., 2017), though this is currently outside of the scope of SMART.

What makes SMART uniquely promising as a cognitive intervention is that it uses new nonsense stimuli across every trial to ensure that the patterns of relational behavior that are trained will apply across stimulus sets, as long as the relevant contextual cue is present. It also holds an advantage over some other kinds of cognitive training in that the complexity increments quite gradually across 70 stages in a theoretically informed manner. For example, N-Back working memory training involves trying to remember the symbol N positions back in a continuous sequence. For example, in the sequence “…A, I, V, L, T”, in the 2-Back condition, the symbol that is two positions back from the current symbol is “V”. N-Back requires comparatively large steps upwards in complexity, with stark differences in the demands put on trainees who complete 1-Back compared to 5-Back.

Although SMART started out with some small studies reporting quite large effects of the training on IQ (Cassidy et al., 2011), researchers in this area have used each study to justify larger, better-controlled studies. So far, there have been three independent conceptual replications of this study employing active control conditions (J. Hayes & Stewart, 2016; McLoughlin, Tyndall, & Pereira, 2020; McLoughlin, Tyndall, Pereira, et al., 2020), with a pre-registered meta-analysis in progress (May et al., 2019). Overall, there is a clear upward trajectory in methodological progress in this area, with researchers going beyond traditional small-N behavioral experiments. While this research program is ongoing, large-scale, well-controlled randomized trials are not possible without first conducting intermediary studies. The unanimously positive results of this approach to cognitive training so far should be notable, given the theoretical consilience across multiple fields (E. O. Wilson, 1998), as highlighted in the present paper.

At least one another approach to cognitive training used inductive reasoning tasks and was quite successful. This inductive reasoning training for solving relational problems is highly verbal, pre-supposing crystallized knowledge of the stimuli used in the training. Klauer (1996, p.57) provides the following example of an item from his inductive reasoning training: “In this series, one expression is out of sequence. Can you tell me which one and why? To creep – to run – to walk – to rush – to race” (cf. Klauer & Phye, 2008 for an overview of this research). However, this training is arguably not optimal for at least three reasons: (i) it is delivered by teachers using a manual rather than being automated, making it more likely that delivery could be contaminated by teacher effects, (ii) it involves collaborative problem solving in a group setting, meaning that there is a lack of control over the schedules of reinforcement involved, and (iii) they use learned categories (e.g., animal names) when priming people to look for symbolic commonalities, rather than getting relating behavior under contextual control via the identification of perceptual regularities amongst semantically arbitrary stimuli. Although this training appears to prime people to use relational reasoning when they encounter new stimulus sets, the transfer effects from SMART are less likely to be contaminated by learned symbolic properties of the training stimuli. This is by virtue of the fact that RFT shows how induction from basic perceptual regularities amongst arbitrary stimuli can be used to establish deductive reasoning to be applied to both physical and symbolic properties of novel stimuli. In other words, far transfer of training effects may be further supported by using multiple exemplars of arbitrary stimuli during training, rather than using stimuli that already exist within one’s semantic networks.

Conclusion

Cognitive psychology, in which the agents causing our behavior are top-down mental processes, is faced with the challenge of moving beyond providing structural models that describe or predict psychological functioning towards changing complex behavior. Contextual, operant psychology may provide a useful way forward in this respect (S. C. Hayes et al., 2012). Indeed, many cognitive behavioral therapists already employ schedules of reinforcement and other behavioral techniques (e.g., exposure) when it comes to affecting clients’ behavior for the better. Interventions that target *cognitive* processes, the hypothesized mental structures that are useful for describing and predicting behavior, have not yet borne fruit when it comes to influencing general cognitive ability (Moreau et al., 2019; Sala et al., 2019). A functional approach to psychological science has borne some fruit in this regard (Stewart, 2016) and is theoretically compatible with contemporary Cognitive Science (Goldwater & Schalk, 2016; Halford et al., 2012), Linguistics (Everaert et al., 2015, 2017; Yang et al., 2017), Education (Alexander et al., 2016; Dumas, 2017; Dumas et al., 2013), Neuroscience (Davis et al., 2017), and Evolution Science (D. S. Wilson & Hayes, 2018). Thus, it is instructive to note that the importance of accounting for and influencing relational reasoning appears across multiple disciplines and paradigmatic approaches regardless of where each scientific perspective might lie on a theoretical deductive-inductive continuum.

Crucially, conceptualizing cognition as AARR provides a technical account of how cross-domain transfer of training effects might be achieved, with supporting basic research studies, helping to address a theoretical gap, *how to influence behavior*, not typically addressed in cognitive psychology. Many of these studies in the RFT literature demonstrate the establishment of relational reasoning abilities as patterns of behavior that are shaped by the non-random environment. This research endeavor is ongoing, however, and further research in this area (cf. McLoughlin, Tyndall, Mulhern, & Ashcroft, 2019 for some suggestions) is warranted. Indeed, further empirical work exploring the relationship between these generalized operant repertoires and cognitive ability would be instructive. For example, one recent study has found that *g* (i.e., the general intelligence factor) and *Gf* (the fluid intelligence factor) may be empirically indistinguishable (Caemmerer et al., 2020), and so those who champion relational reasoning as being the fuel and fire of cognition might test the hypothesis that *Gf* can be operationalized as overlapping patterns of relational reasoning (cf. Chuderski, 2019; Kovacs & Conway, 2019). If this hypothesis is supported by the data, then RFT has already made inroads in terms of how to train relational reasoning as a generalizable skill, making generalized relational operants useful behavioral (rather than cognitive) repertoires to target with cognitive training.

References

Alexander, P. A. (2019). Individual differences in college-age learners: The importance of relational reasoning for learning and assessment in higher education. *British Journal of Educational Psychology*, *89*(3), 416–428. https://doi.org/10.1111/bjep.12264

Alexander, P. A., Jablansky, S., Singer, L. M., & Dumas, D. (2016). Relational reasoning: What we know and why it matters. *Policy Insights from the Behavioral and Brain Sciences*, *3*(1), 36–44. https://doi.org/10.1177/2372732215622029

Andrews, G., & Halford, G. S. (1998). Children's ability to make transitive inferences: The importance of premise integration and structural complexity. *Cognitive Development*, *13*(4), 479–513. https://doi.org/10.1016/S0885-2014(98)90004-1

Andrews, G., Halford, G. S., & Boyce, J. (2012). Conditional discrimination in young children: The roles of associative and relational processing. *Journal of Experimental Child Psychology*, *112*(1), 84–101. https://doi.org/10.1016/j.jecp.2011.12.004

Barnes-Holmes, D. (2000). Behavioral pragmatism: No place for reality and truth. *Behavior Analyst*, *23*(2), 191–202. https://doi.org/10.1007/BF03392010

Barnes-Holmes, D., Regan, D., Barnes-Holmes, Y., Commins, S., Walsh, D., Stewart, I., Smeets, P. M., Whelan, R., & Dymond, S. (2005). Relating derived relations as a model of analogical reasoning: reaction times and event-related potentials. *Journal of the Experimental Analysis of Behavior*, *84*(3), 435–451. https://doi.org/10.1901/jeab.2005.79-04

Barnes, D., Hegarty, N., & Smeets, P. M. (1997). Relating equivalence relations to equivalence relations: A relational framing model of complex human functioning. *The Analysis of Verbal Behavior*, *14*(1), 1–27. https://doi.org/10.1007/bf03392916

Berridge, K. C., & Robinson, T. E. (1998). What is the role of dopamine in reward: Hedonic impact, reward learning, or incentive salience? *Brain Research Reviews*, *28*(3), 309–368.

https://doi.org/10.1016/S0165-0173(98)00019-8

Berwick, R. C., & Chomsky, N. (2019). All or nothing: No half-merge and the evolution of syntax The evolution of syntax. *PLoS Biology*, *17*(11), 1–5. https://doi.org/10.1371/journal.pbio.3000539

Birney, D. P., Halford, G. S., & Andrews, G. (2006). Measuring the influence of complexity on relational reasonings - The development of the latin square task. *Educational and Psychological Measurement*, *66*(1), 146–171. https://doi.org/10.1177/0013164405278570

Brassil, N., Hyland, J., O'Hora, D., & Stewart, I. (2019). Reversing time and size: Mutual entailment of nonarbitrary temporal and magnitude relational responding. *Psychological Record*, *69*(1), 95–105. https://doi.org/10.1007/s40732-018-0323-y

Bull, R., Espy, K. A., & Wiebe, S. A. (2008). Short-term memory, working memory, and executive functioning in preschoolers: Longitudinal predictors of mathematical achievement at age 7 years. *Developmental Neuropsychology*, *33*(3), 205–228. https://doi.org/10.1080/87565640801982312

Caemmerer, J. M., Keith, T. Z., & Reynolds, M. R. (2020). Beyond individual intelligence tests: Application of Cattell-Horn-Carroll Theory. *Intelligence*, *79*, 101433. https://doi.org/10.1016/j.intell.2020.101433

Carpentier, F., Smeets, P. M., & Barnes-Holmes, D. (2002). Matching functionally same relations: Implications for equivalence-equivalence as a model for analogical reasoning. *Psychological Record*, *52*(3), 351–370. https://doi.org/10.1007/BF03395435

Carpentier, F., Smeets, P. M., Barnes-Holmes, D., & Stewart, I. (2004). Matching derived functionally-same stimulus relations: Equivalence-equivalence and classical analogies. *Psychological Record*, *54*(2), 255–273. https://doi.org/10.1007/BF03395473

Cassidy, S., Roche, B., Colbert, D., Stewart, I., & Grey, I. M. (2016). A relational frame skills training intervention to increase general intelligence and scholastic aptitude. *Learning and Individual*

Differences, *47*, 222–235. https://doi.org/10.1016/j.lindif.2016.03.001 1041-6080

Cassidy, S., Roche, B., & Hayes, S. C. (2011). A Relational Frame Training intervention to raise intelligence quotients: a pilot study. *The Psychological Record*, *61*(2), 1–26. https://doi.org/https://doi.org/10.1007/BF03395755

Cassidy, S., Roche, B., & O'Hora, D. (2010). Relational Frame Theory and Human Intelligence. *European Journal of Behavior Analysis*, *11*(1), 37–51. https://doi.org/10.1080/15021149.2010.11434333

Chiesa, M. (1998). Beyond mechanism and dualism: Rethinking the scientific foundations of psychology. *British Journal of Psychology*, *89*(3), 353–370. https://doi.org/10.1111/j.2044-8295.1998.tb02690.x

Chuderski, A. (2019). Even a single trivial binding of information is critical for fluid intelligence. *Intelligence*, *77*(6), 101396. https://doi.org/10.1016/j.intell.2019.101396

Cobb, M. (2020). *The idea of the brain: A history*. Profile Books.

Colbert, D., Dobutowitsch, M., Roche, B., & Brophy, C. (2017). The proxy-measurement of intelligence quotients using a relational skills abilities index. *Learning and Individual Differences*, *57*, 114–122. https://doi.org/10.1016/j.lindif.2017.03.010

Davis, T., Goldwater, M., & Giron, J. (2017). From concrete examples to abstract relations: The rostrolateral prefrontal cortex integrates novel examples into relational categories. *Cerebral Cortex*, *27*(4), 2652–2670. https://doi.org/10.1093/cercor/bhw099

De Houwer, J. (2018). A Functional-Cognitive Framework for cooperation between functional and cognitive researchers in the context of stimulus relations research. *Perspectives on Behavior Science*, *41*(1), 229–240. https://doi.org/10.1007/s40614-017-0089-6

De Houwer, J., Hughes, S., & Barnes-Holmes, D. (2017). Psychological Engineering: A Functional–

Cognitive Perspective on Applied Psychology. *Journal of Applied Research in Memory and Cognition*, *6*(1), 1–13. https://doi.org/10.1016/j.jarmac.2016.09.001

Don, H. J., Goldwater, M. B., Otto, A. R., & Livesey, E. J. (2016). Rule abstraction, model-based choice, and cognitive reflection. *Psychonomic Bulletin and Review*, *23*(5), 1615–1623. https://doi.org/10.3758/s13423-016-1012-y

Dumas, D. (2017). Relational reasoning in Science, Medicine, and Engineering. *Educational Psychology Review*, *29*(1), 73–95. https://doi.org/10.1007/s10648-016-9370-6

Dumas, D., Alexander, P. A., Baker, L. M., Jablansky, S., & Dunbar, K. N. (2014). Relational reasoning in medical education: Patterns in discourse and diagnosis. *Journal of Educational Psychology*, *106*(4), 1021–1035. https://doi.org/10.1037/a0036777

Dumas, D., Alexander, P. A., & Grossnickle, E. M. (2013). Relational reasoning and its manifestations in the educational context: A systematic review of the literature. *Educational Psychology Review*, *25*(3), 391–427. https://doi.org/10.1007/s10648-013-9224-4

Dymond, S., & Barnes, D. (1995). A transformation of self-discrimination response functions in accordance with the arbitrarily applicable relations of sameness and opposition. *Psychological Record*, *46*(2), 271–300. https://doi.org/10.1901/jeab.1995.64-163

Dymond, S., & Roche, B. (2013). *Advances in Relational Frame Theory : Research and Application*. Context Press.

Everaert, M. B. H., Huybregts, M. A. C., Berwick, R. C., Chomsky, N., Tattersall, I., Moro, A., & Bolhuis, J. J. (2017). What is language and how could it have evolved? *Trends in Cognitive Sciences*, *21*(8), 569–571. https://doi.org/10.1016/j.tics.2017.05.007

Everaert, M. B. H., Huybregts, M. A. C., Chomsky, N., Berwick, R. C., & Bolhuis, J. J. (2015). Structures, not strings: Linguistics as part of the cognitive sciences. *Trends in Cognitive Sciences*, *19*(12), 729–743. https://doi.org/10.1016/j.tics.2015.09.008

Farrington-Flint, L., Canobi, K. H., Wood, C., & Faulkner, D. (2007). The role of relational reasoning in children's addition concepts. *British Journal of Developmental Psychology*, *25*(2), 227–246. https://doi.org/10.1348/026151006X108406

Freeman, C. (2019). *Going the Extra Mile! Investigating the Relationship between Relational Complexity and Metaphor Comprehension* [The Chicago School of Professional Psychology]. https://search.proquest.com/docview/2376767114?pq-origsite=gscholar&fromopenview=true

Gentner, D. (1983). Structure-mapping: A theoretical framework for analogy. *Cognitive Science*, *7*(2), 155–170. https://doi.org/10.1016/S0364-0213(83)80009-3

Gladwin, T. E., & Figner, B. (2014). "Hot" cognition and dual systems: Introduction, criticisms, and ways forward. In E. Wilhelms & V. Reyna (Eds.), *Frontiers of Cognitive Psychology Series: Neuroeconomics, Judgment and Decision Making* (pp. 157–180). Psychology Press.

Gladwin, T. E., Figner, B., Crone, E. A., & Wiers, R. W. (2011). Addiction, adolescence, and the integration of control and motivation. *Developmental Cognitive Neuroscience*, *1*(4), 364–376. https://doi.org/10.1016/j.dcn.2011.06.008

Goldwater, M. B. (2017). Grammatical constructions as relational categories. *Topics in Cognitive Science*, *9*(3), 776–799. https://doi.org/10.1111/tops.12272

Goldwater, M. B., Don, H. J., Krusche, M. J. F., & Livesey, E. J. (2018). Relational discovery in category learning. *Journal of Experimental Psychology: General*, *147*(1), 1–35. https://doi.org/10.1037/xge0000387

Goldwater, M. B., & Schalk, L. (2016). Relational categories as a bridge between cognitive and educational research. *Psychological Bulletin*, *142*(7), 729–757. https://doi.org/10.1037/bul0000043

Guinther, P. M. (2017). Contextual influence over deriving others' true beliefs using a relational triangulation perspective-taking protocol (RT-PTP-M1). *Journal of the Experimental Analysis of*

Behavior, *108*(3), 433–456. https://doi.org/10.1002/jeab.291

Guinther, P. M. (2018). Contextual influence over deriving another's false beliefs using a relational triangulation perspective taking protocol (RT-PTP-M2). *Journal of the Experimental Analysis of Behavior*, *110*(3), 500–521. https://doi.org/https://doi.org/10.1002/jeab.480

Halford, G. S. (1984). Can young children integrate premises in transitivity and serial order tasks? *Cognitive Psychology*, *16*(1), 65–93. https://doi.org/10.1016/0010-0285(84)90004-5

Halford, G. S., Andrews, G., Wilson, W. H., & Phillips, S. (2012). Computational models of relational processes in cognitive development. *Cognitive Development*, *27*(4), 481–499. https://doi.org/10.1016/j.cogdev.2012.08.003

Halford, G. S., Bain, J. D., Maybery, M. T., & Andrews, G. (1998). Induction of relational schemas: Common processes in reasoning and complex learning. *Cognitive Psychology*, *35*(3), 201–245. https://doi.org/10.1006/cogp.1998.0679

Halford, G. S., & Busby, J. (2007). Acquisition of structured knowledge without instruction: The Relational Schema Induction Paradigm. *Journal of Experimental Psychology: Learning Memory and Cognition*, *33*(3), 586–603. https://doi.org/10.1037/0278-7393.33.3.586

Halford, G. S., Wilson, W. H., & Phillips, S. (2010). Relational knowledge: The foundation of higher cognition. *Trends in Cognitive Sciences*, *14*(11), 497–505. https://doi.org/10.1016/j.tics.2010.08.005

Hayes, J., & Stewart, I. (2016). Comparing the effects of derived relational training and computer coding on intellectual potential in school-age children. *The British Journal of Educational Psychology*, *86*(3), 397–411. https://doi.org/10.1111/bjep.12114

Hayes, J., Stewart, I., & McElwee, J. (2017). Children's answering of yes-no questions: A review of research including particular consideration of the relational evaluation procedure. *Behavioral Development Bulletin*, *22*(1), 173–182. https://doi.org/10.1037/bdb0000027

Hayes, S. C., Barnes-Holmes, D., & Roche, B. (2001). *Relational Frame Theory: A Post-Skinnerian Account of Human Language and Cognition*. Plenum Press.

Hayes, S. C., Barnes-Holmes, D., & Wilson, K. G. (2012). Contextual behavioral science: Creating a science more adequate to the challenge of the human condition. *Journal of Contextual Behavioral Science*, *1*(1–2), 1–16. https://doi.org/10.1016/j.jcbs.2012.09.004

Horn, J. L., & Cattell, R. B. (1967). Age differences in fluid and crystallized intelligence. *Acta Psychologica*, *26*(C), 107–129. https://doi.org/10.1016/0001-6918(67)90011-x

Hummel, J. E., & Holyoak, K. J. (1997). Distributed representations of structure: A theory of analogical access and mapping. *Psychological Review*, *104*(3), 427–466. https://doi.org/10.1037/0033-295X.104.3.427

Hyland, J. M., O'Hora, D. P., Leslie, J. C., & Smyth, S. (2012). Sequential responding in accordance with temporal relational cues: A comparison of before and after. *Psychological Record*, *62*(3), 463–484. https://doi.org/10.1007/BF03395814

Jablansky, S., Alexander, P. A., Dumas, D., & Compton, V. (2016). Developmental differences in relational reasoning among primary and secondary school students. *Journal of Educational Psychology*, *108*(4), 592–608. https://doi.org/10.1037/edu0000070

Jung, R. E., & Haier, R. J. (2007). The Parieto-Frontal Integration Theory (P-FIT) of intelligence: converging neuroimaging evidence. *The Behavioral and Brain Sciences*, *30*(2), 135–187. https://doi.org/10.1017/S0140525X07001185

Keane, M. T. (1997). What makes an analogy difficult? The effects of order and causal structure on analogical mapping. *Journal of Experimental Psychology: Learning Memory and Cognition*, *23*(4), 946–967. https://doi.org/10.1037/0278-7393.23.4.946

Khemlani, S., & Johnson-Laird, P. N. (2012). Theories of the syllogism: A meta-analysis. *Psychological Bulletin*, *138*(3), 427–457. https://doi.org/10.1037/a0026841

Klauer, K. J. (1996). Teaching inductive reasoning: Some theory and three experimental studies. *Learning and Instruction*, *6*(1), 37–57. https://doi.org/10.1016/S0959-4752(96)80003-X

Klauer, K. J., & Phye, G. D. (2008). Inductive reasoning: A training approach. *Review of Educational Research*, *78*(1), 85–123. https://doi.org/10.3102/0034654307313402

Kovacs, K., & Conway, A. R. A. (2019). What is IQ? Life beyond “general intelligence.” *Current Directions in Psychological Science*, *28*(2), 181–194. https://doi.org/10.1177/0963721419827275

Lupyan, G., & Bergen, B. (2016). How language programs the mind. *Topics in Cognitive Science*, *8*(2), 408–424. https://doi.org/10.1111/tops.12155

Lupyan, G., & Dale, R. (2016). Why are there different languages? The role of adaptation in linguistic diversity. *Trends in Cognitive Sciences*, *20*(9), 649–660. https://doi.org/10.1016/j.tics.2016.07.005

Marr, M. J. (2009). The natural selection: behavior analysis as a natural science. *European Journal of Behavior Analysis*, *10*(2), 103–118. https://doi.org/10.1080/15021149.2009.11434313

May, R. J., Dally, W., Taylor, M., McTiernan, A., McLoughlin, S., Tyndall, I., & Roderique-Davis, G. (2019). *A comprehensive systematic review and meta-analysis of the effects of the Strengthening Mental Abilities with Relational Training (SMART) intervention on measures of intelligence in children and adults*. PROSPERO: International Prospective Register of Systematic Reviews. https://www.crd.york.ac.uk/PROSPERO/display_record.php?RecordID=132404

May, R. J., Stewart, I., Baez, L., Freegard, G., & Dymond, S. (2017). Arbitrarily applicable spatial relational responding. *Journal of the Experimental Analysis of Behavior*, *107*(2), 234–257. https://doi.org/10.1002/jeab.250

McGreal, C., Hyland, J., O’ Hora, D., & Hogan, M. (2016). Mutual entailment of temporal relations in younger and older adults: Reversing order judgments. *Psychological Record*, *66*(3), 419–428.

https://doi.org/10.1007/s40732-016-0182-3

McHugh, L., Barnes-Holmes, Y., & Barnes-Holmes, D. (2004). Perspective-taking as relational responding: A developmental profile. *Psychological Record*, *54*(1), 115–144. https://doi.org/10.1007/BF03395465

McLoughlin, S., & Stewart, I. (2017). Empirical advances in studying relational networks. *Journal of Contextual Behavioral Science*, *6*(3), 329–342. https://doi.org/10.1016/J.JCBS.2016.11.009

McLoughlin, S., Tyndall, I., Mulhern, T., & Ashcroft, S. (2019). Technical Notation as a Tool for Basic Research in Relational Frame Theory. *Psychological Record*, *69*(3), 437–444. https://doi.org/10.1007/s40732-019-00344-7

McLoughlin, S., Tyndall, I., & Pereira, A. (2020). Relational operant skills training increases standardized matrices scores in adolescents: A stratified active-controlled trial. *Journal of Behavioral Education*. https://doi.org/10.1007/s10864-020-09399-x

McLoughlin, S., Tyndall, I., Pereira, A., & Mulhern, T. (2020). Non-verbal IQ gains from relational operant training explain cariance in educational attainment: An active-controlled feasibility study. *Journal of Cognitive Enhancement*, 1–16. https://doi.org/10.1007/s41465-020-00187-z

Melby-Lervåg, M., & Hulme, C. (2016). There is no convincing evidence that working memory training is effective: A reply to Au et al.(2014) and Karbach and Verhaeghen (2014). *Psychonomic Bulletin & Review*, *23*(1), 324–330. https://doi.org/10.3758/s13423-015-0862-z

Miller, E. K., & Cohen, J. D. (2001). An Integrative Theory of Prefrontal Cortex Function. *Annual Review of Neuroscience*, *24*(1), 167–202. https://doi.org/10.1146/annurev.neuro.24.1.167

Ming, S., Mulhern, T., Stewart, I., Moran, L., & Bynum, K. (2018). Training class inclusion responding in typically developing children and individuals with autism. *Journal of Applied Behavior Analysis*, *51*(1), 53–60. https://doi.org/10.1002/jaba.429

Moreau, D., Macnamara, B. N., & Hambrick, D. Z. (2019). Overstating the role of environmental factors in success: A cautionary note. *Current Directions in Psychological Science*, *28*(1), 28–33. https://doi.org/10.1177/0963721418797300

Morris, E. K., Lazo, J. F., & Smith, N. G. (2004). Whether, when, and why skinner published on biological participation in behavior. *Behavior Analyst*, *27*(2), 153–169. https://doi.org/10.1007/BF03393176

Mulhern, T., Stewart, I., & Elwee, J. M. (2017). Investigating relational framing of categorization in young children. *Psychological Record*, *67*(4), 519–536. https://doi.org/10.1007/s40732-017-0255-y

Mulhern, T., Stewart, I., & McElwee, J. (2018). Facilitating relational framing of classification in young children. *Journal of Contextual Behavioral Science*, *8*, 55–68. https://doi.org/10.1016/j.jcbs.2018.04.001

Munnelly, A., Dymond, S., & Hinton, E. C. (2010). Relational reasoning with derived comparative relations: A novel model of transitive inference. *Behavioural Processes*, *85*(1), 8–17. https://doi.org/10.1016/j.beproc.2010.05.007

Munnelly, A., Stewart, I., & Dymond, S. (2019). Symbolic generalization of discriminative functions in accordance with a five-member comparative relational network. *The Psychological Record*, *69*(1), 525–540. https://doi.org/10.1007/s40732-019-00350-9

Neubauer, A. C., & Fink, A. (2009). Intelligence and neural efficiency. *Neuroscience and Biobehavioral Reviews*, *33*(7), 1004–1023. https://doi.org/10.1016/j.neubiorev.2009.04.001

Nowak, M. A., Komarova, N. L., & Niyogi, P. (2001). Evolution of universal grammar. *Science*, *291*(5501), 114–118. https://doi.org/10.1126/science.291.5501.114

O'Hora, D., Barnes-Holmes, D., Roche, B., & Smeets, P. (2004). Derived relational networks and control by novel instructions: A possible model of generative verbal responding. *Psychological*

Record, *54*(3), 437–460. https://doi.org/10.1007/BF03395484

O'Hora, D., Peláez, M., Barnes-Holmes, D., Rae, G., Robinson, K., & Chaudhary, T. (2008). Temporal relations and intelligence: Correlating relational performance with performance on the WAIS-III. *The Psychological Record*, *58*(1), 569–584. https://doi.org/10.1007/BF03395638

Pepper, S. (1942). *World Hypotheses: Prolegomena to systematic philosophy and a complete survey of metaphysics*. University of California Press.

Perez, W. F., Kovac, R., Nico, Y. C., Caro, D. M., Fidalgo, A. P., Linares, I., de Almeida, J. H., & de Rose, J. C. (2017). The transfer of Crel contextual control (same, opposite, less than, more than) through equivalence relations. *Journal of the Experimental Analysis of Behavior*, *108*(3), 318–334. https://doi.org/10.1002/jeab.284

Piaget, J. (1936). *Origins of Intelligence in the Child*. Routledge & Kegan Paul.

Pickering, A. D., & Gray, J. A. (2001). Dopamine, appetitive reinforcement, and the neuropsychology of human learning : An individual differences approach. In *Advances in research on temperament* (pp. 113–149).

Reinhart, A. L., Haring, S. H., Levin, J. R., Patall, E. A., & Robinson, D. H. (2013). Models of not-so-good behavior: Yet another way to squeeze causality and recommendations for practice out of correlational data. *Journal of Educational Psychology*, *105*(1), 241–247. https://doi.org/10.1037/a0030368

Ruiz, F. J., & Luciano, C. (2011). Cross-domain analogies as relating derived relations among two separate relational networks. *Journal of the Experimental Analysis of Behavior*, *95*(3), 369–385. https://doi.org/10.1901/jeab.2011.95-369

Sala, G., Aksayli, N. D., Tatlidil, K. S., Tatsumi, T., Gondo, Y., & Gobet, F. (2019). Near and far transfer in cognitive training: A second-order meta-analysis. *Collabra: Psychology*, *5*(1), 18. https://doi.org/10.1525/collabra.203

Sidman, M. (1960). *Tactics of scientific research.* Basic Books.

Simons, D. J., & Chabris, C. F. (1999). Gorillas in our midst: Sustained inattentional blindness for dynamic events. *Perception*, *28*(9), 1059–1074. https://doi.org/10.1068/p281059

Skinner, B. F. (1957). *Verbal Behavior*. Copley Publishing Group.

Skinner, B. F. (1974). *About Behaviorism*. Random House USA Inc.

Skinner, B. F. (1990). Can Psychology be a science of mind? *American Psychologist*, *45*(11), 1206–1210. https://doi.org/10.1037/0003-066X.45.11.1206

Slattery, B., & Stewart, I. (2014). Hierarchical classification as relational framing. *Journal of the Experimental Analysis of Behavior*, *101*(1), 61–75. https://doi.org/10.1002/jeab.63

Slattery, B., Stewart, I., & O'Hora, D. (2011). Testing for transitive class containment as a feature of hierarchical classification. *Journal of the Experimental Analysis of Behavior*, *96*(2), 243–260. https://doi.org/10.1901/jeab.2011.96-243

Spearman, C. (1927). *The abilities of man: Their nature and measurement*. Macmillan.

Steele, D., & Hayes, S. C. (1991). Stimulus equivalence and arbitrarily applicable relational responding. *Journal of the Experimental Analysis of Behavior*, *56*(3), 519–555. https://doi.org/10.1901/jeab.1991.56-519

Stewart, I. (2016). The fruits of a functional approach for psychological science. *International Journal of Psychology*, *51*(1), 15–27. https://doi.org/10.1002/ijop.12184

Stewart, I., & Barnes-Holmes, D. (2004). Relational Frame Theory and analogical reasoning: Empirical investigations. *International Journal of Psychology and Psychological Therapy*, *4*(2), 241–262. https://doi.org/10.1007/BF03395473

Stewart, I., Barnes-Holmes, D., & Roche, B. (2004). A functional-analytic model of analogy using the relational evaluation procedure. *Psychological Record*, *54*(4), 531–552.

https://doi.org/10.1007/BF03395491

Stewart, I., Barnes-Holmes, D., Roche, B., & Smeets, P. M. (2001). Generating derived relational networks via the abstraction of common physical properties: A possible model of analogical reasoning. *Psychological Record*, *51*(1), 381–408. https://doi.org/10.1007/BF03395405

Stewart, I., Barnes-Holmes, D., Roche, B., & Smeets, P. M. (2002). A functional-analytic model of analogy: A relational frame analysis. *Journal of the Experimental Analysis of Behavior*, *78*(3), 375–396. https://doi.org/10.1901/jeab.2002.78-375

Stewart, I., McLoughlin, S., Mulhern, T., Ming, S., & Kirsten, E. B. (2020). Assessing and teaching complex relational operants: Analogy and hierarchy. In M. Fryling, R. A. Rehfeldt, J. Tarbox, & L. J. Hayes (Eds.), *Applied Behavior Analysis of Language and Cognition* (pp. 198–213). Context Press.

Stewart, I., Slattery, B., Chambers, M., & Dymond, S. (2018). An empirical investigation of part-whole hierarchical relations. *European Journal of Behavior Analysis*, *19*(1), 105–124. https://doi.org/10.1080/15021149.2017.1416525

Tarbox, J., Zuckerman, C. K., Bishop, M. R., Olive, M. L., & O'Hora, D. P. (2011). Rule-governed behavior: Teaching a preliminary repertoire of rule-following to children with autism. *The Analysis of Verbal Behavior*, *27*(1), 125–139. https://doi.org/10.1007/bf03393096

Van Hecke, J., Gladwin, T. E., Coremans, J., Destoop, M., Hulstijn, W., & Sabbe, B. (2010). Prefrontal, parietal and basal activation associated with the reordering of a two-element list held in working memory. *Biological Psychology*, *85*(1), 143–148. https://doi.org/10.1016/j.biopsycho.2010.06.005

Virués-Ortega, J. (2006). The case against B. F. Skinner 45 years later: An encounter with N. Chomsky. *The Behavior Analyst*, *29*(2), 243–251. https://doi.org/10.1007/BF03392133

Wertheim, J., & Ragni, M. (2018). The neural correlates of relational reasoning: A meta-analysis of 47 functional magnetic resonance studies. *Journal of Cognitive Neuroscience*, *30*(11), 1734–1748. https://doi.org/10.1162/jocn_a_01311

Wilson, D. S., & Hayes, S. C. (2018). *Evolution and Contextual Behavioral Science: An Integrated Framework for Understanding, Predicting, and Influencing Human Behavior*. New Harbinger: Context Press.

Wilson, E. O. (1998). Consilience: The unity of knowledge. In *Issues in Science and Technology*. Penguin Random House. https://doi.org/10.5840/pc20024124

Yang, C., Crain, S., Berwick, R. C., Chomsky, N., & Bolhuis, J. J. (2017). The growth of language: Universal Grammar, experience, and principles of computation. *Neuroscience and Biobehavioral Reviews*, *81*(1), 103–119. https://doi.org/10.1016/j.neubiorev.2016.12.023